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Towards a low-carbon and circular economy: Scenarios for metal stocks and flows in the Dutch electricity system

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ABSTRACT

Despite many studies of the metal requirements for a transition towards low-carbon electricity system, the potential of the electricity system as a source for secondary material remains underexplored. We addressed this gap, the potential circularity of the electricity system, by analyzing the stocks and flows in that system towards 2050, including electricity generation, storage and transmission technologies, for both bulk metals and critical minor metals. Our model was applied to the Netherlands and was based upon detailed energy scenarios, presenting various governance structures for the Dutch energy transition. We show that the transition towards a low-carbon electricity system results in a strong growth of metal stocks and flows, both for bulk metals and for minor metals, especially for scenarios with higher levels of self-sufficiency in (renewable) electricity generation. These scenarios also show larger discrepancies between in and outflows. However, metal demand could decline substantially if material efficiencies improve, or when technologies with lower material intensities are chosen, especially for critical raw materials. While the potential for urban mining grows over time, at present a significant share of decommissioned components of the electricity system turns into hibernating stocks and remains unused, resulting in a missed opportunity for repurposing of valuable metals. National policies could therefore be aimed at maximizing collection of metals from the urban mine, together with the deployment of recycling capacity and stimulating material efficiency through technological development.

1. Introduction

To secure future resource supply and limit the generation of waste and emissions, ambitious goals have been set around the world for a transition towards a circular economy (CE) (EC, 2020; McDowall et al., 2017). Urban mining, referring to the recovery of materials from anthropogenic stocks (Cossu and Williams, 2015), presents a cornerstone of the circular economy. Anthropogenic stocks of materials embedded in products and structures are increasingly gaining interest as a potential source of secondary materials, but also because they form the drivers for environmental impacts. They generate waste, and generate emissions directly via their life cycles and energy usage (Fishman et al., 2021; Peled and Fishman, 2021; Wiedenhofer et al., 2019). Analyzing the dynamics of these stocks over time can provide valuable information on waste and emissions, but also on the potential for closing material loops (Pauliuk et al., 2012).

The electricity system is such a stock. Its dynamics are of high interest because of rapid growth in electricity demand and the transition towards a renewable energy system (IEA, 2021a). Global trends show an exponential growth of renewable energy technologies (Sprecher and Kleijn, 2021). The stocks in this system therefore not only grow, but also change. Diverging pathways to reach a net zero energy system by 2050 have been formulated (IEA, 2021a; O'Neill et al., 2017; Ouden et al., 2020), all having different implications for material demand and the recovery potential from the urban mine (Deetman et al., 2021). How different energy transition pathways affect material stock dynamics therefore presents an important research direction in support of both circular and low-carbon policy goals.

Previous literature on stock dynamics has focused largely on buildings (e.g. Deetman et al., 2020; Fishman et al., 2021;Heeren and Hellweg, 2018). Some studies addressed stock dynamics of infrastructure (Tanikawa et al., 2015), electronic appliances and vehicles (Deetman et al., 2018; Wang et al., 2018; Watari et al., 2019). In recent years, also the electricity system has gained increasing scientific interest. Research

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on this topic concentrates largely on metal requirements for materials for energy technologies (de Koning et al., 2018; Junne et al., 2020; Kleijn et al., 2011; Lee et al., 2020; Månberger and Stenqvist, 2018; Tokimatsu et al., 2018). Such studies demonstrate the growing and potentially critical material demand associated with the transition from a fossil-based energy system towards clean energy technologies.

Only few studies assessed the potential to repurpose metal outflows from the electricity system. These focus mainly on electricity generation technologies (Cao et al., 2019; Elshkaki and Shen, 2019). Recent insights indicate that large metal stocks are also present in the electricity transmission and distribution (T&D) grid, including electricity cables, substations, transformers and high voltage pylons (Deetman et al., 2021; Kalt et al., 2021; Li et al., 2020). The expected growth of electricity demand and renewable electricity generation technologies will result in a significant growth of the T&D grid, in due time leading to a larger outflow of waste materials. A third part of the electricity system is storage. Presently, the storage capacity is minor, but when a large part of the electricity relies on intermittent sources, sufficient storage capacity will be very important (Child et al., 2019). No clear picture exists yet of what a mature electricity storage system would look like, but likely it will contain metals, and especially critical materials, as well (Nadeem et al., 2019).

Finally, material stock-flow studies tends to neglect retired stocks that remain in place unused: hibernating stocks (Kapur and Elshkaki, 2006). These stocks might be substantial for the electricity system due to the placement of some of the components under the ground or under sea, making them difficult to extract (Chen et al., 2021; Krook et al., 2011).

This article focuses on the interplay between the energy transition and circular economy, taking the electricity system of the Netherlands as a case study. Transitioning to a renewable electricity system will require a large investment of materials, but also raises the possibility of urban mining to supply these materials. Because we are dealing with a system in transition, it is an open question to what degree the discarded materials match the newly required materials. We analyze the stock dynamics of both bulk and minor metals in the T&D grid and electricity generation and storage technologies. We specify the material requirements for the future sustainable electricity system, but we also investigate what share of the stock becomes available for recovery after the use phase, and what share enters the hibernating stock.

The starting point of our analysis is a detailed bottom-up inventory of metal stocks in the current electricity system. We couple the inventory to three scenarios for the development of the electricity system towards 2050, taken from detailed energy models developed for the Dutch network operators (CE 2017; Ouden et al., 2020). These models and scenarios are used for long-term capacity allocation planning. In all three scenarios energy ambitions are met, with different levels of self-sufficiency in electricity supply. The present work is built on detailed energy models used for real-world policy making. This allows us to explore the interaction between of climate and circularity related policy goals resulting in meaningful policy recommendations.

2. Methods

2.1. Approach

In this section we describe the approach for calculating material stocks and flows in the electricity system. Fig. 1 presents an overview of the analysis steps. The calculations were executed with a Python based model, utilizing the “Open software framework for DYnamic Material systems” (ODYM) module developed by Pauliuk & Heeren (2020). This module presents an open source framework for modeling dynamic material systems, including inflow-driven (Van der Voet et al., 2002) and stock-driven (Müller, 2006) modeling. ODYM enables standardized computation of material flow analysis (MFA) models and systematic use and manipulation of large and complex datasets. The model follows the different age-cohorts and uses a survival function based upon a lifetime distribution to calculate what share of the stock implemented in year t_0 survives after t years.

