



LUND UNIVERSITY

Global metal flows in the renewable energy transition

Exploring the effects of substitutes, technological mix and development

Månberger, André; Stenqvist, Björn

Published in:
Energy Policy

DOI:
[10.1016/j.enpol.2018.04.056](https://doi.org/10.1016/j.enpol.2018.04.056)

2018

Document Version:
Publisher's PDF, also known as Version of record

[Link to publication](#)

Citation for published version (APA):
Månberger, A., & Stenqvist, B. (2018). Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy*, 119, 226-241.
<https://doi.org/10.1016/j.enpol.2018.04.056>

Total number of authors:
2

Creative Commons License:
CC BY-NC-ND

General rights

Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

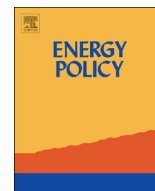
Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00



Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development

André Månberger^{a,*}, Björn Stenqvist^b

^a Environmental and Energy Systems Studies, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

^b Physical Chemistry, Lund University, P.O. Box 124, SE-221 00 Lund, Sweden

ARTICLE INFO

Keywords:

Climate change mitigation
Critical material
Transition
Resource
Scarcity
Substitutes

ABSTRACT

This study analysed demand for 12 metals in global climate mitigation scenarios up to 2060 and quantified the impacts on demand of different assumptions on improvements and technological mix. Annual and cumulative demands were compared with reserves and current mining rates. The study results showed that reserves are sufficient to support the total level of solar power, wind power and electric motors. Insufficient reserves may very well constrain certain sub-technologies, but substitutes that take the role of 'back-stop' technologies can be used instead. The exception is batteries, since lithium battery chemistries and reserves were incompatible with the scenarios analysed. Batteries of moderate size, lithium-free chemistry or reserve expansion would make the transition feasible.

Choice of sub-technology (e.g. type of solar PV) had a decisive impact on demand for certain metals. Perceptions that many metals are critical and scarce for renewable energy transitions appear exaggerated if a dynamic view on technological development is adopted. Policy-relevant conclusions can be drawn from this, regarding e.g. the benefits of technological diversity, increasing metal intensity, recycling and integrating infrastructure and energy policies (e.g. fast chargers).

1. Introduction

In 2016, fossil energy represented approximately 80% of the global energy mix (IEA, 2017b). Fossil resources are finite and the combustion process produces emissions that are harmful to the environment. One option is to replace fossil energy with renewable energy.¹ The flows that renewable energy technologies utilise are abundant and often not as geographically concentrated as fossil fuels. However, renewable energy technologies can require the use of metals with geographically concentrated deposits. These metals are sometimes perceived as critical when a high possibility of disruption is combined with high importance, see e.g. (DoE, 2011).

Interest in assessing the criticality of metals has increased among academia and policymakers in recent years, for a review of the literature see (Graedel and Reck, 2016; Jin et al., 2016). Criticality is dynamic over time, but Erdmann and Graedel (2011) and Jin et al. (2016) found that criticality assessments frequently overlook the role of recycling, innovation, substitution and time horizons.

A handful of previous studies have quantified the amount of embedded metals in batteries, various types of renewable production and

end-use technologies, and the amounts of metals that would be required to meet certain climate mitigation targets, see e.g. (Candelise et al., 2011; Elshkaki and Graedel, 2013; Moss et al., 2013). Metal supply bottlenecks that can restrain adoption have been identified for some current technologies, such as solar photovoltaics (PV) (Elshkaki and Graedel, 2013; Grandell and Thorenz, 2014) and energy systems that meet climate mitigation targets (Grandell et al., 2016). For example, some metals are produced as by-products, making the supply dependent on the extraction rate of the host metal.

However, previous studies have estimated the aggregated metal requirement from either one technology or one set of technologies while adopting a static assumption on metal intensity over a certain period, e.g. up until 2050. This is not consistent with historical experience of improved material intensity over time. Two exceptions are Davidsson and Höök (2017), who examine currently adopted technologies of solar PV alone, and Viebahn et al. (2015), who focus on Germany. No previous study has adopted a global perspective on several technologies or provided justifications for the expected annual improvements. Deetman et al. (2018) analysed demand for five metals in global scenarios with various levels of climate mitigation, gross

* Corresponding author.

E-mail address: Andre.Manberger@miljo.lth.se (A. Månberger).

¹ Other techno-economic options include improved efficiency, carbon sequestration and storage and nuclear power.

Table 1
Summary of stocks in society in the ‘beyond 2 degree’ (B2D) scenario, 2015–2060.

	Stock in society (2015)	Stock in society (2060)	Stock increase
Personal vehicles: Battery electricity (million)	1.5	1300	87000%
Personal vehicles: Hybrid, plug-in hybrid and fuel cells (million)	14	710	5000%
Electric bikes (million)	460	1600	300%
Buses: Battery electric, hybrid, plug-in hybrid and fuel cell (million)	0	31	N/A
MFT and HFT: Battery electric, hybrid, plug in hybrid and fuel cell (million)	0	130	N/A
Wind power (GW)	430	4200	1000%
Solar photovoltaic (GW)	220	6700	3000%
Solar thermal (GW)	21	1300	6000%

Note: For simplicity, the data in this table is compounded from the 45 sub-categories used in the study model into eight different categories (see [supplementary material](#) for disaggregated data). MFT = medium freight transport, HFT = heavy freight transport.

domestic product and population growth rate. Tokimatsu et al. (2017) analysed global metal demand up to 2100 for business-as-usual and a 2-degree climate mitigation target met by centralised coal and nuclear or decentralised gas and renewable energy technologies. Future research needs identified by Tokimatsu et al. (2017) included: metal demand for global renewable energy systems and coverage of more metals and technologies, such as fuel cells. Moreover, some metals can be substituted, with trade-offs such as higher cost, increased weight and lower efficiency, but no previous study has addressed how this might affect metal demand and criticality.

This study aims to fill the research gaps described above by analysing how different technological development trajectories affect the demand for different metals over time and how it is affected by using technological substitutes. This study also addresses the role of recycling to meet supply which connects this study to the emerging field of the circular economy. This provides a dynamic perspective on theories and assessments of what makes resources critical and how this can be mitigated.

Twelve metals were included in this study, namely cobalt, copper, dysprosium, gallium, indium, lithium, neodymium, nickel, platinum, selenium, silver and tellurium. The criteria for inclusion were that the metal is critical for some renewable energy production, storage or end-use technology or can be used as a substitute for critical metals.

Data on metal embedded in various renewable energy technologies were obtained from the published literature and was used to develop four scenarios with different assumptions on sub-technologies market share, recycling rate, size of batteries and future metal intensity improvements. All four scenarios are compatible with a climate mitigation scenario developed by IEA (2017a) and would provide a global energy system that is in line with the Paris agreement.

Estimated demand for virgin metals was compared against current mining rates and reserves. The study shows that reserves are sufficient to support the total level of solar power, wind power and electric motors. Insufficient reserves and mining bottlenecks could constrain certain sub-technologies, their growth rates or make the metal more expensive, but substitutes that take the role as ‘back-stop’ technologies can be used instead. Increased lithium demand is identified as the main long-term obstacle and policy options to manage this are proposed.

2. Method

This study adopted the ‘beyond 2 degree’ (B2D) scenario from the energy technology perspective study by IEA (2017a). This is a normative scenario generated by a cost optimisation model that shows how the global energy system can transition to become consistent with the Paris climate mitigation agreement. The scenario extends to 2060 and provides annual data on installed capacity of different renewable power technologies (offshore wind, onshore wind, solar PV and solar thermal) and the mix of end-use transportation technologies (personal vehicles, light trucks, heavy trucks, mini- and hybrid-busses, plug-in hybrids, battery electricity and fuel cells, and whether they are used in urban or

rural areas). Table 1 provides a summary of societal stocks of various technologies at the beginning and end of the scenario timeframe. Annual flow to society was calculated based on stock change and assumptions on the life expectancy of each technology (see [supplementary material](#) for assumptions on life expectancy). Thus, cumulative flow to society was higher than the difference in stock between 2015 and 2060, since assumed technology life expectancy was lower than 45 years.

Previous literature was reviewed and data were obtained on material embedded in the technologies used in the B2D scenario. Material intensity was calculated as weight of material times the amount embedded in one unit (GW installed production, kW motor or fuel cell power, kWh energy storage) of technology y , e.g. weight of lithium embedded in 1kWh battery storage. Data on trends in metal intensities over time and possibilities to replace metals directly or using a technological substitute were also taken from the literature. These data were then used to construct four scenarios that were all consistent with the B2D scenario, but with different assumptions on the mix of sub-technologies, recycling rates, metals used in different technologies and trajectories of metal intensities. Assumptions on current recycling rates were taken from previous studies (Sverdrup et al., 2017; UNEP, 2011).

Finally, cumulative demand and peak annual demand for each metal were compared against current known reserves and mining rates, using data from USGS (2018) complemented with data from (Habib and Wenzel, 2014; Sverdrup et al. (2017)). Reserve is defined as the part that can be economically extracted or produced at the time of determination (USGS, 1980). Improved extraction technology and higher market price increase the size of the reserve. Resources are (much) larger, but have lower economic feasibility of being produced and lower reliability. The degree of geological scarcity (i.e. exhaustion time of extractable global resources) does not provide a price mechanism of early warning of mineral exhaustion (Henckens et al., 2016).² Cumulative metal demand was therefore primarily compared with reserves, since this provides a comparison with the amount that can be mined at today’s market prices. It also illustrates how much reserves needs to grow. In the discussion we highlight cases where cumulative demands are comparable to resources.

3. Electricity production

3.1. Solar PV

Two main designs of solar PV are currently used: crystalline silicon and thin film (see Fig. 1). These are sometimes referred to as first- and second-generation solar PV technologies, respectively. Crystalline silicon has a market share of approximately 90%. Cadmium-telluride (CdTe) has the second largest market share, but copper-indium-gallium-

² Geological factors are one aspect of scarcity. The concept of scarcity is dynamic and can be understood as a result of “actors’ perceived difficulties to access a resource” (Vikström, 2016).

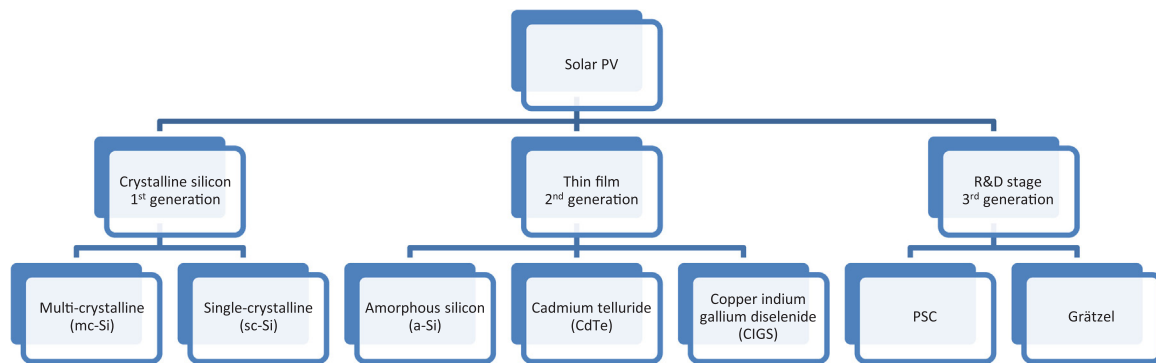


Fig. 1. Schematic diagram showing different solar photovoltaic (PV) technologies.

(di)selenide (CIGS) may become more common in the future as a result of high efficiency, low cost and lower toxicity, see e.g. (Viebahn et al., 2015). Amorphous silicon (aSiGe) has a low market share and its low efficiency makes it unattractive for most applications compared with the other technologies.

Crystalline silicone consists of a silicon wafer in which the structure and properties are either constant throughout the material (single-crystalline) or consist of multiple grains (multi-crystalline), making the cell cheaper to produce, but with lower efficiency. In terms of material requirements, silicon is abundant, but needs to be purified. The intensity of silicon is determined by the thickness of the silicon wafer. The thickness has declined over time, from 370 μm in 1997 to 180 μm in 2005 (Saga, 2010). This corresponds to an annual improvement of around 9% over eight years. VDMA (2017) estimates that, by 2027, the thickness of single-crystalline will have declined to 140 μm and that of multi-crystalline to 150 μm , using technology that is known today. The decline in thickness may proceed faster, to 110 μm instead, according to the same source. At present, 10–20 t silver/GW are used as a paste in the cell (Elshkaki and Graedel, 2013; VDMA, 2017).³ The lower value was used in the present study. VDMA (2017) estimates that silver intensity will decline by 8% annually up to 2027. However, silver intensity can be reduced by 5% of today's level (Goodrich et al., 2013) or replaced entirely by e.g. nickel-copper plating (Rehman and Lee, 2014), aluminium or ultrasonic welding (García-Olivares, 2015). Replacing silver paste with nickel-copper plating will lower cell resistance and increase the efficiency (Kim and Lee, 2013). Crystalline silicone is assumed to contain 884 t copper/GW (Fizaine and Court, 2015).

Thin film solar cells require less material than crystalline silicon, but contain metals that are rarer and found in lower concentrations than silver. For example CdTe contains (per GW): 70 t tellurium, 62 t cadmium (Kavlak et al., 2015) and 5181 t copper (Fizaine and Court, 2015), CIGS contains (per GW) 13 t indium, 4 t gallium, 41 t selenium (Kavlak et al., 2015) and 450 t copper (Kavlak et al., 2015). Amorphous silicon contains (per GW) 0.714 t tin, 5.32 t indium (Moss et al., 2013) and 1005 t copper (Fizaine and Court, 2015). Indium can be replaced by germanium in amorphous silicon (Elshkaki and Graedel, 2015) but this option was not explored here due to the low abundance of germanium. The metal intensities of thin film solar PV are far from their theoretical limit and can thus decline further (Wadia et al., 2009). It is also theoretically possible to replace indium and gallium with carbon nanomaterials (Arvidsson and Sandén, 2017).

Several third-generation technologies are being developed, but so far none has been commercialised. One option is mixed organic-inorganic halide perovskites (PSC) (Green et al., 2014). These cells have exceeded 20% efficiency in laboratory tests and mainly use commonly available elements (carbon, hydrogen, nitrogen) (Song et al., 2016). Iodine is often used, but more abundant halogens such as chlorine can

be used instead. The scarcest metal required in PSC is lead.⁴ Lead can be replaced by tin, which is a less toxic element but also less abundant in the Earth's crust. The requirement for lead is $5.98 \cdot 10^{-11} \text{ kg/cm}^2$ (Espinosa et al., 2015). Assuming 20% cell efficiency and conditions with 1000 W/m^2 , intensity for lead is 2.99 kg/GW.

Another third-generation technology is dye-sensitised solar cells (DSSC), also referred to as Grätzel cells. These cells have lower efficiency than conventional cells, but can be produced at a low cost. Some chemistries contain platinum or ruthenium, but this can be replaced with the more abundant cobalt sulphide (Wang et al., 2009).

3.2. Solar thermal

Solar thermal, or concentrated solar power (CSP), concentrates solar energy, heats up a medium or a metal plate and converts the heat into electricity using either a turbine or a Stirling engine. Four different CSP technologies exist: solar tower, parabolic trough, Fresnel and dish Stirling. Solar tower and parabolic trough were assessed in this study. One advantage with these technologies is the possibility to integrate heat storage that enables production at night-time. Pihl et al. (2012) assessed their material intensities and found that tower configurations contain (per GW): 1400 t copper, 1800 t nickel and 16 t silver. Parabolic trough contain (per GW): 3200 t copper, 940 t nickel and 13 t silver. Pihl et al. (2012) also identified possibilities to reduce and replace metals. For example, silver used in the reflector and can be replaced with aluminium, but this reduces the maximum reflectivity from 95% to 90%.

3.3. Wind power

There are two main technical designs of wind power plants: direct drive (electrically excited or high content permanent magnet (PM) using a synchronous generator) and gearbox (electromagnet or low share permanent magnet generator), see Fig. 2. Direct drives based on high-temperature super conductors (HTS) are still at an early research stage and were not included here.

Blades and generator rotate at the same speed in direct drive configurations. A gearbox makes the generator rotate faster than the blades and enables lighter magnets to be used, as the torque is reduced, but the gearbox itself is heavy and requires maintenance. Moreover, efficiency is reduced by up to 15% (Habib and Wenzel, 2016). The gearbox design is therefore less competitive in larger plants and offshore. Direct drive configurations are predicted to dominate the future offshore market, assuming that wind power plant size continues to increase (Viebahn et al., 2015). Gearboxes can be combined with permanent magnets, in which case the weight of the magnets is reduced by 75–90% depending on the gear ratio (Viebahn et al., 2015).

³ Assuming 20% cell efficiency and 1000 W/m^2 .

⁴ Less common metals are sometimes used (e.g. lithium and silver) but these have been replaced by more abundant ones in various studies, e.g. (Liu et al., 2014).

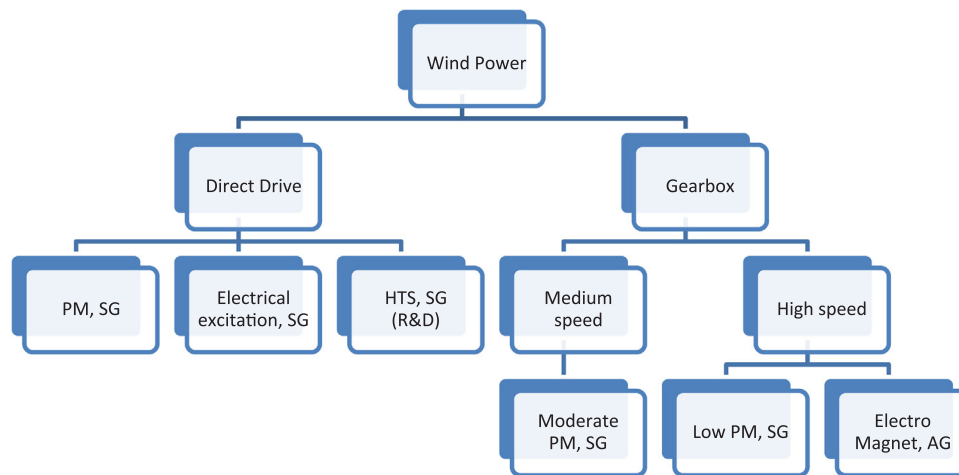


Fig. 2. Illustration of different wind power configurations. PM = permanent magnet, HTS = high-temperature super conductors, SG = synchronous generator, AG = asynchronous generator. Adapted from (Habib and Wenzel, 2016; Pavel et al., 2017b).

Direct drive generators use 2–3 times as much copper as gearbox configurations but the difference is lower for the plant as a whole (Habib and Wenzel, 2016; Lacal-Arántegui, 2015). The multipole generator is either an electrical excitation type using reactive power to generate a magnetic field, or permanent magnets. A drawback with electrical excitation generators is their large volume and 6% lower efficiency than the most efficient plants with permanent magnets (Habib and Wenzel, 2016). Efficiency losses vary and are mainly an issue when the generator operates below its rated power, which is common for a wind power plant (Lacal-Arántegui, 2015).

Different metals can be used in the permanent magnet. The most common types use rare earth elements (REE) in the magnet (approximately 30% neodymium and 3–4.5% dysprosium in the total magnet weight, the remainder is iron and boron). Dysprosium sintering is used to increase magnet coercivity, which increases the upper bound of working temperature from 80 °C to at least 120 °C (Hoenderdaal et al., 2013). Dysprosium can be reduced or even eliminated if the cooling is improved (Pavel et al., 2017a), a convenient consideration since it is a heavy REE and thus more expensive than neodymium. Furthermore, dysprosium can be replaced with terbium, although this is not realistic at the moment as terbium is required in e.g. LED lights (Pavel et al., 2016). It is technically possible to use other magnets such as ferrite magnet's containing iron and strontium. Use of a ferrite magnet reduces the efficiency by 3% compared with using an REE magnet (Habib and Wenzel, 2016). Improvements in REE magnets have slowed down as a result of reaching technical maturity and major reductions are unlikely without technological breakthroughs, according to Elshkaki and Graedel (2013). However, Lacal-Arántegui (2015) claims the opposite and estimates that use of neodymium will increase by almost 30% between 2015 and 2030. This corresponds to a mean annual improvement of ~2%. Viebahn et al. (2015) assumed that the mean annual improvements will be ~1% up to 2050, higher in the beginning of the period and lower in the end. Up to 25% of neodymium can be replaced with praseodymium (Lacal-Arántegui, 2015).

Direct drive permanent magnet (DD PM) generators and generators that use electrical excitation (PM-free) were included in this study. DD PM generators contain (per GW): 4700 t copper, 200 t neodymium and 13 t dysprosium, PM-free generators contain 4982 t copper (Habib and Wenzel, 2016).⁵ Both generators are assumed to contain 377 t nickel per GW (Fizaine and Court, 2015).

A future option is to use HTS which would improve performance by reducing weight and the use of rare earth elements in direct drive

turbines. However, cost reductions and technical progress are needed for this to materialise. HTS would be beneficial in off-shore locations, as they enable much larger plants (> 10 MW) (Lacal-Arántegui, 2015). HTS reduce the use of neodymium and dysprosium, but require 0.3 t Yttrium per GW (Viebahn et al., 2015).

4. Transportation

4.1. Electric vehicle motors

Electric motors are used in battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and two-wheel E-bikes (pedal assist, scooter, motorcycle). Hybrid vehicles contain an internal combustion engine (ICE) and one or several electric motors.

Electric motors use magnetic field(s) generated on a stationary part (i.e. the stator) to push a rod's magnetic field (i.e. the rotor), thus generating a torque such that the rod rotates.⁶ All commercially available electric vehicle motors use radial flux, but transverse flux motors are being developed. The benefit with transverse flux engines is reduced magnet weight. Rahman (2004) constructed comparable prototypes and found that the weight of the magnet could be reduced by 60%. However, the motor was 75% heavier and copper use increased by 45% compared with a radial flux motor.

From a material perspective, electric motors can be grouped into three categories: i) motors with only interior permanent magnets (which can be either REE or ferrous), ii) motors that do not use permanent magnets (e.g. electricity is used to generate the internal magnetic field) and iii) a hybrid version that combines (i) and (ii), see Fig. 3. The main trade-offs with not using permanent magnets are lower efficiency at partial load, larger size, higher weight and increased use of copper. Interior permanent magnets is therefore preferable in PHEV and HEV, since such engines are smaller and used to complement an ICE at low and variable speed. Most hybrid cars sold today utilise engines with permanent magnets.

The rotor's magnetic field can come from either permanent magnets or electromagnets. Motors using permanent magnets on the rotor have a magnetic field on the stator which is synchronous with the speed of the rotor. These engines have a high torque density, low volume and weight, and are used in most electric traction motors. They are

⁶ The opposite can be found in brushed DC-engines where the polarity of the magnetic field in the rotor shift as it rotates while as the polarity of the stator remains constant. This type of motor is not suitable in vehicles because dust requiring maintenance is formed in the engine as brushes wear out.

⁵ Figures have been weighted to compensate for efficiency differences.

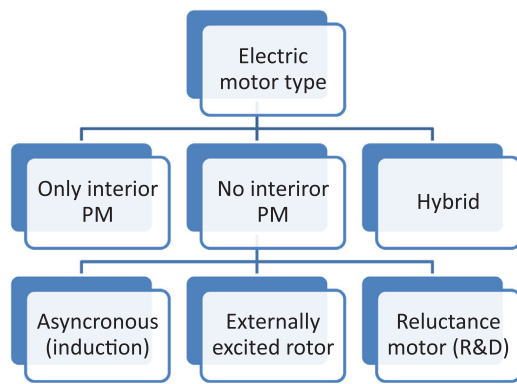


Fig. 3. Illustration of different types of electric motors (based on descriptions in (Pavel et al., 2017b; Riba et al., 2016; Widmer et al., 2015)).

Table 2

Summary of assumptions made in the four scenarios studied.

	Colour in figures	Technology mix	Battery size	Recycling rates	Metal intensity improvement
Scenario 1: Current technology and intensity	Black	Back-stop	Moderate	Current	None
Scenario 2: Current technology and improved intensity	Red	Back-stop	Moderate	Current	Between 2% and 5%
Scenario 3: New technology mix and improved recycling	Blue	Novel	Big	Improved recycling rates	None
Scenario 4: New technology mix and improved intensity	Green	Novel	Big	Current	Between 2% and 5%

Table 3

Summary of assumptions made on reserves, mining rates, recycling rates and metal intensities.