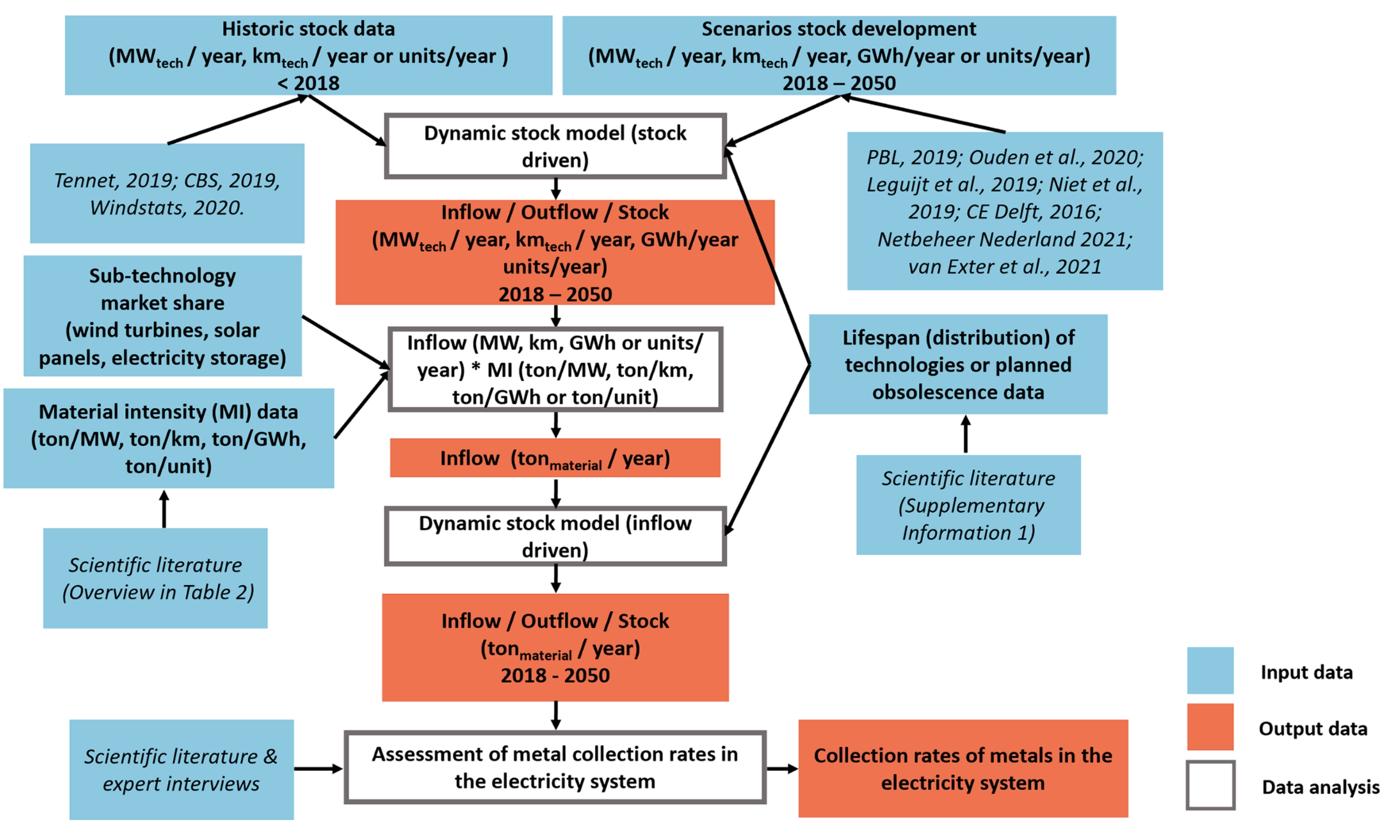

Fig. 1. Overview of study approach, presenting input data, data analysis steps, and data analysis outputs.

To assess the material stock in our base year, we largely used product-specific and spatially explicit data points. While this study focused on quantifying the stock dynamics and excluded spatial analysis, information on location of stocks could be used to facilitate recycling logistics. The stock inventory served as a basis for the dynamic stock analysis. We defined time series from the past and linked the historic stock data to scenario data for the development of the electricity system towards 2050. The stock (*S*) was presented in installed capacity (electricity generation and storage technologies), installed kilometers (electricity cables), or installed units (transformers, substations and high voltage pylons). Together with information on lifetime distributions or planned decommissioning dates of the products (ϕ) we calculated inflows and outflows from 2018 to 2050. We used a stock-driven approach to calculate the annual inflow (*I*) of the technology (*tech*) for each year (*t*) (Equation.1):

$$I_{tech}(t) = \Delta S(t) + \sum_{t'=0}^{t} I(t')\phi(t-t') \quad (1)$$

We then applied material intensities (*MI*) to the inflows, specific per technology. The material intensities were constant or specific per sub-technology (*sub*) or cohort (*co*). The material inflow (*Imat*) calculations can be summarized as follows (Equation.2):

$$Imat_{tech}(t) = MI_{sub\ 1,\ co\ 1} * I_{tech}(t) * MS_{sub\ 1} + MI_{sub\ x,\ co\ y} * I_{tech}(t) * MS_{sub\ x} \quad (2)$$

where *MS* refers to the market share of the sub-technology. Outflows and stocks were materialized similar to the inflows in the case of one technology and constant material intensities. In the case of multiple sub-technologies (solar, wind, electricity cables, electricity storage) or cohort specific material intensities, an inflow-driven dynamic stock model was used to obtain the metal stock and outflow development over time. In the final analysis step we calculated the theoretical share of the decommissioned stock that would become available for recovery and what share enters hibernating stocks.

Our model relies on assumptions for the future that are inherent to uncertainty. To assess the sensitivity of the model outcomes to these assumptions, we include a set of alternative assumptions for the energy transition pathway, material efficiency improvements of key technologies, and market share of various storage technologies. Scenarios for the energy transition pathway are discussed in Section 2.2. and assumptions for material compositions and technology shares are discussed in Section 2.3.

2.2. Scenarios for the development of the electricity system

Three scenarios were adopted to assess the material stock and flow development related to the Dutch electricity system: scenario Middle of the road (M), scenario High Renewable (H) and scenario Low Renewable (L) (Table 1). Final electricity demand was based upon projections made by Statistics Netherlands (e.g. CBS, 2013) and ambitions outlined in the Dutch climate agreement (*Klimaatakkoord*, 2019). While assumptions for population and household growth were identical for each scenario, electricity demand differed per scenario depending on sectoral developments, e.g. the extent of electrification and isolation in buildings, the adaptation of electric vehicles, and industrial growth (Ouden et al., 2020). Scenario M aligns with the goals for implementation of renewable electricity towards 2050 as defined in the Dutch climate agreement and other related policy reports (*Klimaatakkoord*, 2019; PBL, 2020). In addition to scenario M, a relatively ambitious scenario with regard to renewable energy supply and self-sufficiency in electricity supply (scenario H) and a scenario showing a relatively low implementation of renewable energy technologies and high electricity imports (scenario L) were adopted. Scenarios H and L were developed by independent consultancies in collaboration with Dutch network providers (CE 2017; Ouden et al., 2020). Scenario H entails the largest expansion of the electricity generation capacity. In this scenario, large scale projects are executed including solar parks and offshore and onshore wind parks. Scenario L assumes an open international energy market, where the Netherlands is not self-sufficient and depends on the import of hydrogen, biomass and biofuel. In all three scenarios, climate targets set by the Dutch government are met, albeit with different means.

Table 1
Summary of scenarios for the electricity system in the year 2050. Based on (CE 2017;Leguijt et al., 2019); Netbeheer Nederland, 2021; Ouden et al., 2020; van der Niet et al., 2019, 2020) .