	Cobalt	Copper	Dysprosium	Gallium	Indium	Lithium	Neodymium	Nickel	Platinum	Selenium	Silver	Tellurium
Reserve (ton)	7100000	790000000	55000	5200	47100	16000000	4100000	74000000	44100	100000	530000	31000
Mining (ton/year)	110000	19700000	1350	555	720	43000	21000	2100000	200	3300	25000	420
Recycling rate (current)	40%	60%	15%	15%	40%	10%	15%	60%	70%	5%	80%	0%
Metal intensity (ton/GW)												
Wind power (induction)		4982						377				
Wind power (PM)		4700	13				200	377				
Solar PV (Si)		884									10	
Solar PV (aSiGe)		1005			5.32							
Solar PV (CdTe)		5181										70
Solar PV (CIGS)		450		4	13					41		
CSP (parabolic)		3200						940			13	
CSP (central tower)		1400						1800			16	
Metal intensity end use												
Motor PM (kg/kW)		0.19835	0.0000516				0.0038					
Motor induction (kg/kW)		0.48105										
Battery (kg/kWh)	0.4	0.4				0.2		0.6				
Fuel cell (kg/kW)									0.00015			

Note: CSP = concentrated solar power, PM = Permanent Magnet. For assumptions on end-use technical specifications (e.g. motor size for different vehicles), see [supplementary material](#).

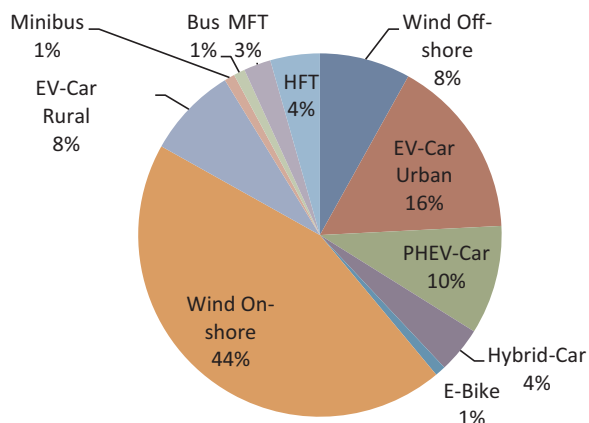


Fig. 4. Relative demand for permanent magnets per sector in Scenario 3.

particularly well suited for cars with dual drive trains, due to their compact design. They also have high efficiency over a wide and varying power range, which makes them suitable for vehicles used in cities. The motor is mainly made from iron, aluminium and copper. Similarly to generators, neodymium-iron-boron (NdFeB) magnets contain dysprosium to increase their operating temperature.⁷

Synchronous motors without permanent magnets on the rotor can be constructed in the same way as those that do, but instead use external excitation of rotor winding to generate a magnetic field. A second option is to induce alternating current in the stator, in which case the rotor and the magnetic field rotate at different speeds (i.e. asynchronous with a slip). Both of these engine types are used in commercial electric cars (e.g. Renault Zoe and some Tesla models). In terms of materials, motors in this group are made of iron, copper and aluminium. It is also possible to construct hybrid motors that use both permanent magnets and an electric-generated magnetic field.

This study examined two different motor configurations: i) permanent magnet motors containing (per kW) 0.20 kg copper (Burrell et al., 2011), 0.0038 kg neodymium and 0.000052 kg dysprosium, and ii) induction motors containing 0.48 kg copper per kW (Dorrell et al., 2010). Values for copper include copper in the inverter and on-board charger. A study by Hawkins et al. (2013) estimated that inverter and charger require 5.1 and 4.2 kg copper, respectively, in a Nissan Leaf sized-BEV (80 kW). It was therefore assumed that all electric, plug-in hybrids and fuel cell vehicles contain additional 0.11625 kg copper/kW power.

Further research can bring more materially efficient technologies to the market and increase the performance of existing technologies. Reluctance motors, not yet commercialised, use the force generated by magnetic field lines that align to pull the rotor and make it rotate.

⁷ It is possible to use less dysprosium in bike motors than car motors, since bike motors operate at lower temperatures (Pavel et al., 2017b).

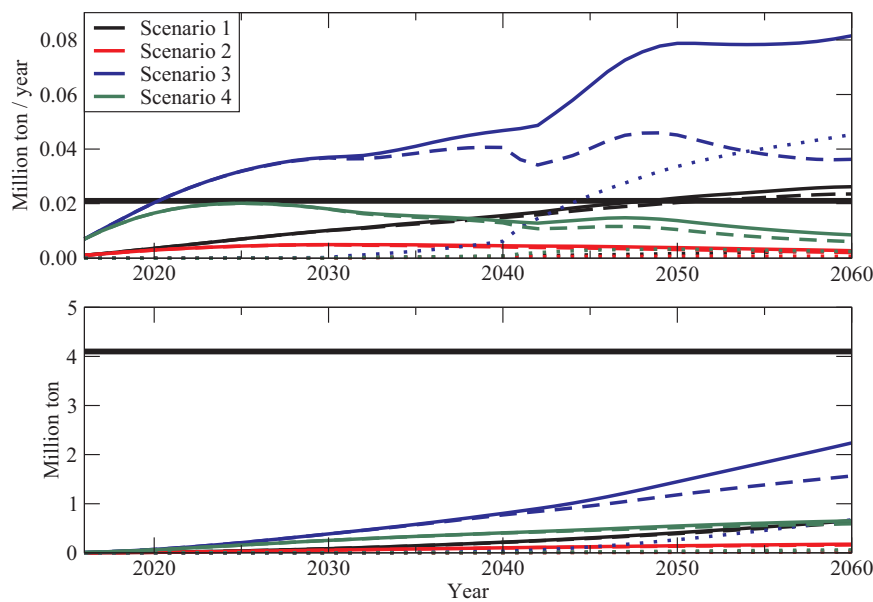


Fig. 5. Demand for neodymium in Scenario 1 back-stop (black); Scenario 2 back-stop improved intensity (red); Scenario 3 new technology mix (blue); and Scenario 4 new technology mix improved intensity (green). Top diagram shows cumulative demand, bottom diagram shows annual demand. Solid line is gross metal demand, dashed line is demand for virgin metal, dotted line is recycled metal, horizontal lines are current annual mining rate (top) and reserves (bottom).

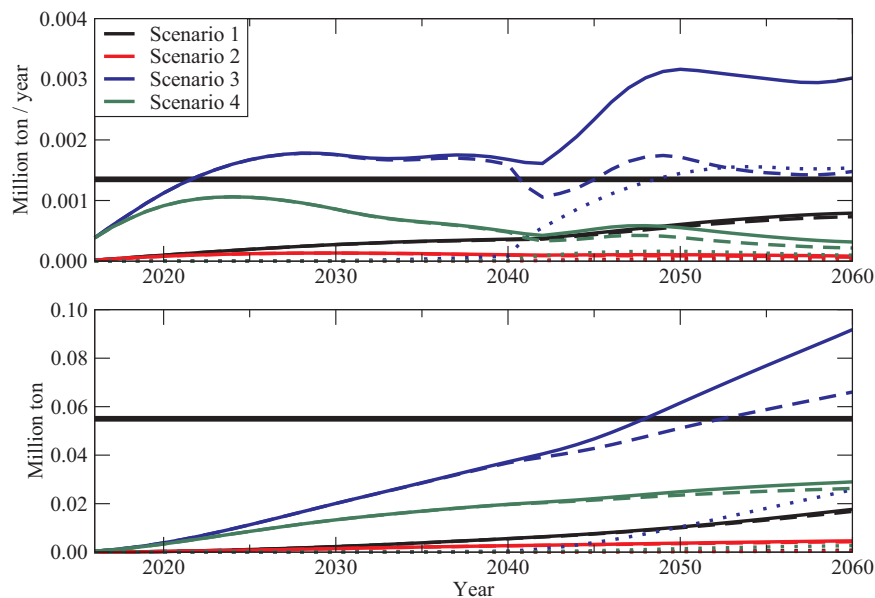


Fig. 6. Demand for dysprosium (for explanation, see Fig. 5).

Advantages include no use of permanent magnets and reduced use of copper (0.27 kg copper per kW) compared with induction motors (Dorrell et al., 2010). However, they generate high noise, have lower efficiency than motors using induction or permanent magnets and the torque ripples a low revs.

The weight of magnets has decreased over time. In the mid-1990s, Oman and Simpson-Clar (1996) estimated that a 100 kW electric automobile motor requires 10 kg NdFeB magnet, corresponding to 0.1 kg PM per kW power. Today's EV motors that use PM have magnets that typically weight less than 3 kg, many in the range 1–2 kg (Speirs et al., 2013). A 2010 Toyota Prius has a 60 kW PM motor with a total magnet mass of 0.768 kg (Burruss et al., 2011) or 0.0128 kg PM per kW. This corresponds to an annual material efficiency reduction of almost 13% over a period of 15 years. The Prius from 2004 had a 50 kW motor with 1.232 kg magnet (0.02464 kg/kW) and used 6.8 kg of copper in the stator (0.136 kg/kW), whereas the 60 kW 2010 model uses 4.93 kg (0.082 kg/kW) (Burruss et al., 2011). This corresponds to annual efficiency improvements of 10% for the magnet and 8% for copper during a

6 year period. Such improvements are likely to continue, as there are various options to improve material intensity further, see e.g. (Pavel et al., 2017b).

4.2. Energy storage in vehicles

4.2.1. Battery

The batteries currently used in vehicle contain lithium in the positive cathode, graphite (carbon) in the negative anode and lithium salt electrolyte. There are several different chemistries and they contain different elements and/or different proportions of the elements. Lithium-cobalt oxide (LCO) was the first commercialised lithium chemistry to reach the mass market, in the 1990s. Due to safety and lifetime concerns, LCO batteries have since lost market share to nickel-cobalt-aluminium (NCA), nickel-manganese-cobalt (NMC) and lithium-ironphosphate (LFP) batteries. All of these chemistries contain lithium, with the lowest theoretical value found in LCO (129.5 g /kWh) and the highest in LFP (172.6 g/kWh) (Speirs et al., 2013). Estimates of metal

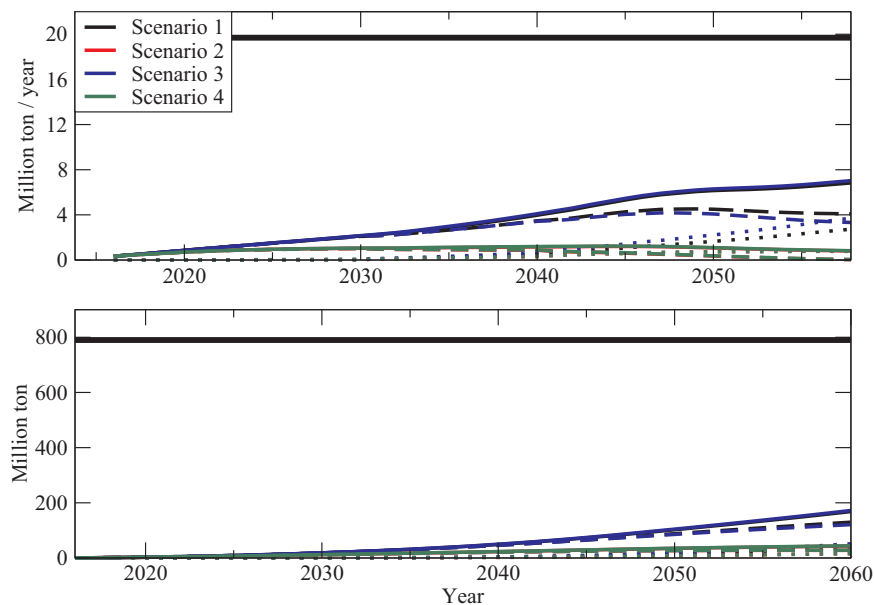


Fig. 7. Demand for copper (for explanation, see Fig. 5).

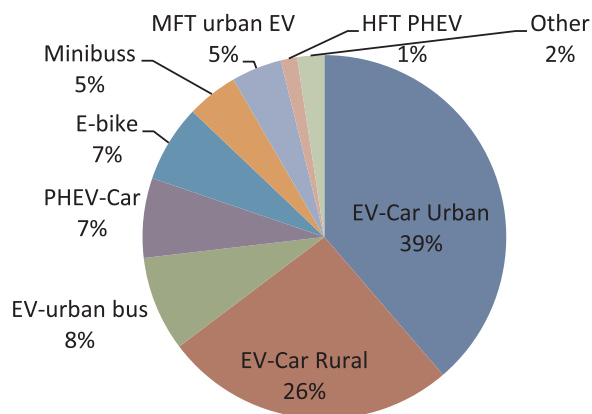


Fig. 8. Relative demand for batteries per sector, assuming moderate-size batteries.

intensity in reality are higher, around 0.20 kg Li/kWh or 1 kg Li carbonate/kWh (Speirs et al., 2013).

The share of materials in the respective chemistries has changed over time in response to the relative price of the metals. The NMC chemistry formerly had a 1:1:1 ratio of nickel, manganese and cobalt, but the lower relative cost of nickel has incentivised development of other ratios, such as 4:4:2, 5:3:2 and 6:2:2 (Chung and Lee, 2017; Xiong et al., 2017). Different chemistries of cathode elements and mixes within those chemistries result in a wide range of potential metal intensities. Approximate ranges are: cobalt 0–1.7 kg/kWh, copper 0.145–1.37 kg/kWh, manganese 0–1.6 kg/kWh and nickel 0–1.7 kg/kWh (Richa et al., 2014). It was assumed here that 1 kWh battery contains: 0.2 kg lithium, 0.4 kg cobalt, 0.4 kg copper and 0.6 kg nickel. However, it should be noted that the LFP chemistry does not contain cobalt or nickel. Therefore, our assumptions overestimate the demand for these metals and underestimate the demand for lithium if this chemistry becomes widely adopted.

Other lithium chemistries currently researched, e.g. lithium oxygen batteries, have higher energy density per weight than the current chemistries, yet they require about the same amount of lithium per kWh (Wadia et al., 2011). Adopting these batteries would reduce the demand for cobalt, but not for lithium.

Chemistries that do not use lithium may gain market share in the

future. It is possible to use the abundant element sodium instead of lithium. Using sodium in the cathode also enables copper to be replaced by cheaper aluminium (Yabuuchi et al., 2014). Sodium batteries have theoretically lower energy density, but it is possible to construct sodium batteries that are competitive with existing lithium batteries (Braga et al., 2017). Another possibility is to use sulphur or magnesium, which has higher gravimetric capacity (i.e. theoretically higher energy density) than sodium, but lower than lithium. Future advances may well provide batteries with little or no lithium, while performing adequately for electric vehicles. Energy density for lithium batteries has improved by 5% annually (Srinivasan, 2008) which translates into lower total metal demand for a defined level of energy storage.

4.2.2. Fuel cells

Hydrogen can be used to store energy, which can be converted to electricity in fuel cells. The best suited technology in vehicles is the proton exchange membrane fuel cell (PEMFC), partly because it operates at low temperature (Simons and Bauer, 2015). PEMFC has an anode typically loaded with platinum, which catalyses hydrogen into positive ions and negative electrons. The US DoE hydrogen programme keeps track of the costs, technological maturity and material requirements of fuel cells.⁸ In 2013, they estimated that a 10 kW fuel cell contains 2.3 g platinum (0.23 g/kW) (Battelle, 2013). An FCEV with 80 kW motor would thus contain approximately 18.5 g platinum. An estimate in 2012 concluded that an 80 kW system in 2010 contained 0.21 g platinum /kW, but that this could be reduced to 0.15 g platinum /kW in 2020 (DoE, 2012), representing an annual material intensity reduction of 3.3%. Simons and Bauer (2015) argued that the DoE forecast was too conservative and only contained average characteristics of fuel cells, so they developed a scenario representing small to medium-sized passenger vehicles and concluded that 0.11 g platinum /kW could be sufficient in 2020 (corresponding to 6.2% annual metal intensity reduction). These predicted rates of improvement of 3.3–6.2% can be compared with the historical annual rate of 13% from 2000 to 2010.⁹ Sun et al. (2011) assumed platinum loading would decline by almost 14% annually for a period of 15 years (2010–2025) and then stabilise at 0.08 g platinum /kW (6 g/vehicle).

⁸ For more information on the program, see <https://www.hydrogen.energy.gov/>.

⁹ Handley et al. (2002) estimated that a 70 kW system in 2000 contained 60 g Pt or 0.86 gPt/kW.

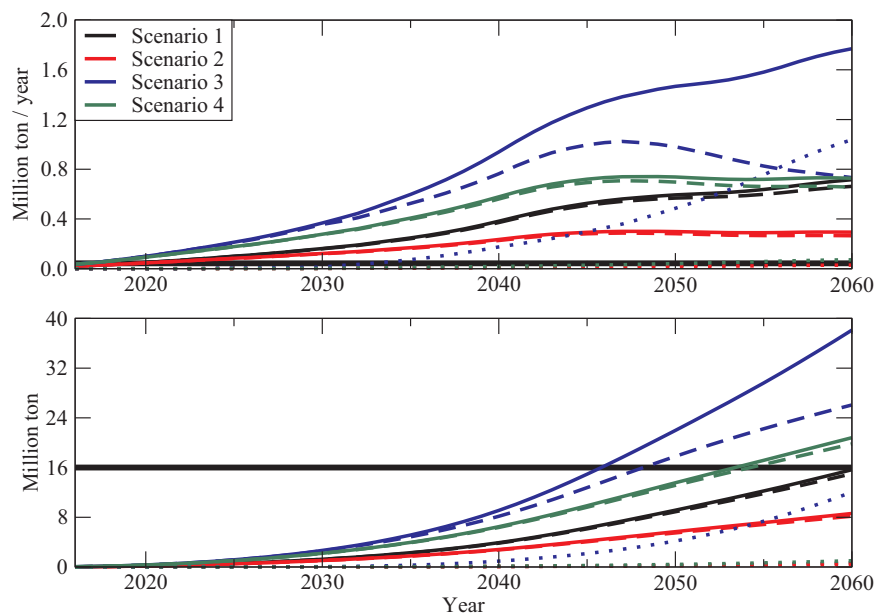


Fig. 9. Demand for lithium (for explanation, see Fig. 5).

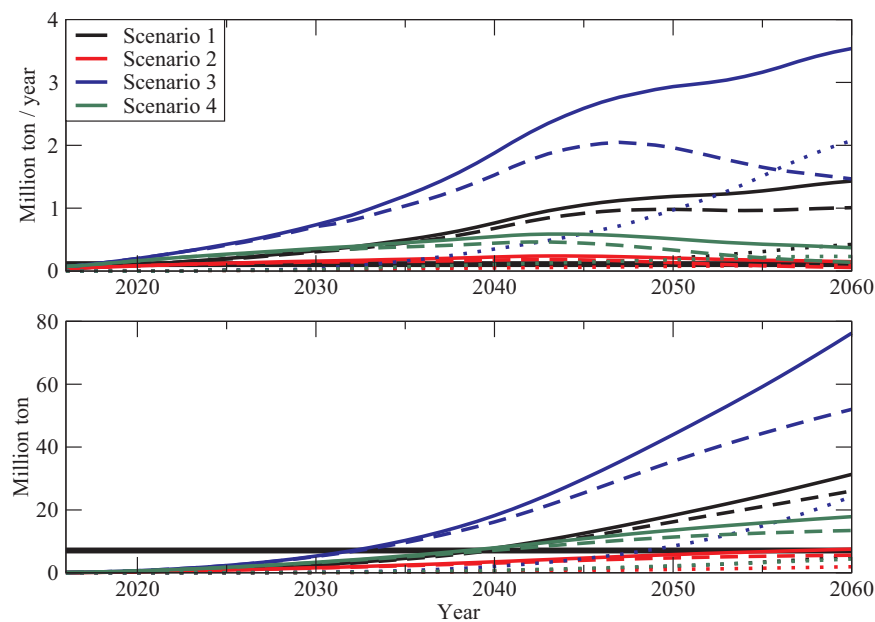


Fig. 10. Demand for cobalt (for explanation, see Fig. 5).

It is possible to replace most of the platinum with palladium and obtain an electrolyte membrane with 65% less platinum and similar performance as a conventional fuel cell (Antolini et al., 2011). The use of platinum per fuel cell vehicle (FCV) may decline further, since platinum-free converters with high performance are being researched (Dai et al., 2015). In this study, we assume that fuel cells contain 0.15 g platinum/kW.

It should be noted that platinum is used in the catalytic converter in ICE vehicles to reduce emissions of pollutants. The intensity is approximately 1–2 g/car. Hybrid cars will therefore also require platinum and electric vehicles that replace ICE vehicles would reduce the platinum demand by approximately 1 g per vehicle.

5. Metal demand and resource availability

5.1. Scenario assumptions

The four scenarios developed in this study were all compatible with the B2Dscenario. They differed depending on the assumptions made on: i) the sub-technologies used (e.g. market share of thin film solar PV vs crystalline silicon), ii) battery size in electric vehicles (battery capacity is either moderate or similar to the biggest batteries currently sold), iii) recycling rates (today's recycling rates or increased recycling), and iv) metal intensity improvement (none or between 2% and 5% annual improvement). These assumptions are summarised in Table 2.

The technology mix was assumed to be either dominated by 'back-

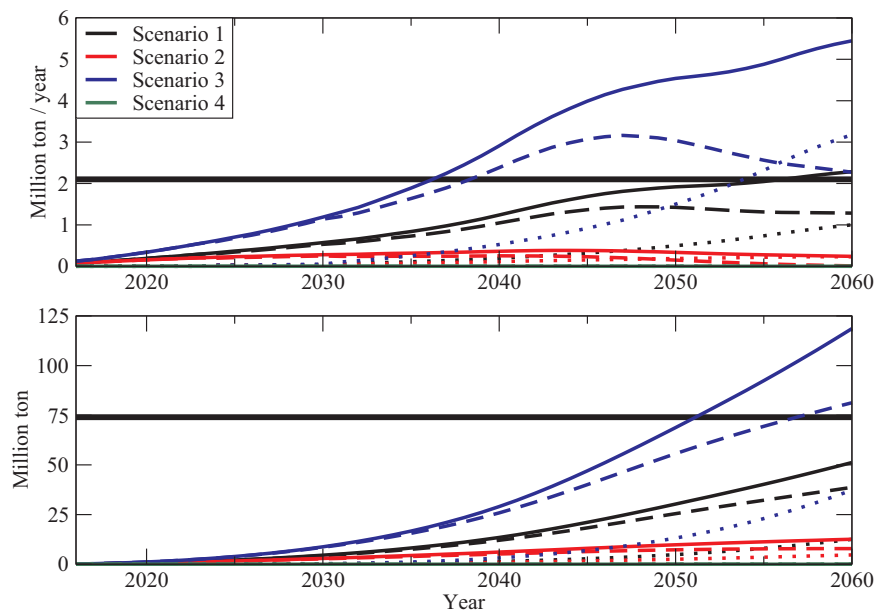


Fig. 11. Demand for nickel (for explanation, see Fig. 5).