Electricity system characteristics	Scenario Low Renewable (L)	Middle of the Road (M)	High Renewable (H)
Scenario description	Low self-sufficiency, high electricity imports (biomass, H_2 and biogas)	Medium self-sufficiency, some electricity imports	High self-sufficiency, low electricity imports
Expansion of installed capacity for electricity generation compared to 2018	373% increase	425% increase	591% increase
Wind turbines	31.0%	32.4%	37.0%
Solar panels	31.0%	34.3%	39.1%
Gas-fired power plants	4.1%	1.8%	0.0%
Biomass & waste incineration plants	0.6%	0.4%	0.2%
Hydrogen electricity plants	33.4%	31.1%	23.7%
Expansion of transmission & distribution grid compared to 2018	39.4% increase	41.5% increase	43.6% increase
Electricity storage technologies (2018 = 0 GWh)	200 GWh	300 GWh	400 GWh

For the required electricity storage capacity, we use the results of a recent study by Dutch network providers (Netbeheer Nederland, 2021). Until 2030, the growth of electricity storage is expected to remain relatively low (van Exter et al., 2021). A larger increase is expected towards 2050, with an installed capacity twice as large in scenario H as in scenario L by 2050. For scenario M we use the mean of scenario H and scenario L.

The size of T&D grid is not linearly related to the installed capacity of electricity generation technologies. The percentage overloading on the grid is used to calculate the required expansion of the cables (in km), specific for each scenario, based upon projections of (Leguijt et al., 2019) and van der Niet et al. (2019, 2020). The authors identified bottlenecks and percentage of overloading in the high voltage grid for 2050 for different energy scenarios (CE 2017). The total percentages of overloading for the three provinces assessed by these authors were averaged to estimate the required expansion of the grid for the whole country. For the medium and low voltage grid, bottlenecks were identified as well, but not the percentage overloading. We assumed an overloading percentage of 200% of the capacity on the medium and low voltage grid, so that the bottlenecks are solved by additionally installing the same type of cable next to the existing one. Details on the calculations for the grid expansion can be found in the Supplementary Information (SI 2). We calculated the number of high-voltage pylons, substations and transformers per kilometer of cable, based upon detailed LCA studies of the English and British electricity network (Harrison et al., 2010; Turconi et al., 2014). Substations and transformer frequencies were specific for the voltage level (high-voltage, medium-voltage and low-voltages) and high-voltage pylons are only used for the overhead high-voltage electricity lines.

2.3. Material compositions

We included three bulk metals in the analysis: steel, aluminum and copper, together with 12 minor metals that are characterized as critical raw materials (CRM) (in addition to Al) (EC, 2020): silver (Ag), cadmium (Cd), gallium (Ga), indium (In), germanium (Ge), silicon (Si), neodymium (Nd), praseodymium (Pr), dysprosium (Dy) terbium (Tb), lithium (Li) and cobalt (Co). The minor metals are mainly applied in solar panels, wind turbines and electricity storage.

The material compositions of the components in the electricity system were based upon scientific literature and expert consultants. We initially assume a static material intensity for all technologies, but also explore how the results change under assumptions of increased material efficiencies (see below). For electricity cables, material intensities were expressed in metric ton (hereinafter referred to as ton) per kilometer of cable, for transformers and substations in ton per unit and for batteries in ton per gigawatt-hour (GWh). Material compositions of other technologies were expressed in ton per installed megawatt (MW).

The material composition of solar panels were based upon studies of Carrara et al. (2020) and Viebahn et al. (2015). Four sub-technologies with different metal compositions were distinguished: amorphous silicon (a-Si), copper-indium-gallium-selenide (CIGS), cadmium tellurium (CdTe) and wafer-based crystalline silicon (c-Si) panels. Until 2005 we assumed that only c-Si technologies entered the electricity market (Berenschot, 2011). Further developments of the technology share were based upon the projections made by Viebahn et al. (2015) and Carrara et al. (2020). More information on the material compositions for solar panels can be found in the Supplementary Information (SI 1).

For wind turbines, material intensity data was available specific for rated capacity of the wind turbine, hub-height, manufacturer, drive train technology and location (offshore or onshore) (Roelofs, 2020). Multiple drive train technologies and changes in their market share, developments in rated capacity, hub height and the share onshore versus offshore were taken into account. Details on compilation of the material compositions can be found in the Supplementary Information (SI 1).

We explored how increased material efficiencies affect material flow dynamics for solar and wind technologies. Material efficiency improvements were assessed specifically for these technologies because they present a substantial and growing share in the electricity system. Furthermore, material efficiency improvements are projected for these technologies in several studies, especially for the CRM (e.g. Carrara et al., 2020; Viebahn et al., 2015). Technology specific assumptions were made for reduced material intensities. For structural materials in wind turbines, a gradual reduction in the material intensity was assumed towards 20% less materials per unit of power in 2050 compared to 2018. For dysprosium, neodymium, praseodymium and terbium an annual reduction in the material intensity of 5% was assumed. For solar panels, material efficiency improvements were defined per metal for the year 2030 and 2050. Between these years, a linear annual reduction in material intensities was assumed (see SI 1 for details).

Material intensities for electricity storage were specified per battery type (see SI 1 for a complete overview). The market share of battery technologies was based upon scenarios defined by the IEA (2021b). The following technologies were included in the analysis: Lithium-Iron-Phosphate batteries (LFP), Manganese Oxide batteries (LMO), Nickel-Cobalt Aluminum Oxide batteries (NCA+), All Solid State Batteries (ASSB) and various types of Nickel Manganese Cadmium Oxide batteries (NMC-111, NMC-811, NMC-622 and NMC-523). We assume a development of storage technologies under current market trends, showing an increasing share of batteries with low quantities of cobalt (e.g. NMC 811 and ASSB). We additionally explore how the results change under a larger growth of technologies with low CRM intensities. In the latter, ASSB present the largest market share in 2040, and LFP batteries become dominant towards 2050.

A distinction is made in the T&D grid between high voltage (including off-shore) (> 110 kV), medium voltage (1–50 kV) and low voltage (< 1 kV) underground cables and overhead lines, high voltage pylons, substations and transformers. Changes in the applied conducting material in cables and lines over time were considered as well (see SI 1 for details), encompassing a transition from copper conductors towards aluminum conductors, with exception of offshore electricity cables. For substations and transformers, material compositions were specific for the voltage level as well.

3. Results

We here present the results for total installed capacity and km (Section 3.1), the stock, in and outflow of metals for the three scenarios (Section 3.2) and the collection rate at the end-of-life (Section 3.3). Table 2 presents an overview of the mean material intensities for bulk metals in the different components, based upon the share of sub-technologies, when applicable, for the year 2018. For details of the lifetime assumptions, the specific assumptions per sub-technology (wind turbines, solar panels, electricity cables and electricity storage), we refer to the Supplementary Information (SI 1).