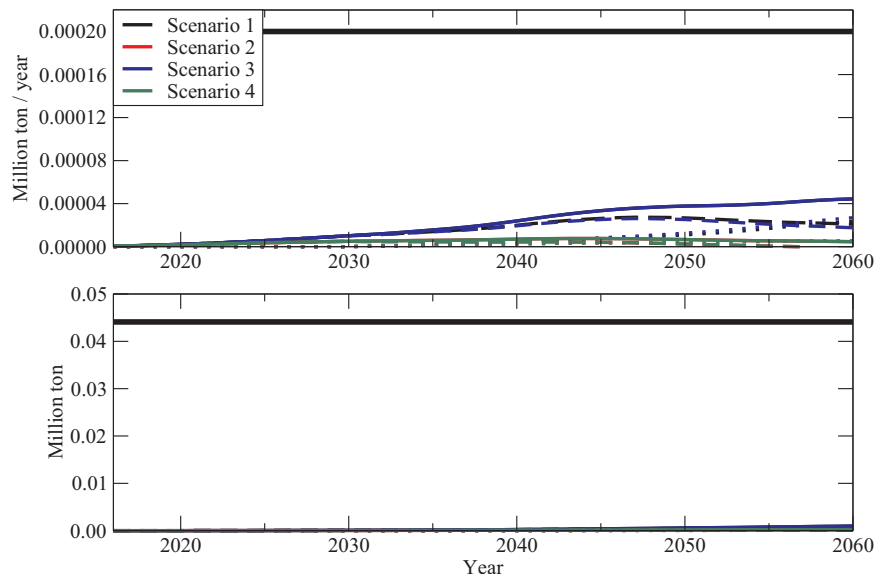


Fig. 12. Demand for platinum (for explanation, see Fig. 5).

stop' technologies, in which permanent magnets are solely used in offshore wind generators and vehicles that have a dual drive train (hybrids), or 'novel' technologies, in which permanent magnets are used in all wind generators and electric motors. Concerning solar PV, crystalline silicon was either assumed to maintain 90% market share or a share declining to 50% by 2035, while at the same time as CdTe and CIGS increased their shares to 15% and 35%, respectively. Amorphous silicon was assumed to have a 1% market share in all scenarios.

Batteries in personal vehicles were either assumed to be moderate size (urban cars use 20 kWh and rural cars use 40 kWh batteries) or a size similar to current top of the line models (75 kWh urban, 100 kWh rural). Moderate size batteries will require a network of fast chargers and/or a change in how cars are used.

The lifespan of the different technologies was the same in all scenarios, between 8 and 30 years depending on technology (see [supplementary material](#) for lifetime of each technology), after which the metal

was recycled in the following year. Assumptions on current recycling rates ranged from 10% (lithium) to 80% (silver), see [Table 3](#). In Scenario 3, with Improved recycling rates, all metals were assumed to reach 80% recycling rate after 2040 (linear increase from 2016 level).

The improved intensity scenarios (Scenario 2 and 4) assumed an annual 2% increase for lithium and 5% for other metals. This is because lithium intensity in batteries is closer to its theoretical minimal value than for other metals. Moreover, we found no research on lithium chemistries with a lower theoretical value than those currently used.

Net metal demand (difference between total demand and recycled volume, i.e. required mine supply) was calculated on an annual basis and compared with current mining rates, see [Table 3](#). Current mining rates provided a point of reference on whether and how much mining needs to increase to meet demand, it is not a ceiling. The cumulative values were compared with currently known reserves. It should be noted that reserves are a subset of resources, and reserves may therefore

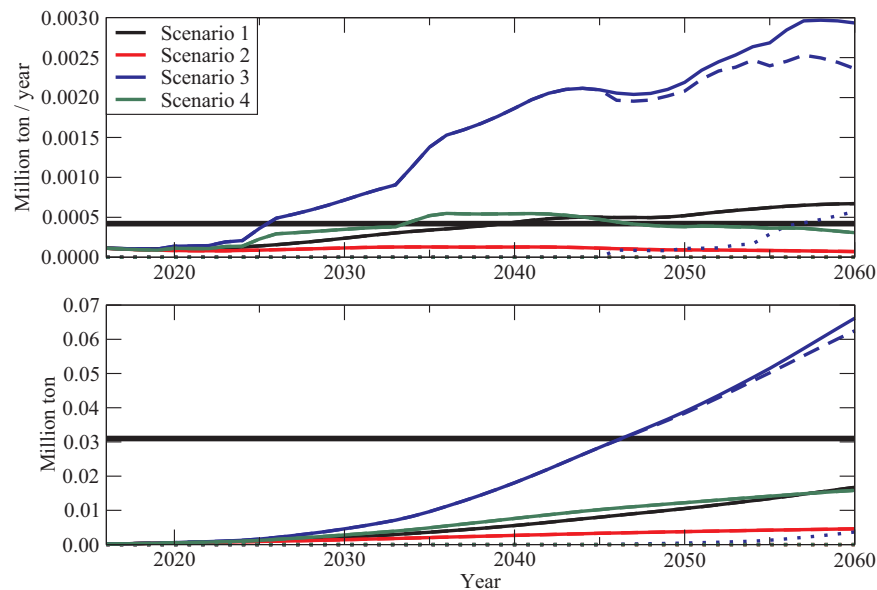


Fig. 13. Demand for tellurium (for explanation, see Fig. 5).

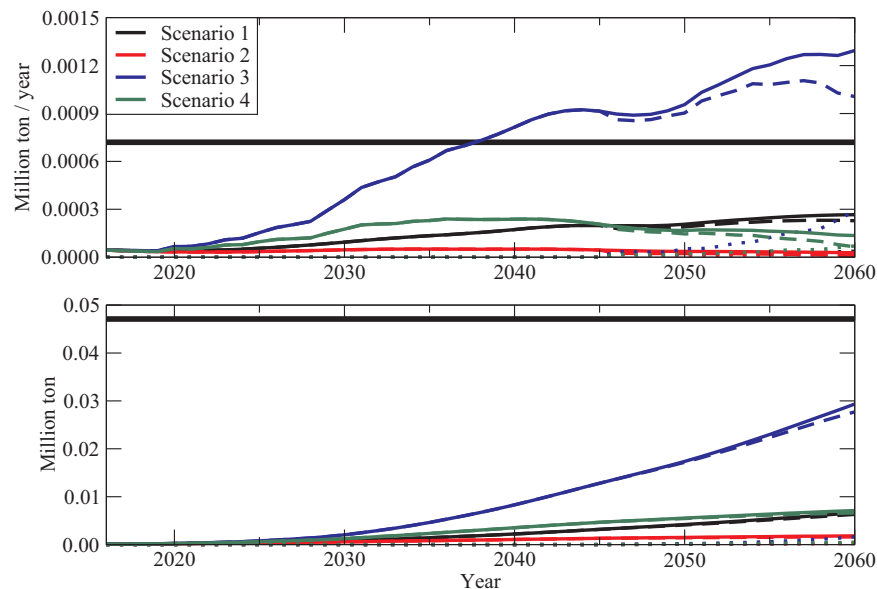


Fig. 14. Demand for indium (for explanation, see Fig. 5).

change over time as technology develops, prices change and more exploration is conducted.

5.2. Neodymium, dysprosium and copper

The generators and electric motors modelled either used permanent magnets containing neodymium, dysprosium and copper, or a higher quantity of copper alone. Assumptions on future technology mix had a large impact on demand for metals used in permanent magnets. Assuming permanent magnets are used in all generators and vehicle motors, Scenarios 3 and 4 more than doubled the demand for permanent magnets compared with Scenarios 1 and 2, see Fig. 4. This illustrates the possibility to substitute a majority of neodymium and dysprosium demand using currently available technologies.

Currently known reserves of neodymium were sufficient in all scenarios, while dysprosium reserves were depleted by the mid-2040s in Scenario 3, see Figs. 5 and 6. Scenario 3 also required mining rates to increase, since the annual demand for these metals surpassed current

mining in the 2020 s. As can be seen in Figs. 5 and 6, gross demand for these metals increased during the first 10 years, reached a plateau lasting ~15 years and increased again for 10 years around 2040, after which a new plateau was reached. The reason for this was the increasing growth rate, which then levelled off. However, components reaching their end of life need to be replaced in order to maintain the stock in society. Therefore, the demand for generators increased after 2040 when they reached their end of life. Unless recycling rates increase from today's level, mining needs to increase accordingly to satisfy this demand.

Scenario 1 (back-stop) resulted in a demand for virgin neodymium to reach about the same level as current mining. Demand for dysprosium reached about half the level of current mining.

Current mining rates of copper were more than four times higher than peak demand for virgin copper in the scenario with the highest demand (Scenario 1), see Fig. 7. The incremental demand that resulted from PM-free motors and generator in Scenarios 1 and 2 was negligible when compared with Scenario 3 and 4.

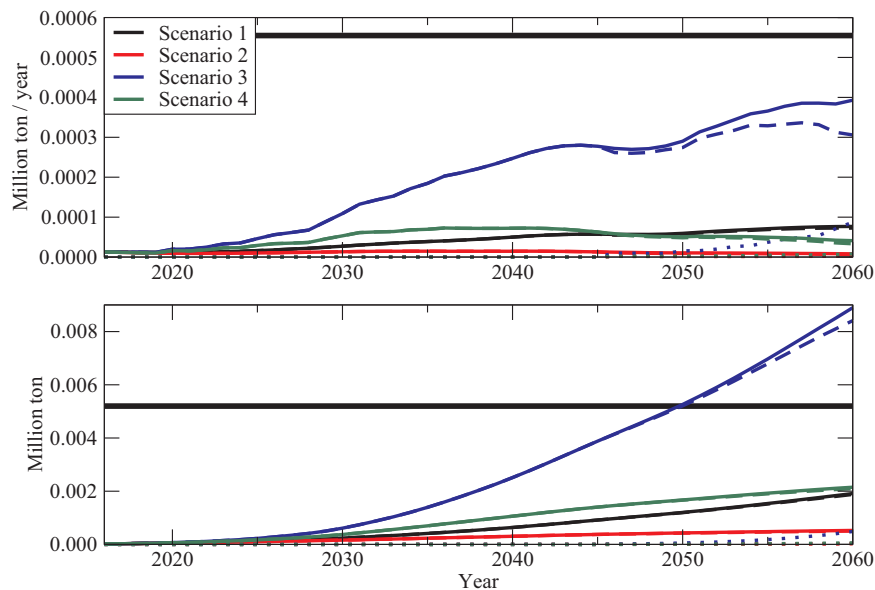


Fig. 15. Demand for gallium (for explanation, see Fig. 5).

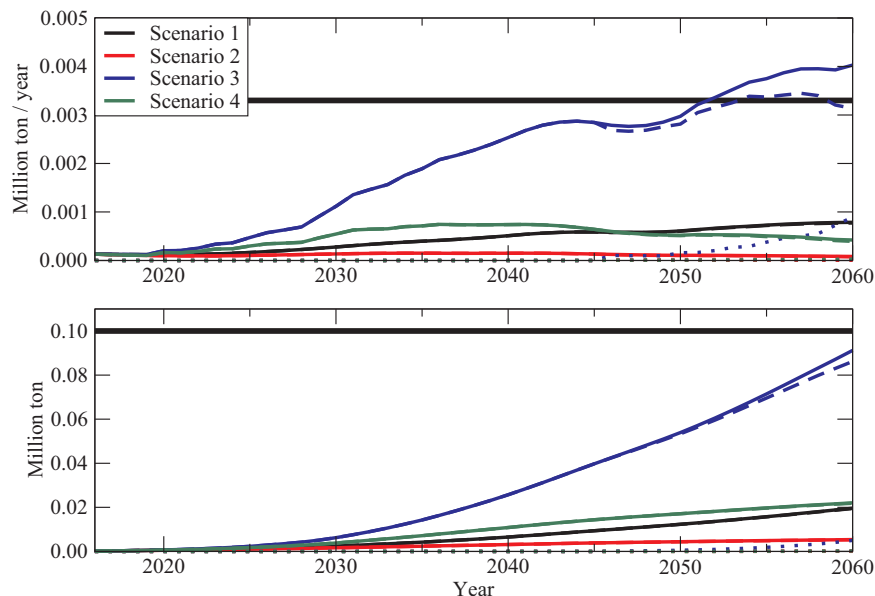


Fig. 16. Demand for selenium (for explanation, see Fig. 5).

5.3. Lithium, cobalt, nickel and platinum

The modelled energy storage technologies either use batteries containing lithium, cobalt and nickel, or platinum fuel cells. Even in scenarios with moderate-size batteries, personal electric vehicles had the majority (65%) of the battery capacity. The largest share (39%) was found in urban cars, see Fig. 8. This indicates that the scenarios for future metal demand are sensitive to assumptions on the number of cars and size of battery in these cars. The number of cars can be lower, if e.g. public transport increases its share or demand for transport decreases as a result of spatial planning.

All four scenarios required an increase in lithium mining to satisfy the demand, see Fig. 9. Scenario 1 (back-stop) depleted currently known reserves by the late 2050s. Scenarios 3 and 4 (new technology mix) depleted lithium reserves by 2040, even with improved recycling rates or intensity. The current recycling rate of lithium is low (10%), but an increase to 80% only postponed the depletion point by a few

years when large size batteries were used. This was a result of the expanding use of batteries in the transport sector, which required virgin metal to be mined. Thus, current lithium reserves were inadequate to support large-size batteries using current technology. Low-grade lithium resources, moderate-size batteries and/or lithium-free batteries will be required for the B2D scenario to be feasible.