3.1. Development of the electricity system

Fig. 2a shows the resulting development of installed capacity of electricity generation technologies until 2050. While at present fossil fuel based technologies still play a dominant role of the electricity supply, a gradual decrease of these technologies is visible towards 2050. In all scenarios wind, solar and hydrogen dominate the electricity system by 2050. However, scenario H shows a substantially larger growth of especially solar and wind technologies compared to scenario M and L. The growth of the T&D grid shows a different pattern than that of electricity generation technologies (Fig. 2b). Changes are small for the three scenarios, and growth is relatively small compared to electricity generation technologies. The lower growth for the cables can be explained by the expectation that grid expansion will be limited to a number of bottlenecks. Until 2021, the installed capacity for electricity storage is negligible, and growth is expected to remain low until 2030 (Fig. 2c). In all scenarios, the installed capacity in 2030 is assumed to be 12 GWh. Towards 2050, changes between the scenarios become apparent, showing a larger demand for electricity storage in scenarios with a large installed capacity of renewable electricity generation technologies.

3.2. Metal stocks and flows

We present the results for total metal stocks and flows in the electricity system and then zoom in on two bulk metals (steel and copper). We also zoom in to the metals applied in solar panels, wind turbines and electricity storage, as these technologies contain significant amounts of (critical) minor metals, and their stocks are expected to grow in the coming decades. Detailed results for all metals can be found in the Supplementary Information (SI 3).

Fig. 3 shows the resulting total in-use stock of the included metals in the electricity system. By 2050, the metal stock exceeds the 15 million tons for each scenario, and reaches 27 million tons in scenario High Renewable due to the large implementation of renewable electricity generation technologies. Annual metal demand increases to between 0,8 and 1,5 million tons per year in 2050 and annual metal outflow to between 0,3 and 0,5 million tons.

Steel presents the largest bulk of the metal stocks and flows (Fig. 4). The stock of steel in het electricity system increases roughly by a factor 5 (scenario L) to 9 (scenario H) by 2050 (13,5–24,2 million tons) compared to 2018. The largest steel stocks are located in wind turbines and solar panels, and smaller stocks are located in the electricity grid and hydrogen power plants. The annual steel demand increases up to a

Table 2
Bulk metal intensities for analyzed technologies. In the case of multiple sub-technologies, the mean for the year 2018 was calculated. Details on material intensities (including CRM intensities) of components (wind turbines), sub-technologies and cohorts (electricity cables, wind turbines, solar panels and electricity storage) can be found in the Supplementary Information (SI 1).

Technology	Total	Unit	% Steel	Aluminum	Copper	Sources
Electricity cables	1,2	ton/km	2,4	19,7	77,9	(Enexis, personal communication, 2019; Harrison et al., 2010; Turconi et al., 2014)
Substations & transformers	2,9	ton/unit	60,7	25,5	13,8	(Harrison et al., 2010; Turconi et al., 2014)
High voltage pylons	10,3	ton/unit	100,0			(Harrison et al., 2010)
Wind turbines onshore	123,9	ton/MW	97,7	0,3	3,1	(Roelofs, 2020)
Wind turbines offshore	446,9	ton/MW	99,3	0,1	0,6	(Roelofs, 2020)
Solar panels	80,0	ton/MW	84,9	9,4	5,8	(Carrara et al., 2020; Moss et al., 2011; Viebahn et al., 2015)
Gas-fired power plants	17,4	ton/MW	89,3	5,3	5,3	(Faist-Emmenegger et al., 2007; Moss et al., 2013)
Coal-fired power plants	79,5	ton/MW	96,9	1,3	1,9	(Dones et al., 2007; Moss et al., 2013; Sullivan et al., 2011)
Nuclear power plants	62,8	ton/MW	97,3	0,3	2,3	(Dones, 2007; Moss et al., 2011)
Biomass & waste incineration plants	33,9	ton/MW	99,1	0,8	0,1	(Bauer, 2007; Moss et al., 2013)
Hydrogen power plants	17,4	ton/MW	89,3	5,3	5,3	(Faist-Emmenegger et al., 2007; Moss et al., 2013)
Electricity storage	0,5	ton/MWh	63,1	10,1	26,8	(van Exter et al., 2021)

factor 9 (scenario H) in 2050 compared to 2018. While remaining below the inflow, steel outflow increases to between 0,3 and 0,5 million tons per year in 2050. The results indicate that towards 2050 a substantially larger share of steel demand could be met by outflow from the urban mine.

The stock and flow development of copper shows a different pattern compared to that of steel (Fig. 5). The stock of copper experiences moderate growth, increasing roughly by a factor 2 to 3 by 2050 compared to 2018. The stock and outflow of copper in electricity cables decreases due to substitutions by aluminum as conductor material. A small inflow of copper in cables remains due to its applications in specific applications, i.e. electricity transmission from offshore wind turbines. Outflow of copper is currently dominated by the T&D grid, but will gradually shift towards solar panels.

Under the assumption of constant material intensities in solar panels and windturbines, stocks and flows of minor metals show a strong growth in the coming decades. For minor metals applied in wind turbines, the stock increases with a factor 35 to 65 by 2050 compared to 2018. The stock of minor metals applied in solar panels increases with a factor 8 to 16 in 2050 compared to 2018. Although remaining relatively small compared to their respective annual inflows, the annual outflows of these metals show a strong growth towards 2050. The differences between in and outflow are larger in scenarios with a stronger growth in wind and solar technologies (scenario M and H).

The stocks and flows of metals in solar panels and wind turbines substantially change under decreasing material intensity assumptions. Bulk metals show a decrease in annual demand by 2050 of between 31% and 44%, and CRM a decrease of between 75% to 76%, compared to constant material intensities (see SI 3 for results of all metals). The outflows show smaller changes due to the delay caused by the products' lifespans. As a result, metal outflow approximates and in some cases exceeds the size of the inflows. For instance, the annual inflow of indium and neodymium decreases with 75% and 81% respectively by 2050, compared to constant material intensity assumptions. The annual outflow of indium and neodymium decreases with roughly 25% and 35% respectively by 2050. As a result, the annual outflow of neodymium approaches the inflow by 2050, and the annual outflow of indium exceeds the inflow by 2050. Overall, the results suggest that material efficiency improvements increase the potential to close (minor) metal loops.

Metal stocks in electricity storage technologies show a strong growth from 2030 onwards. While the associated bulk metal demand remains relatively low compared to the other assessed technologies, the storage technologies require significant amounts of CRM. In scenario M, under current market trend assumptions, 69, 22 and 22 tons of neodymium, praseodymium and dysprosium are stored in electricity storage technologies by 2050 respectively, presenting 1% of the neodymium stock, 22% of the praseodymium stock and 7% of the dysprosium stock in the electricity system. Cobalt and lithium stocks present totals of respectively 26 thousand and 32 thousand tons in 2050 for scenario M. Within the electricity system, lithium is only applied in electricity storage. 98% of the cobalt stock in 2050 is applied in electricity storage. The other 2% of the cobalt stock is located in hydrogen electricity plants (see SI 3 for details).