The average size of batteries and annual reduction in metal intensity were more important than recycling rates in determining the upward trajectory and peak level of virgin lithium demand. The trajectory after the mid-2040s became more sensitive to assumptions of recycling rates, since a large stock in the techno-sphere was then available. Increasing recycling rate to 80% resulted in peak demand for virgin lithium in the mid-2040s, followed by a slow decline after which recycled lithium overtook virgin lithium in the mid-2050s as the largest supply source.

In the scenarios that assumed current level of metal intensity (Scenario 1 and 3), demand for virgin cobalt grew strongly up until the mid-2040s, see Fig. 10. After that point, mining reached a plateau and

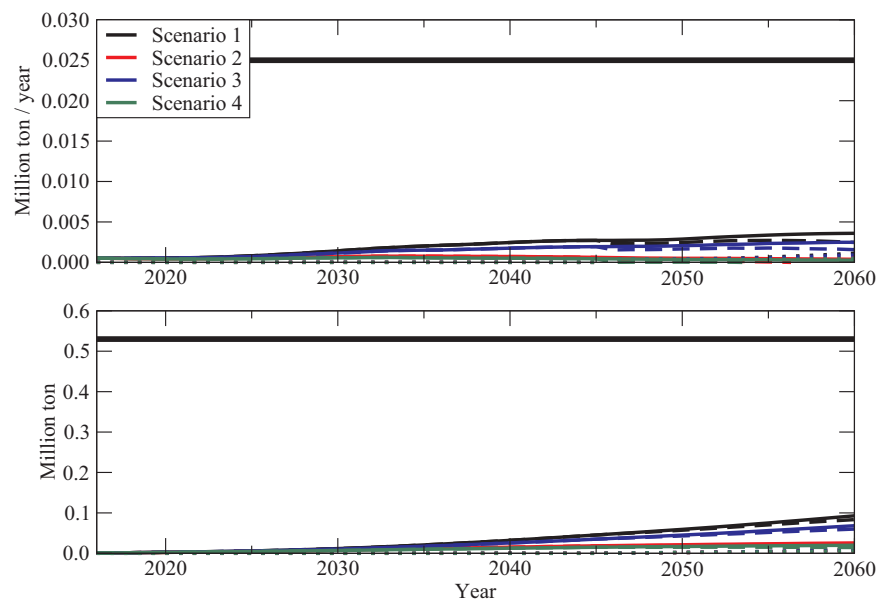


Fig. 17. Demand for silver (for explanation, see Fig. 5).

Table 4
Cumulative demand for metals (with and without recycling) as a percentage of reserves.

	Cobalt	Copper	Dysprosium	Gallium	Indium	Lithium	Neodymium	Nickel	Platinum	Selenium	Silver	Tellurium
Scenario 1												
No recycling	441%	21%	34%	37%	14%	99%	17%	69%	2%	20%	18%	54%
With recycling	366%	16%	33%	36%	13%	95%	16%	52%	2%	20%	16%	54%
Scenario 2												
No recycling	106%	5%	8%	10%	4%	54%	4%	17%	1%	5%	5%	15%
With recycling	79%	4%	8%	10%	3%	51%	4%	11%	0%	5%	4%	15%
Scenario 3												
No recycling	1074%	22%	167%	171%	62%	238%	55%	160%	2%	91%	13%	213%
With recycling	733%	15%	120%	162%	59%	163%	38%	110%	2%	86%	11%	202%
Scenario 4												
No recycling	251%	6%	53%	41%	15%	130%	16%	38%	1%	22%	4%	51%
With recycling	190%	4%	48%	40%	14%	124%	14%	24%	0%	22%	3%	51%

Table 5
Year of maximum annual demand for virgin metals (with and without recycling) and mean annual growth rate in demand.

	Cobalt	Copper	Dysprosium	Gallium	Indium	Lithium	Neodymium	Nickel	Platinum	Selenium	Silver	Tellurium
Scenario 1												
No recycling	2060	2060	2060	2060	2060	2060	2060	2060	2060	2060	2060	2060
Growth (%/y)	6%	1%	1%	0%	1%	7%	2%	2%	0%	0%	0%	2%
With recycling	2060	2049	2060	2060	2058	2060	2060	2048	2047	2060	2045	2060
Growth (%/y)	6%	1%	1%	0%	1%	7%	2%	2%	0%	0%	0%	2%
Scenario 2												
No recycling	2043	2045	2030	2034	2034	2048	2030	2043	2044	2034	2034	2034
Growth (%/y)	5%	0%	1%	0%	0%	7%	2%	1%	0%	0%	0%	2%
With recycling	2043	2030	2030	2034	2034	2047	2030	2040	2030	2034	2034	2034
Growth (%/y)	4%	0%	1%	0%	0%	7%	2%	0%	0%	0%	0%	2%
Scenario 3												
No recycling	2060	2060	2050	2060	2060	2060	2060	2060	2060	2060	2059	2058
Growth (%/y)	8%	1%	4%	1%	2%	9%	4%	3%	0%	2%	0%	5%
With recycling	2047	2047	2028	2057	2057	2047	2049	2047	2047	2057	2045	2057
Growth (%/y)	10%	1%	8%	1%	2%	11%	4%	3%	0%	2%	0%	5%
Scenario 4												
No recycling	2044	2044	2024	2036	2036	2049	2025	2044	2044	2036	2033	2036
Growth (%/y)	7%	0%	9%	1%	2%	9%	9%	1%	0%	1%	0%	4%
With recycling	2043	2030	2024	2036	2036	2047	2025	2041	2030	2036	2033	2036
Growth (%/y)	7%	0%	9%	1%	2%	10%	9%	1%	0%	1%	0%	4%

Note: Growth calculated as mean annual growth from 2017 to the year of maximum demand, assuming demand from other sectors is the same as in 2017. 0% growth rate means the annual growth is < 0.5%.

recycled metal covered an increasing share of the demand. Current mining rates needed to increase 9-fold in Scenario 1 and more than 18-fold in Scenario 3 to meet the demand. However, scaling up the mining to meet demand from Scenario 1 would deplete currently known reserves in the latter half of the 2030s. Similarly to lithium, increased recycling rates had a limited effect on the upslope and peak demand for virgin cobalt, but resulted in declining demand after the mid-2040s and recycled cobalt overtook virgin metal in the mid-2050s as the largest supply source. Scenario 2 (back-stop improved intensity) resulted in cumulative demand for virgin cobalt that was less (79%) than currently known reserves.

Nickel is currently primarily used in production of stainless steel. Assuming moderate-size batteries and today's level of nickel intensity (Scenario 1) resulted in battery production demanding slightly more than half of current mining output in the early 2040s, after which demand reached a plateau, see Fig. 11. This can be explained by a relatively high recycling rate for nickel (60%). The scenario demanded around half of current reserves, which indicates a need to grow reserves or improve intensity.

Assuming use of large-capacity batteries in personal vehicles resulted in modelled demand for virgin nickel outstripping current mining rates by the late 2030s and cumulative demand reached approximately the same level as reserves by the mid-2050s.

Demand for platinum was low compared with currently known reserves and with mining rate, see Fig. 12. It should be noted that the largest use of platinum today comes from catalysing emissions in vehicle exhaust systems. Reducing the number of ICE vehicles would thus reduce the demand for virgin platinum and enable recycled platinum to be used to manufacture fuel cells. The current mining rate of platinum is sufficient to produce slightly more than 10 million FCEV annually and reserves are sufficient to produce more than 3.5 billion FCEV. These figures would double if palladium were used too. In the B2D scenario, annual FCEV production was below 3 million until the late 2040s and never surpassed 4 million. From a metal supply perspective, it is thus possible to increase the number of FCEV far more than in the B2D scenario.

5.4. Tellurium, indium, gallium, selenium and silver

Scenarios 3 (new technology mix) and 4 (new technology, and improved intensity) both involved a strong growth of thin film solar PV. Scenario 3 required mining of tellurium and indium to increase, with peak demand for virgin gallium reaching about 60% of today's level in the latter half of the 2040s, see Figs. 13–16. This scenario depleted current reserves of tellurium (first half of 2040s), gallium (second half of 2040s) and about 60% of indium reserves by 2060. Here, recycling had a very limited role due to the long lifetime of solar cells.

Mining of tellurium needed to increase to meet the requirement even in Scenario 1 where thin film solar PV had a market share of only 10%. Moreover, Scenario 1 had depleted the majority of the reserves by the end of the modelled period. In Scenarios 1, 2 and 4, mining rates and reserves of indium, gallium and selenium were higher than annual and cumulative demand, respectively. Scenarios 1 and 2 increased the demand for silver instead of indium, gallium, selenium and tellurium, see Fig. 17. However, the increase in demand for silver is low compared with current mining rates and silver reserves.

Thus, the results show that current metal intensities and reserves are incompatible with a high market share of thin film solar PV, even if recycling rates increase. However, technological developments that reduce metal intensities may make it compatible. On top of that, sufficient silver is available to enable crystalline silicon to be used as a back-stop technology instead of thin film panels.

6. Discussion

6.1. Scenario similarities and differences: cumulative demand and growth rates

All scenarios resulted in fairly high cumulative demand for lithium and cobalt compared with reserves, see Table 4. The highest demand was found in Scenario 3, with 38 million ton (238% of reserve) without recycling and 26 million ton (163% of reserve) with recycling. These figures can be compared with resource estimates of about 53 million ton (USGS, 2018). In other words, Scenario 3 depleted about half of the resource by 2060 even when lithium recycling increased to 80%. Furthermore, since there is a demand for virgin metal in 2060 (0.8 million ton/year) reserves will need to grow beyond cumulative demand at the end of the scenario timeframe. Lithium also had the highest annual mean growth rate (mining needed to increase by > 7% from today's level for at least 30 years in all scenarios), see Table 5. All of these results are based on the assumption that batteries last the lifetime of the vehicle. To check sensitivity of this assumption, we tested how lithium demand was affected if batteries needed to be replaced once during the lifetime of the vehicle. Shortening batteries life expectancy has a limited impact on mining growth rates but the level of peak mining is raised by up to 79% and delayed by up to ten years. In Scenarios 1, 2 and 4 (current recycling rates), cumulative demand for virgin lithium increase with about 55%. In Scenario 3, demand increase by less than half (23%) since recycling has been improved. However, without recycling demand for virgin lithium would be 62 million ton in Scenario 3, i.e. 9 million ton more than the estimated resource. This illustrates the benefits from extended lifetime and improved recycling rates to mitigate scarcity in the long term. Given the inherent uncertainty in resource estimates and marginal extraction costs, high and fast uptake of personal electric vehicles may require new battery technologies or average battery capacity that provides a shorter range than current ICE vehicles. Another possibility is to use fuel cells instead of batteries, since platinum demand and growth rate were low in all scenarios.

Cumulative virgin cobalt demand with recycling was 52 million ton (i.e. 733% of reserve) in Scenario 3. This can be compared with a terrestrial resource of about 25 million ton and more than 120 million ton on the ocean floor (USGS, 2018). Growth rates were also fairly high (> 4% per year), considering cobalt is primarily mined as a by-product. However, as noted in Section 4.2.1 lithium batteries can be produced without cobalt and this study may have overestimated demand for cobalt.

Cumulative demand and growth rates for other metals differed widely between the scenarios. Scarcity resulting from depletion and the metals that are critical will therefore depend on the mix of sub-technologies for most metals. Comparing Scenarios 1 and 3, the back-stop technologies adopted in Scenario 1 resulted in much lower growth rates and cumulative demand for tellurium, selenium, gallium, dysprosium and neodymium. It is difficult to increase mining of some of these metals, since they are mined as by-products, making the flow dependent on the host metal.

Recycling does not change the upslope of the demand curve (initial growth-phase) but it affects the peak and cumulative demand, particularly if the technology has a short lifespan. Recycling is therefore a long-term option to mitigate scarcity, but insufficient in itself to mitigate short-term criticality. One example is the limited impact of on cumulative demand for metals used in solar PV, since they have long life time (30 years), while cumulative demand for metals used primarily in batteries was reduced by about 30% in Scenario 3 as a result of recycling.