The demand for critical metals can be reduced when batteries with lower CRM intensities are chosen. Together with increased material efficiencies in solar panels and wind turbines, the cumulative minor metal outflow approaches the demand by 2050 (Fig. 6). However, less CRM intensive batteries require higher quantities of steel and copper (see SI 3 for details). By 2050, annual metal demand increases to between 5 thousand and 11 thousand tons per year under current market trend assumptions, and to between 14 thousand and 28 thousand tons per year when choosing for less CRM intensive batteries. Outflows also become significant towards 2050, presenting roughly 4 thousand tons per year in scenario M.

3.3. Collection and recovery

The collection rates of stocks in the electricity system at the end-of-life in the Netherlands is relatively high, as the country presents a relatively small and densely population area and hence space is valuable. Hibernation of stocks, referring to end-of-life stocks that are not collected, is however more likely for technologies that are hidden from the eye. Interviews with network operators revealed that between 65% and 85% of decommissioned electricity cables remain unused in the ground and become part of the hibernating stock (P. Soepboer, personal communication, April 9, 2020; J. Smit, personal communication, April 30, 2020). While this value is subject to uncertainty, it implies that the hibernating stock is substantial in size, resulting in a missed opportunity to access valuable secondary resources of high quality copper and aluminum. Based upon the estimated percentages, the amount of copper and aluminum that enters the hibernating stock each year rises to a few thousand tons per year, and the total size of the hibernating cable stock in 2050 is estimated to become roughly 300 thousand tons of aluminum and 150 thousand tons of copper. This equals roughly half of the current copper and aluminum stock in the electricity system. At present, however, collecting these material generally not of economic interest, because these materials are difficult to extract (Krook et al., 2011). On the other hand, these hibernating stocks provide an opportunity: they are not used anymore, and therefore are available right now.

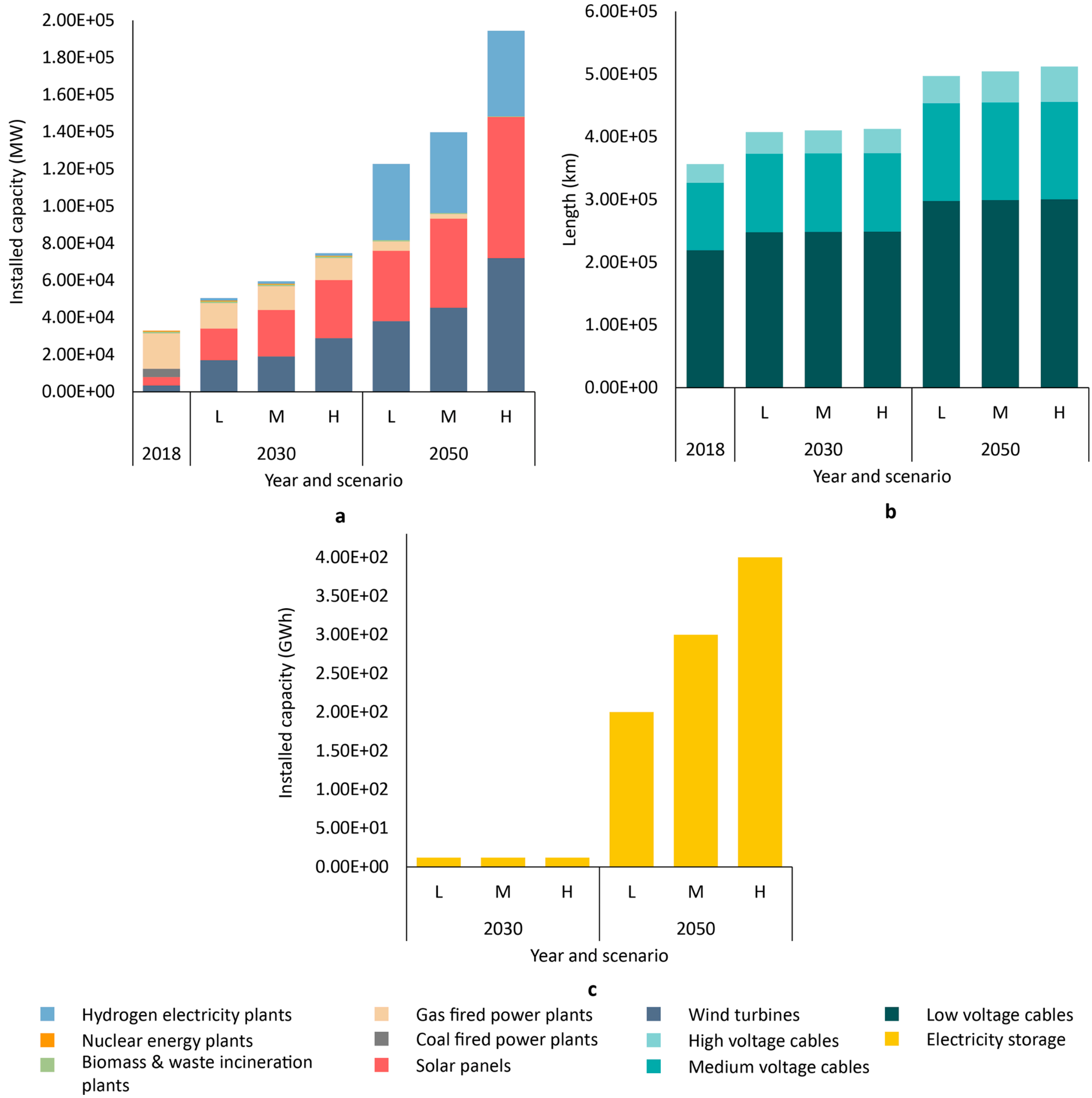

Fig. 2. a: Installed capacity of electricity generation technologies per scenario, b: Kilometers of electricity cables/lines per scenario, c: Installed capacity of electricity storage technologies per scenario (0 GWh in 2018).

Hibernating stocks also originate from decommissioned offshore wind turbine materials. Although the collection rate of steel in wind turbines is typically high, the supporting structure or foundation for offshore wind turbines ("monopiles") are usually cut off a few meter below seabed, resulting in a residual steel mass that accounts for approximately 57% of the monopile (Topham et al., 2019). If business as usual continues, this could result in an unused stock of between roughly 430 thousand and 690 thousand tons of steel, depending on the scenario. This value equals roughly 20% of the current steel stock in the electricity system.

End-of-life stocks that enter a waste stream most likely follow the recycling pathway (Chen et al., 2021; Chowdhury et al., 2020; Padoan et al., 2019; Pirani, 2020). Current practices often entail significant losses in material quality, even when processed in specialized recycling facilities, e.g. for solar panels or electricity cables (R. Doggenaar, personal communication, 18 June 2020; M. Rijnsburger, personal communication, July 7, 2020). Recycling of metals in clean energy technologies is complicated by the growing number of metals applied (Reck and Graedel, 2012). These metals are rarely applied in pure form, but rather as alloys. The increasing variety of alloys that are being developed for specific technological purposes complicates metal separation and often results in the mixing of alloys (Nakajima et al., 2013; Pirani, 2020; Reck and Graedel, 2012). This prevents reuse of the material in similar high-value applications. Selective recycling, e.g. magnet

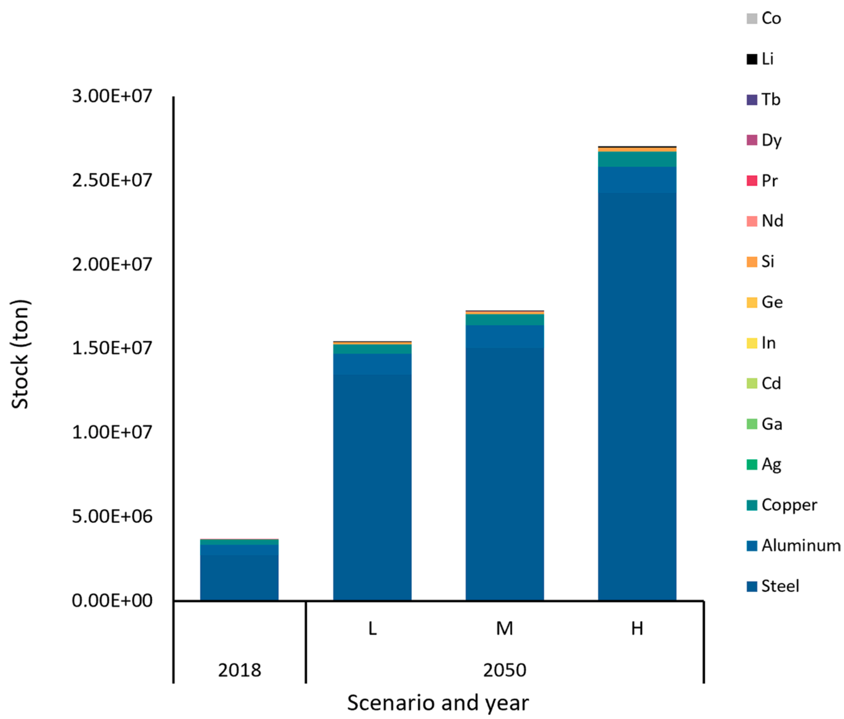

Fig. 3. Total stock of selected metals in 2018 and in 2050 for scenario L, M and H.

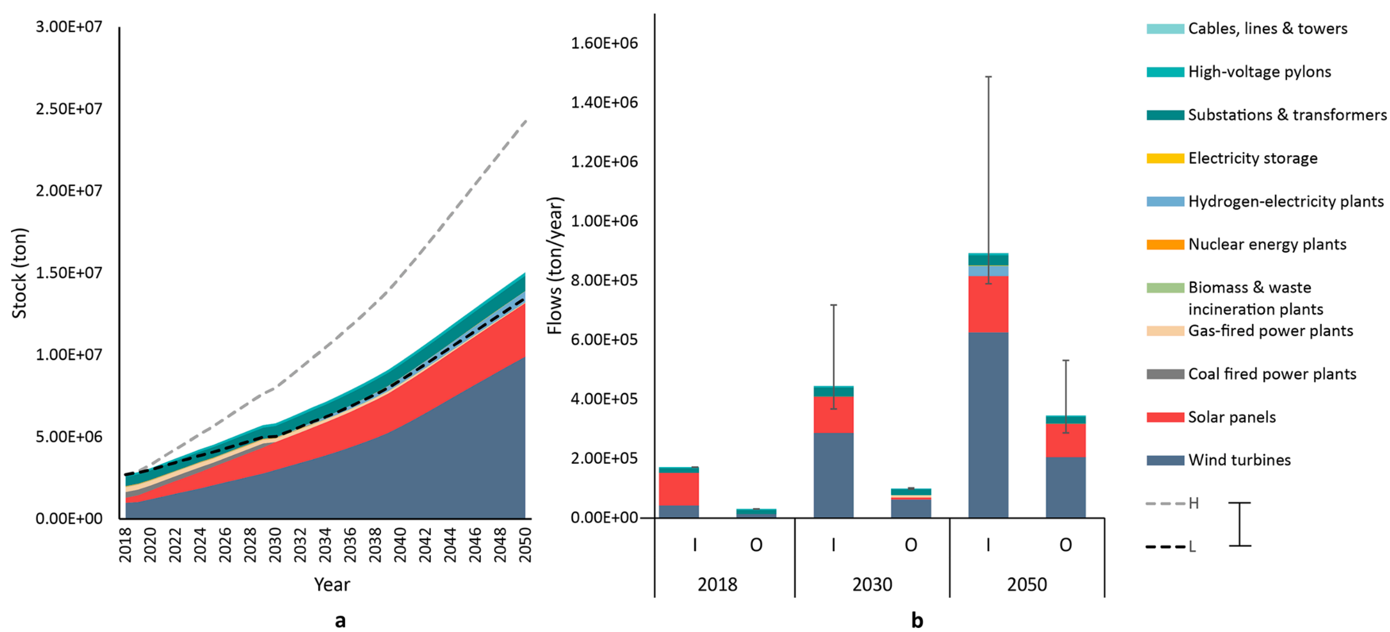

Fig. 4. a: Steel stock development in the electricity system from 2018 to 2050. The stacked graph presents the results for scenario M, broken down per technology. The dotted black line presents the steel stock development for scenario L, and the dotted gray line the results for scenario H. b: inflows (I) and outflows (O) of steel in the electricity system for the years 2018, 2030 and 2050. The stacked graph presents the results for scenario M, and the error bars show the results for scenario H (upper limit) and scenario L (lower limit).

to magnet recycling (Walton et al., 2015) could present a solution to this problem, but requires sufficient scale for dedicated recycling facilities and more effort in collection and sorting. Less common end-of-life routes include the re-use of the technology at product (e.g. reuse of wind turbines elsewhere (Straver, 2016)) or component level (e.g. direct reuse of wafers in c-Si solar panels (Tao and Yu, 2015)). In the case of energy plants, reuse of the facility for other purposes is a possibility, e.g. the conversion from a gas-fired power plant to a hydrogen electricity plant (Goldmeer, 2019) or conversion for commercial purposes. While further assessment of metal recovery was beyond the focus of this research, the results highlight the need to increase both collection and recovery rates in order to enable the closing of metal loops in the future.