6.2. Substitution and criticality

The most basic type of substitution is element by element, e.g. aluminium can be used as a substitute for copper in many electrical

applications (NMAB, 1972). This type of substitution is a fairly straightforward short-term response by producers when prices for materials go up, since the same technology can be used. For instance, higher copper prices in recent years have incentivised replacement in new applications, such as auto wire harness (Onstad et al., 2016). It is also possible to replace copper with aluminium in the rotor (Finley and Hodowanec, 2001) and winding material (Kimiabeigi et al., 2016) with minor changes to weight, size and efficiency¹⁰ A further possibility is to mix materials, e.g. copper-clad aluminium (Sullivan, 2008), but this comes with the drawback of more difficult recycling. Abundant metal substitutes are not available for all technologies and many metals can therefore be considered critical if certain sub-technologies are used.

This study examined the role of technical substitution, i.e. using a technology substitute to provide similar performance for the end user, but operating using a different construction and metal. This type of substitution comes with a larger threshold than metal-by-metal substitution, since it can require a different set of knowledge and production technology and therefore takes place over longer time frames. For example, an induction motor can be used instead of an REE PM motor, with the drawback of slightly lower efficiency at partial load and higher weight.¹¹ One option to speed up the response would be for policy-makers to prioritise technological diversity. The cost of doing so is a hedging strategy and the level can be guided by risk aversion preference.

Future studies can assess how other types of substitution affect metal demand, e.g. providing urban mobility through public transport instead of electric vehicles.

6.3. Technological development

Technological development has previously enabled metal intensities to improve, but previous success is not a proof of future success. Many of the technologies identified in this study with better metal intensity than current technologies and/or using a different set of metals are currently only available at laboratory scale and some may never reach commercialisation. It is not possible to know which will succeed and which will fail and, as noted above, historical estimates of technologies maturing to the point of no further improvement have been wrong. Technological optimists have repeatedly overstated the speed of which entire energy systems transition, see e.g. (Grubler et al., 2016).

Scenarios 1 and 3 assumed no technological progress up to 2060 and Scenario 2 and 4 assumed annual metal intensity improvements of 2–5%. Including these two groups provided the possibility to check sensitivity and draw robust conclusions, e.g. the growth rate of lithium demand is likely to be high if future demand for lithium batteries resembles the demand in the BD2 scenario. It also illustrated the uncertainty in growth rates and how demand for different metals can develop.

6.4. Normative scenarios and criticality assessment

This study adopted the normative B2D scenario and the result is therefore not a prediction (i.e. the most likely future). The B2D scenario appears unlikely at the moment, given the lack of agreement between nationally determined climate contributions and the 1.5 degree target. However, analysing the metal demand in such scenarios can provide insights into whether they are feasible. Some parts of the scenarios may also occur for reasons other than mitigating climate change, e.g.

¹⁰ Ayat et al. (2017) compared aluminium and copper winding in 60 kW motors and reported a 2% loss of efficiency over a driving cycle. Replacing copper with aluminium in the squirrel cage in a large stationary motor resulted in less than 1% lower efficiency (Yabiku et al., 2010).

¹¹ Dorrell et al. (2010) compared PM-motor, IM and reluctance motors and found that efficiency at low rev was 91.3%, 83.1% and 85.2%, respectively, and at high revs 96.1%, 95.2% and 88.2% respectively.

renewable energy can be used to replace imported fossil energy and electrification improve efficiency and can hedge high and volatile energy prices. Solutions to problems identified by using normative scenarios may then be transferable to other circumstances.

7. Conclusions and policy implications

This study analysed the metal requirements to transition the global energy system up to 2060. It can be concluded that reserves are unlikely to constrain growth rates and total levels of solar power, wind power and electric motors. However, reserves and annual mining rates are likely to influence the technological mix and maximum growth rates of some sub-technologies, e.g. thin film solar PV. Policies promoting technological diversity are preferable from this perspective. Currently used battery technologies and known reserves are not compatible with the B2D transition scenario as a result of insufficient cobalt and lithium reserves. Batteries containing less or no cobalt are feasible. Lithium is much more difficult to replace with maintained performance and cost. Both supply- and demand-related policies can be used to mitigate the issue, including: construction of charging stations that make smaller-sized batteries feasible, researching lithium-free batteries, lowering the cost of extracting low-grade lithium, establishing recycling schemes, supporting hydrogen infrastructure and reducing demand for urban cars by spatial planning and public transport.

Mining of several metals needs to increase, assuming future metal intensities will resemble current levels. However, metal intensities have improved historically and if this continues, the required growth in mining rates and cumulative demand will be much lower. Improved intensity would also enable recycled metals to meet a larger share of demand by the end of the studied period. Most technologies can be substituted by back-stop technologies with slightly lower performance (or higher cost), but constructed from non-critical metals for which additional demand is low compared to current mining rates. The exception is lithium batteries, which are superior to current rivals as a result of higher energy and power density.

Increased use of renewable energy technologies has raised awareness among policymakers that this may increase the demand for critical metals. However, this study showed that in most cases, whether metals was critical or not depended more on the specific sub-technologies used than the share or amount of renewable energy used. Metals may therefore be perceived as more critical in the medium to long-term today than is actually the case if policies that reduce vulnerabilities are implemented. Policymakers and researchers examining metals criticality should consider this finding and focus more on how to reduce vulnerability by developing technologies that utilise abundant metals, improve metal intensity and/or increase recycling. These options would also provide synergies with a circular economy.

Acknowledgement

This publication is a deliverable of MISTRA GEOPOLITICS, which is funded by the MISTRA – The Swedish Foundation for Strategic Environmental Research (DIA 2016/11 #5).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.enpol.2018.04.056>.

References

- Antolini, E., Zignani, S.C., Santos, S.F., Gonzalez, E.R., 2011. Palladium-based electrodes: a way to reduce platinum content in polymer electrolyte membrane fuel cells. *Electrochim. Acta* 56, 2299–2305. <http://dx.doi.org/10.1016/j.electacta.2010.11.101>.
- Arvidsson, R., Sandén, B.A., 2017. Carbon nanomaterials as potential substitutes for scarce metals. *J. Clean. Prod.* 156, 253–261. <http://dx.doi.org/10.1016/j.jclepro.2017.04.056>.