4. Discussion

This study analyzed the interaction between the energy transition and circular economy, based upon detailed energy transition scenarios. Our findings support the more widely known phenomenon that a

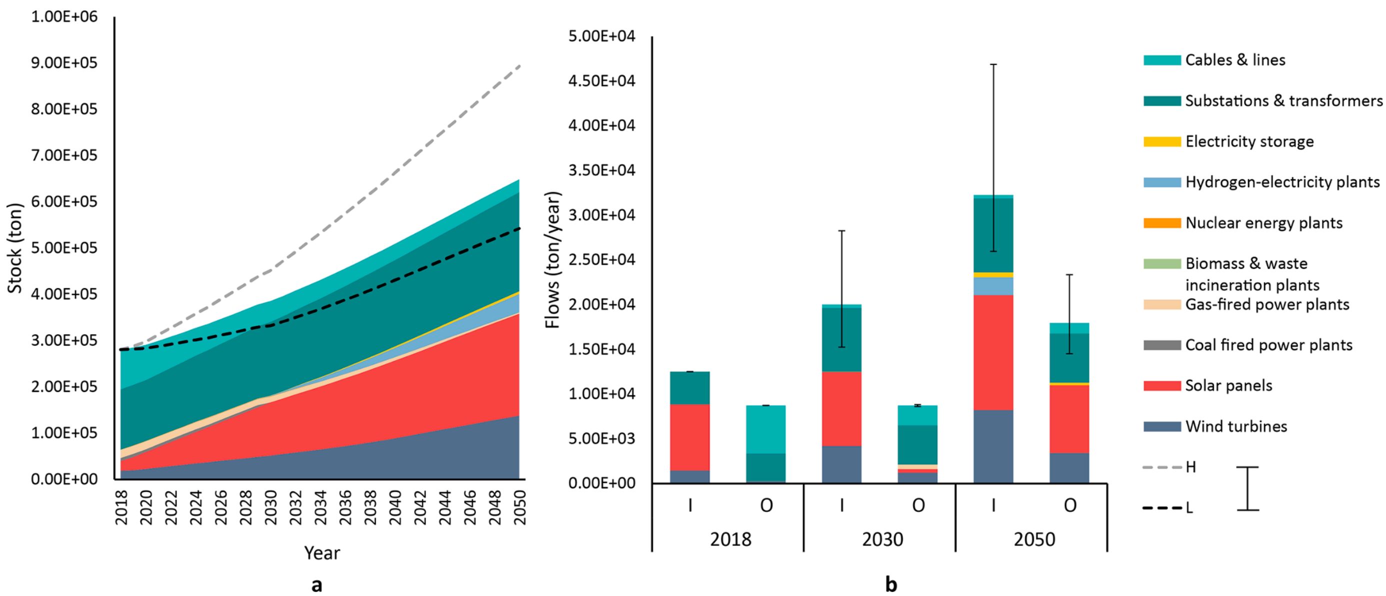

Fig. 5. a: Copper stock development in the electricity system from 2018 to 2050. The stacked graph presents the results for scenario M, broken down per technology. The dotted black line presents the copper stock development for scenario L, and the dotted gray line the results for scenario H. b: inflows (I) and outflows (O) of copper in the electricity system for the years 2018, 2030 and 2050. The stacked graph presents the results for scenario M, and the error bars show the results for scenario H (upper limit) and scenario L (lower limit).

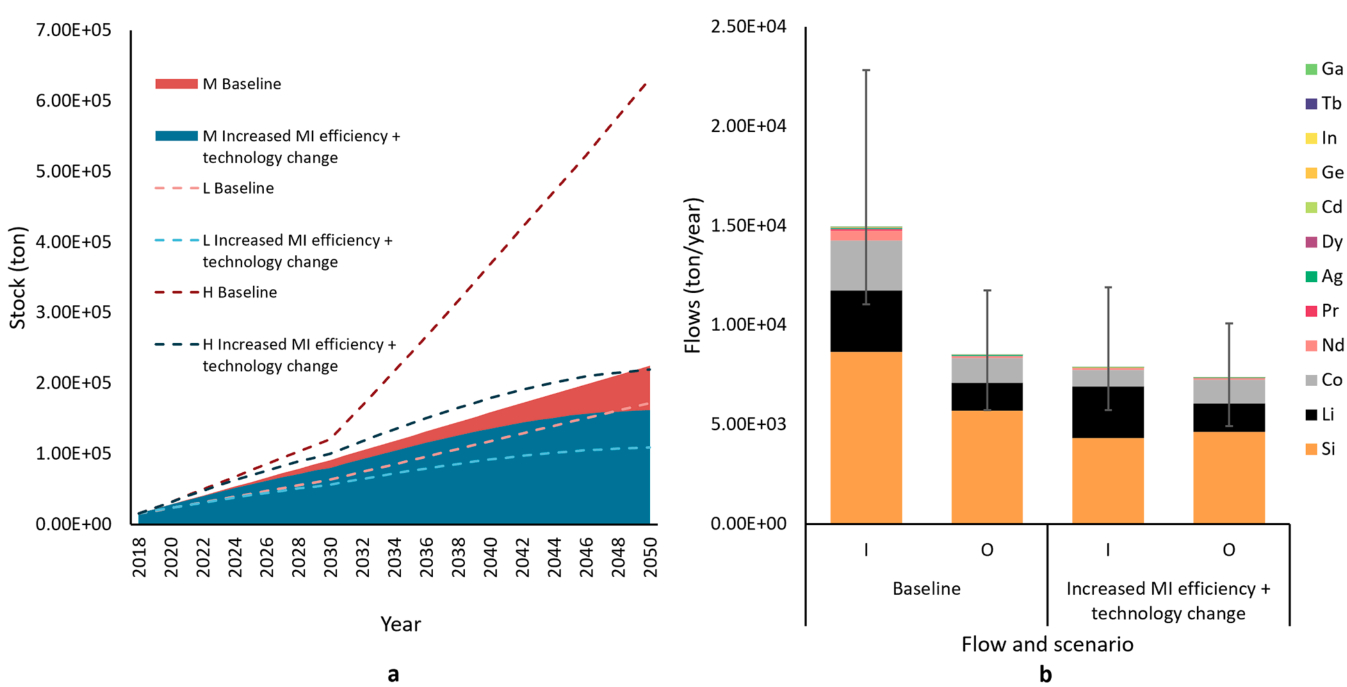

Fig. 6. a: Minor metal stock development in the electricity system (solar panels, wind turbines and electricity storage) from 2018 to 2050. The stacked graph presents the results for scenario M. The dotted lines presents the stock development for scenario L and H. b: inflows (I) and outflows (O) of minor metals in the electricity system for the year 2050. The stacked graph presents the results for scenario M, and the error bars show the results for scenario H (upper limit) and scenario L (lower limit). Results for all metals, and details on stock dynamics, can be found in the Supporting Information (SI 3).

significant and rapidly growing amount of metals is contained in the electricity system (Deetman et al., 2018; Li et al., 2020). The metals are not only present in more often assessed solar panels and wind turbines, but also in the transmission & distribution (T&D) grid and electricity storage technologies, highlighting the importance to include these products in urban mining research and CE strategies. The stocks are also significant in comparison to other sectors. For instance, copper and aluminum stocks in the system are of similar magnitude to those in buildings and vehicles (Oorschot et al., 2019; van Oorschot et al., 2020), and several critical minor metal stocks are of similar magnitude to electric cars and electric appliances (Bosch et al., 2019; Oorschot et al., 2019).