- 2017.04.048.
- Ayat, S., Wrobel, R., Baker, J., Drury, D., 2017. A comparative study between aluminium and copper windings for a modular-wound IPM electric machine, in: Proceedings of the 2017 IEEE International Electric Machines and Drives Conference (IEMDC), pp. 1–8. <http://dx.doi.org/10.1109/iemdc.2017.8002010>.
- Battelle, 2013. Manufacturing Cost Analysis of 10 kW and 25 kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Material Handling Applications, Report Prepared for: U.S. Department of Energy. Battelle Memorial Institute, Columbus.
- Braga, M.H., Grundish, N.S., Murchisona, A.J., Goodenough, J.B., 2017. Alternative strategy for a safe rechargeable battery. *Energy Environ. Sci.* 10, 331–336. <http://dx.doi.org/10.1039/C6EE02888H>.
- Burress, T.A., Campbell, S.L., Coomer, C.L., Ayers, C.W., Wereszczak, A.A., Cunningham, J.P., Marilino, L.D., Seiber, L.E., Lin, H.T., 2011. Evaluation of the 2010 Toyota Hybrid Synergy Drive System. Oak Ridge National Laboratory, Oak Ridge.
- Candelise, C., Speirs, J.F., Gross, R.J.K., 2011. Materials availability for thin film (TF) PV technologies development: a real concern? *Renew. Sustain. Energy Rev.* 15, 4972–4981. <http://dx.doi.org/10.1016/j.rser.2011.06.012>.
- Chung, J., Lee, J., 2017. Asian battery makers eye nickel top-up as cobalt price bites. Reuters, <<https://www.reuters.com/article/us-southkorea-battery-cobalt/asian-battery-makers-eye-nickel-top-up-as-cobalt-price-bites-idUSKBN1AJOS8>>.
- Dai, L., Xue, Y., Qu, L., Choi, H.-J., Baek, J.-B., 2015. Metal-free catalysts for oxygen reduction reaction. *Chem. Rev.* 115, 4823–4892. <http://dx.doi.org/10.1021/cr5003563>.
- Davidsson, S., Höök, M., 2017. Material requirements and availability for multi-terawatt deployment of photovoltaics. *Energy Policy* 108, 574–582. <http://dx.doi.org/10.1016/j.enpol.2017.06.028>.
- Deetman, S., Pauliuk, S., van Vuuren, D.P., van der Voet, E., Tukker, A., 2018. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environ. Sci. Technol.* <http://dx.doi.org/10.1021/acs.est.7b05549>.
- DoE, 2011. Critical Materials Strategy. U.S. Department of Energy, Washington D.C.
- DoE, 2012. Fuel Cell Technologies Office: Multi-Year Research, Development, and Demonstration Plan. US Department of Energy, Washington DC.
- Dorrell, D.G., Knight, A.M., Popescu, M., Evans, L., Staton, D.A., 2010. Comparison of Different Motor Design Drives for Hybrid Electric Vehicles, Energy Conversion Congress and Exposition (ECCE). IEEE, Atlanta. <http://dx.doi.org/10.1109/ECCE.2010.5618318>.
- Elshakki, A., Graedel, T.E., 2013. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *J. Clean. Prod.* 59, 260–273. <http://dx.doi.org/10.1016/j.jclepro.2013.07.003>.
- Elshakki, A., Graedel, T.E., 2015. Solar cell metals and their hosts: a tale of oversupply and undersupply. *Appl. Energy* 158, 167–177. <http://dx.doi.org/10.1016/j.apenergy.2015.08.066>.
- Erdmann, L., Graedel, T.E., 2011. Criticality of non-fuel minerals: a review of major approaches and analyses. *Environ. Sci. Technol.* 45, 7620–7630. <http://dx.doi.org/10.1021/es200563g>.
- Espinosa, N., Serrano-Luján, L., Urbina, A., Krebs, F.C., 2015. Solution and vapour deposited lead perovskite solar cells: ecotoxicity from a life cycle assessment perspective. *Sol. Energy Mater. Sol. Cells* 137, 303–310. <http://dx.doi.org/10.1016/j.solmat.2015.02.013>.
- Finley, W.R., Hodowanec, M.M., 2001. Selection of copper versus aluminum rotors for induction motors. *IEEE Trans. Ind. Appl.* 37, 1563–1573. <http://dx.doi.org/10.1109/28.968162>.
- Fizaine, F., Court, V., 2015. Renewable electricity producing technologies and metal depletion: a sensitivity analysis using the EROI. *Ecol. Econ.* 110, 106–118. <http://dx.doi.org/10.1016/j.ecolecon.2014.12.001>.
- García-Olivares, A., 2015. Substituting silver in solar photovoltaics is feasible and allows for decentralization in smart regional grids. *Environ. Innov. Soc. Transit.* 17, 15–21. <http://dx.doi.org/10.1016/j.eist.2015.05.004>.
- Goodrich, A., Hacke, P., Wang, Q., Sopori, B., Margolis, R., James, T.L., Woodhouse, M., 2013. A wafer-based monocrystalline silicon photovoltaics road map: utilizing known technology improvement opportunities for further reductions in manufacturing costs. *Sol. Energy Mater. Sol. Cells* 114, 110–135. <http://dx.doi.org/10.1016/j.solmat.2013.01.030>.
- Graedel, T.E., Reck, B.K., 2016. Six Years of Criticality Assessments: what Have We Learned So Far? *J. Ind. Ecol.* 20, 692–699. <http://dx.doi.org/10.1111/jiec.12305>.
- Grandell, L., Thorenz, A., 2014. Silver supply risk analysis for the solar sector. *Renew. Energy* 69, 157–165. <http://dx.doi.org/10.1016/j.renene.2014.03.032>.
- Grandell, L., Lehtilä, A., Kivinen, M., Koljonen, T., Kihlman, S., Lauri, L.S., 2016. Role of critical metals in the future markets of clean energy technologies. *Renew. Energy* 95, 53–62. <http://dx.doi.org/10.1016/j.renene.2016.03.102>.
- Green, M.A., Ho-Baillie, A., Snaith, H.J., 2014. The emergence of perovskite solar cells. *Nat. Photon* 8, 506–514. <http://dx.doi.org/10.1038/nphoton.2014.134>.
- Grubler, A., Wilson, C., Nemet, G., 2016. Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions. *Energy Res. Social. Sci.* 22, 18–25. <http://dx.doi.org/10.1016/j.erss.2016.08.015>.
- Habib, K., Wenzel, H., 2014. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. *J. Clean. Prod.* 84, 348–359. <http://dx.doi.org/10.1016/j.jclepro.2014.04.035>.
- Habib, K., Wenzel, H., 2016. Reviewing resource criticality assessment from a dynamic and technology specific perspective – using the case of direct-drive wind turbines. *J. Clean. Prod.* 112 (Part 5), 3852–3863. <http://dx.doi.org/10.1016/j.jclepro.2015.07.064>.
- Handley, C., Brandon, N.P., van der Vorst, R., 2002. Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells. *J. Power Sources* 106, 344–352. [http://dx.doi.org/10.1016/S0378-7753\(01\)01019-9](http://dx.doi.org/10.1016/S0378-7753(01)01019-9).
- Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2013. Corrigendum to: comparative environmental life cycle assessment of conventional and electric vehicles. *J. Ind. Ecol.* 17, 158–160. <http://dx.doi.org/10.1111/jiec.12011>.
- Henckens, M.L.C.M., van Ierland, E.C., Driessen, P.P.J., Worrell, E., 2016. Mineral resources: geological scarcity, market price trends, and future generations. *Resour. Policy* 49, 102–111. <http://dx.doi.org/10.1016/j.resourpol.2016.04.012>.
- Hoenderdaal, S., Tercero Espinoza, L., Marscheider-Weidemann, F., Graus, W., 2013. Can a dysprosium shortage threaten green energy technologies? *Energy* 49, 344–355. <http://dx.doi.org/10.1016/j.energy.2012.10.043>.
- IEA, 2017a. Energy Technology Perspectives. OECD, Paris.
- IEA, 2017b. World Energy Outlook. OECD, Paris.
- Jin, Y., Kim, J., Guillaume, B., 2016. Review of critical material studies. *Resour. Conserv. Recycl.* 113, 77–87. <http://dx.doi.org/10.1016/j.resconrec.2016.06.003>.
- Kavlat, G., McNeerney, J., Jaffe, R.L., Trancik, J.E., 2015. Metal production requirements for rapid photovoltaics deployment. *Energy Environ. Sci.* 8, 1651–1659. <http://dx.doi.org/10.1039/c5ee00585j>.
- Kim, D.H., Lee, S.H., 2013. Investigation on plated Ni/Cu contact for mono-crystalline silicon solar cells. *Electron. Mater. Lett.* 9, 677–681. <http://dx.doi.org/10.1007/s13391-013-2169-4>.
- Kimiabeigi, M., Widmer, J.D., Sheridan, R.S., Walton, A., Harris, R., 2016. Design of high performance traction motors using cheaper grade of materials, In: Proceedings of the 8th IET International Conference on Power Electronics, Machines and Drives (PEMD2016), pp. 1–7. <http://dx.doi.org/10.1049/cp.2016.0287>.
- Lacal-Arátégui, R., 2015. Materials use in electricity generators in wind turbines – state-of-the-art and future specifications. *J. Clean. Prod.* 87, 275–283. <http://dx.doi.org/10.1016/j.jclepro.2014.09.047>.
- Liu, J., Wu, Y., Qin, C., Yang, X., Yasuda, T., Islam, A., Zhang, K., Peng, W., Chena, W., Han, L., 2014. A dopant-free hole-transporting material for efficient and stable perovskite solar cells. *Energy Environ. Sci.* 7, 2963–2967. <http://dx.doi.org/10.1039/c4ee01589d>.
- Moss, R.L., Tzimas, E., Kara, H., Willis, P., Kooroshy, J., 2013. The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. *Energy Policy* 55, 556–564. <http://dx.doi.org/10.1016/j.enpol.2012.12.053>.
- NMAB, 1972. Mutual Substitutability of Aluminum and Copper. National Materials Advisory Board of the National Academy of Sciences, Washington D.C.
- Oman, H., Simpson-Clar, R., 1996. Permanent magnets for vehicle-propulsion motors: cost/availability, In: Proceedings of the 31st Intersociety Energy Conversion Engineering Conference. IEEE, Washington DC. <http://dx.doi.org/10.1109/IECEC.1996.552851>.
- Onstad, E., Obayashi, Y., Shamseddine, R., 2016. Auto, Power Firms Save Millions Swapping Copper for Aluminum. Reuters. Thomson Reuters, London.
- Pavel, C.C., Marmier, A., Tzimas, E., Schleicher, T., Schüler, D., Buchert, M., Blagoeva, D., 2016. Critical raw materials in lighting applications: substitution opportunities and implication on their demand. *Phys. Status Solidi (A)* 213, 2937–2946. <http://dx.doi.org/10.1002/pssa.201600594>.
- Pavel, C.C., Lacal-Arátégui, R., Marmier, A., Schüler, D., Tzimas, E., Buchert, M., Jenseit, W., Blagoeva, D., 2017a. Substitution strategies for reducing the use of rare earths in wind turbines. *Resour. Policy* 52, 349–357. <http://dx.doi.org/10.1016/j.resourpol.2017.04.010>.
- Pavel, C.C., Thiel, C., Degreif, S., Blagoeva, D., Buchert, M., Schüler, D., Tzimas, E., 2017b. Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. *Sustain. Mater. Technol.* 12, 62–72. <http://dx.doi.org/10.1016/j.susmat.2017.01.003>.
- Pihl, E., Kushnir, D., Sandén, B., Johnsson, F., 2012. Material constraints for concentrating solar thermal power. *Energy* 44, 944–954. <http://dx.doi.org/10.1016/j.energy.2012.04.057>.
- Rahman, Z., 2004. Evaluating radial, axial and transverse flux topologies for ‘In-wheel’ motors. *Power Electron. Transp.* 75–81. <http://dx.doi.org/10.1109/PET.2004.1393803>.
- Rehman, A., Lee, S., 2014. Review of the potential of the Ni/Cu plating technique for crystalline silicon solar cells. *Materials* 7, 1318. <http://dx.doi.org/10.3390/ma7021318>.
- Riba, J.-R., López-Torres, C., Romeral, L., Garcia, A., 2016. Rare-earth-free propulsion motors for electric vehicles: a technology review. *Renew. Sustain. Energy Rev.* 57, 367–379. <http://dx.doi.org/10.1016/j.rser.2015.12.121>.
- Richa, K., Babbitt, C.W., Gaustad, G., Wang, X., 2014. A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour., Conserv. Recycl.* 83, 63–76. <http://dx.doi.org/10.1016/j.resconrec.2013.11.008>.
- Saga, T., 2010. Advances in crystalline silicon solar cell technology for industrial mass production. *NGP Asia Mater.* 2, 96–102. <http://dx.doi.org/10.1038/asiamat.2010.82>.
- Simons, A., Bauer, C., 2015. A life-cycle perspective on automotive fuel cells. *Appl. Energy* 157, 884–896. <http://dx.doi.org/10.1016/j.apenergy.2015.02.049>.
- Song, Z., Waththage, S.C., Phillips, A.B., Heben, M.J., 2016. Pathways toward high-performance perovskite solar cells: review of recent advances in organo-metal halide perovskites for photovoltaic applications. *J. Photonics Energy* 6, 022001. <http://dx.doi.org/10.1117/1.jpe.6.022001>.
- Speirs, J., Houari, Y., Contestabile, M., Gross, R., Gross, B., 2013. Materials availability: Potential constraints to the future low-carbon economy, Working Paper II: Batteries, Magnets and Materials. UKERC, London.
- Srinivasan, V., 2008. Batteries for Vehicular Applications, AIP Conference Proceedings, pp. 283–296. <http://doi.org/10.1063/1.2993726>.
- Sullivan, C.R., 2008. Aluminum windings and other strategies for high-frequency magnetics design in an era of high copper and energy costs. *IEEE Trans. Power Electron.* 23, 2044–2051. <http://dx.doi.org/10.1109/tpe.2008.925434>.

- Sun, Y., Delucchi, M., Ogden, J., 2011. The impact of widespread deployment of fuel cell vehicles on platinum demand and price. *Int. J. Hydrog. Energy* 36, 11116–11127. <http://dx.doi.org/10.1016/j.ijhydene.2011.05.157>.
- Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2017. An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity. *J. Clean. Prod.* 140, 359–372. <http://dx.doi.org/10.1016/j.jclepro.2015.06.085>.
- Tokimatsu, K., Wachtmeister, H., McLellan, B., Davidsson, S., Murakami, S., Höök, M., Yasuoka, R., Nishio, M., 2017. Energy modeling approach to the global energy-mineral nexus: a first look at metal requirements and the 2 degreeC target. *Appl. Energy* 207, 494–509. <http://dx.doi.org/10.1016/j.apenergy.2017.05.151>.
- UNEP, 2011. *Recycling Rates of Metals: a Status Report*. United Nations Environment Programme, Paris.
- USGS, 1980. Geological Survey Circular 831: Principles of a Resource/reserve Classification for Minerals. The U.S. Bureau of Mines and the U.S. Geological Survey Arlington.
- USGS, 2018. Mineral Commodity Summaries 2018. U.S. Geological Survey, Reston. <http://dx.doi.org/10.3133/70194932>.
- VDMA, 2017. *International Technology Roadmap for Photovoltaic (ITRPV)*. German Engineering Federation (VDMA), Frankfurt am Main.
- Viebahn, P., Soukup, O., Samadi, S., Teubler, J., Wiesen, K., Ritthoff, M., 2015. Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. *Renew. Sustain. Energy Rev.* 49, 655–671. <http://dx.doi.org/10.1016/j.rser.2015.04.070>.
- Vikström, H., 2016. A scarce resource? The debate on metals in Sweden 1870–1918. *Extr. Ind. Soc.* 3, 772–781. <http://dx.doi.org/10.1016/j.exis.2016.03.009>.
- Wadia, C., Alivisatos, A.P., Kammen, D.M., 2009. Materials availability expands the opportunity for large-scale photovoltaics deployment. *Environ. Sci. Technol.* 43, 2072–2077. <http://dx.doi.org/10.1021/es8019534>.
- Wadia, C., Albertus, P., Srinivasan, V., 2011. Resource constraints on the battery energy storage potential for grid and transportation applications. *J. Power Sources* 196, 1593–1598. <http://dx.doi.org/10.1016/j.jpowsour.2010.08.056>.
- Wang, M., Anghel, A.M., Marsan, B., Cevy Ha, N.-L., Pootrakulchote, N., Zakeeruddin, S.M., Grätzel, M., 2009. CoS supersedes Pt as efficient electrocatalyst for triiodide reduction in dye-sensitized solar cells. *J. Am. Chem. Soc.* 131, 15976–15977. <http://dx.doi.org/10.1021/ja905970y>.
- Widmer, J.D., Martin, R., Kimiabeigi, M., 2015. Electric vehicle traction motors without rare earth magnets. *Sustain. Mater. Technol.* 3, 7–13. <http://dx.doi.org/10.1016/j.susmat.2015.02.001>.
- Xiong, D.J., Ellis, L.D., Li, J., Li, H., Hynes, T., Allen, J.P., Xia, J., Hall, D.S., Hill, I.G., Dahn, J.R., 2017. Measuring Oxygen Release from Delithiated $\text{LiNi}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$ and Its Effects on the Performance of High Voltage Li-Ion Cells. *J. Electrochem. Soc.* 164, A3025–A3037. <http://dx.doi.org/10.1149/2.0291713jes>.
- Yabiku, R., Fialho, R., Teran, L., Santos, A., Rangel, E., Dutra, D., 2010. A comparative study between copper and aluminum induction squirrel cage constructions, Petroleum and Chemical Industry Conference (PCIC), San Antonio, pp. 1–9. <http://doi.org/10.1109/pcic.2010.5666832>.
- Yabuuchi, N., Kubota, K., Dahbi, M., Komaba, S., 2014. Research development on sodium-ion batteries. *Chem. Rev.* 114, 11636–11682. <http://dx.doi.org/10.1021/cr500192f>.