The composition of the future electricity system is inherently uncertain. We therefore assessed several energy transition scenarios. Scenarios with a higher level of self-sufficiency in renewable electricity supply result in a higher metal demand. However, in all scenarios the outflow of metals from the urban mine related to the electricity system remains relatively small compared to its metal demand. This imbalance is caused by the build-up of a renewable electricity system and the long lifespans of the products (typically > 20 years). The results align with recent insights that decarbonization of the electricity system will reduce fossil fuel demand while increasing metal extraction (World Bank, 2020). However, the high demand for virgin metals may be limited to the energy transition period. During this period, the development of responsible mining practices are therefore crucial (Sprecher and Kleijn, 2021; Watari et al., 2021). After the completion of transition, metal outflow may catch up with the inflow, enlarging the potential to close metal cycles.

Uncertainty also exists for the technology specific developments. Different assumptions are made in literature for the future material compositions and technology shares of solar and wind technologies (e.g. Carrara et al., 2020; Månberger and Stenqvist, 2018; Viebahn et al., 2015). Also, the deployment of utility scale batteries is uncertain, especially for novel battery types such as flow batteries. New batteries are being developed at rapid pace and their exact material composition and intensity in the future commercial configuration is inherently largely unknown (IEA, 2021b). We found that changes in technology share and increased materials efficiencies significantly reduce demand for (especially critical) metals and further enables the closing of metal loops. As the results are sensitive to the alternative assumptions, future research might need to be directed towards more detailed technology assessments. Nevertheless, the results suggest that circular and low-carbon policy ambitions can be pursued simultaneously when steering towards less (critical) metal intensive technologies.

Sensitivity of the results to changes in the products' lifespan was not assessed due to the limited timeframe set and the typically long lifespans of the components. Investigation of the effect of different lifespan (distribution) assumptions on stock dynamics would be interesting when looking at the more distant future, as these changes can have significant effect on the calculated flows (Miatto et al., 2017). Particularly for components in the T&D grid and novel battery types, the lifespan distribution remains uncertain. Although life time data is more widely available for wind turbines and solar panels, life time estimates differ substantially in literature and could also change as a result of novel technology developments (Elshkaki and Shen, 2019; Roelofs, 2020; Zimmermann, 2013). Investigating the effects of lifetime changes on material dynamics in more detail and for a broader timeframe therefore presents a direction for future research.

Our results reveal that significant amounts of stocks go into hibernation after their use phase. At present, recovery of hibernating stocks is often not considered profitable. To further close the material cycles in the future, collection of these stocks could possibly be incentivized by strategic planning, e.g. combining maintenance work at the designated location with collection of hibernating stocks (Krook et al., 2011). Also metal recovery still involves significant quality losses. Advancements in metal recycling techniques are however made at rapid pace (IEA, 2021b). While this gives reason for optimism for the future, such developments might need to be incentivized with targeted policies, such as minimum recycling rates and virgin material taxes (Söderholm and Ekvall, 2020). Thus, stimulation of enhanced collection and recovery rates can be considered as an important policy priority in order to promote the transition towards a circular economy.

Closing metal loops within the electricity system might be feasible after the energy transition, provided that collection rates improve and electricity demand stabilizes. Circularity within the electricity system could be relevant in the case of product or component re-use, e.g. silicon wafers in solar panels (Xu et al., 2018). The capacity for reuse will however remain limited during the energy transition, because of a mismatch between the materials of the fossil fuel based technologies that become available for urban mining and the demand for renewable technologies. Although our results show that the outflows from renewable technologies grows in the coming decades, recovery at product or component level is complicated by rapid technological advancements, e.g. in batteries and solar panels (Carrara et al., 2020; Nadeem et al., 2019). Recovery through recycling will therefore likely remain predominant during the energy transition.

A better understanding of the composition of alloys in products could help to steer product design and recycling technologies. This is important because the increasing diversity of alloys applied in products complicates metal extraction at the end-of-life (Pirani, 2020; Reck and Graedel, 2012). While we accounted for a wide range of metals in this study, data on alloy compositions in products was scarce. Better monitoring of alloys in products is therefore still important. Furthermore, as recycling is typically not limited to one sector but often includes a wide range of product, the research could be broadened to a wider range of urban stocks.

Analysis of different energy pathways on material flows can provide insight in the level of dependency of nations on energy and material imports. Global trends show an exponential growth of renewable energy technologies (Sprecher and Kleijn, 2021) and with that a potentially critical demand for base- and minor metals. Many nations including the Netherlands strongly depend on a select number of regions, mainly China, for material supply (Elshkaki and Shen, 2019; Patrahau et al., 2020). Nationwide scenario analysis can help to identify opportunities to increase self-sufficiency in material supply through circular activities. Such an assessment can complement similar studies on a more aggregate level of world regions (e.g., (Deetman et al., 2021), Fishman et al., 2021).

An advantage of a smaller spatial scope is the availability of more detailed data. In our analysis for instance, product specific data points for wind turbines were available, containing information on turbine size, building year, rated capacity, location and drive train technology. The data allowed us to make a highly detailed bottom-up analysis of metal stocks in society which, in combination with the scenarios, resulted in a level of detail that was beyond that of previous studies. Most of our historic data also had a spatial component, which additionally can be used to assess where certain metal stocks eventually become available for urban mining, hence facilitating the collection and recovery logistics. Spatial data can also be useful to facilitate the recovery of hibernating stocks, e.g. to locate cables that remain in the ground after their use-phase or monopiles that are not entirely collected after decommissioning.

5. Conclusion

In this paper we assessed how the transition towards a low-carbon electricity system affects the potential for urban mining of metals. We analyzed three energy transition scenarios, encompassing different levels of self-sufficiency in renewable electricity supply. Our study shows that the energy transition results in a growth of metals that can be recovered from the urban mine, but the outflow remains relatively small compared to the metals required to build-up a low-carbon electricity system, at least for the coming decades. The metal demand is substantially larger in scenarios with a higher level of self-sufficiency in (renewable) electricity generation, thereby showing a potential trade-off between climate and circularity related policy goals.

While the growth in metal demand may be justified by the build-up of a reliable and low-carbon electricity system, several opportunities can be identified to limit the demand for virgin resources and increase urban mining of metals. The development of metal stocks and flows in electricity storage, solar and wind technologies are sensitive to changes in technology mix and material efficiency improvements, especially for critical minor metals. Steering towards increased material efficiencies and technologies with low CRM intensities could lower the demand for primary metals in the future and enhance the closing of metal cycles. Circularity can be further enhanced when collection and recovery rates improve. We found that at present, a significant share of the end-of-life stocks are not collected but become hibernating stocks. Metal recovery also remains challenging due to a mismatch between products that become available for urban mining and the demand new technologies with rapidly changing metal compositions. Further investigation of possible material efficiency improvements and enhancing collection and recycling rates therefore present important directions for future research.

Author statement

J. van Oorschot: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing – Original Draft. **B. Sprecher**: Supervision, Validation, Writing – Review & editing. **B. Roelofs:** Conceptualization, Formal analysis, Writing – Review & editing. **J. van der Horst:** Conceptualization, Formal analysis, Writing – Review & editing. **E. van der Voet**: Supervision, Validation, Conceptualization, Methodology, Writing – Review and Editing

Declaration of Competing Interest

The authors declare that they have now known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.106105.

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