Materials Availability:

Potential constraints to the future low-carbon economy

Working Paper II: Batteries, Magnets and Materials

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function. The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is useful to policymakers.

This working paper addresses some of the issues arising in the contemporary debate on materials availability, specifically examining metals critical to the development of low carbon technologies. The subject of this assessment was indicated as of importance independent experts from government, academia and the private sector.

Executive Summary

The impact that resource scarcity might have on the achievability of global carbon dioxide reduction targets and associated targets for renewable energy is the focus of a series of working papers and reports by the UK Energy Research Centre (UKERC). These focus on methodological issues as well as the range of findings that exist in current literature. This Working Paper is the second in this series and considers issues related to the availability of lithium and neodymium for electric vehicle (EV) and wind turbine generators.

The paper examines *demand* for lithium and neodymium from the EV industry. Lithium is used in Li-Ion EV batteries and neodymium is used in permanent magnets in electric motors and wind turbine generators. Global demand scenarios for EVs vary widely, though all anticipate a considerable growth in the EV market over the coming decades, driven largely by decarbonisation goals.

The material intensity, or quantity of metal required per EV, is also variable, and is influenced by the performance characteristics of the vehicle, determined by the specific power and energy of batteries, and the specific power of magnets in electric motors. By deriving an average for these variables and applying this to the annual sales of EVs an estimate of EV demand for lithium or neodymium may be estimated. However, these variables are likely to change over time as technologies improve, and consumer preferences change. It is therefore necessary to examine the development of these variables over time when estimating demand over decadal timescales.

Ranges of potential demand were derived by combining estimates of future EV demand with the analysis on future material intensity. In 2050 demand for lithium from EVs could be between 184,000 and 989,000 tonnes per year based on a lithium intensity of 190 and 380 grams of lithium per kilowatt hour (kWh). Demand for neodymium in the same year was estimated at between 15,000 and 111,000 tonnes per year based on an EV magnet weight of between 1 and 3.6kg per vehicle.

The paper then examines wind turbines, another low carbon use of neodymium. Again global demand for wind turbines and estimates of future material intensity are key to understanding future demand. It is also important to estimate the number of turbines using permanent magnet designs, since generators without permanent magnets are in common use. Decarbonisation goals are predicted to drive demand for wind turbines in the future, with several studies agreeing that future manufacturing of turbines will increase significantly. Based on this analysis, demand for neodymium from wind turbines could be between 600 and 6,000 tonnes per year by 2050.

The *supply* of lithium and neodymium provides the other side of the picture. These materials are found in very different types of deposit and are recovered in very different ways. Lithium is commonly recovered from concentrated salt brines, or from ore such as spodumene. There are also marginal resources not currently considered economically recoverable, ranging from the low concentration deposits in the Bolivian Salar de Uyuni to the highly speculative recovery of lithium from seawater. The USGS estimate that global production of lithium in 2011 reached 34,000 tonnes, while reserves of 13,000,000 tonnes were reported.

In contrast, neodymium is not recovered on its own, but is produced from ore rich in a range of metals referred to as the Rare Earth Elements (REE). These include the lanthanide series of metals plus scandium and yttrium. Data on REE production and reserves are commonly reported in aggregate, creating difficulty for any analysis of individual metals in the group. However, by assuming a fixed proportion of neodymium in REEs we estimate ~17,000 tonnes of neodymium (20,000 tonnes neodymium oxide) has been produced in 2010. Using similar assumptions global reserves of neodymium are estimated at ~ 13 million tonnes.

Recycling has the potential to contribute to supply, though current recycling markets are small given the relatively low price of both lithium and neodymium. However, recycling has the potential to contribute significantly in the future once large scale deployment of EVs is achieved. The availability of materials from the recycling of end-of-life EVs will be delayed by the average lifetime of vehicles or their components, with optimistic estimates suggesting that around half of future lithium supply may be recycled material. It is also estimated that current in-use stocks of neodymium are four times the annual extraction rate, providing a valuable potential addition to available reserves.

Examining the findings on both supply and demand it is estimated that lithium demand by 2050 could be 540-2900% greater than production in 2011, and 250-900% greater than forecasts of production in 2020. Neodymium demand in 2050 is estimated to be 80-600% greater than production in 2011 and 90-270% greater than forecasts of production in 2030.

The paucity of literature and poor quality of available data is a significant concern for the evaluation of materials and their potential to influence decarbonisation rates. As a result of these issues, the emerging uncertainties in analyses such as this are significant, and reducing these uncertainties to meaningful ranges is a significant challenge. However, it is difficult to improve the literature base without improvement in the available data. Given the proprietary nature of data such as technical specifications of battery and motor technologies, and the sensitive nature of corporate or national reserve data, it is unlikely that significant improvement in data and its availability will occur in the near term.

Although the outlook appears challenging, there is no evidence to suggest that production cannot be increased in the future to meet expected future demand. In the case of lithium, identified resources excluding seawater appear substantial, and end-of-use recycling could contribute to future supply if the vehicle market grows as strongly as forecast by the IEA, although it is unclear at what lithium price level recycling will become viable. For neodymium, REE projects outside China as well as recycling of magnet scrap are options for increasing future supply.

Moreover, the market for electric vehicles includes a number of technological substitutes for batteries and motors. Batteries are likely to continue using lithium even in foreseeable substitute battery technologies. Improvements in induction motor performance may well lead to an elimination of neodymium demand for vehicle motors. This is also true for wind turbines, where direct drive generators compete with a number of other drive train concepts and technologies that do not use neodymium. Thus, there is no reason to believe that the future deployment of electric vehicles and wind turbines *per se* will be undermined by lithium and neodymium availability.

Future analysis of material demand for electric vehicles and wind turbines is needed to assess the issue of present and future material intensity, in order to reduce uncertainty concerning the quantity of both lithium and neodymium demand per battery or motor in the future. Analyses of the production potential of both metals is also needed to better assess which parts of identified lithium resources are economic and, in the case of neodymium, disaggregate the information relating to the supply of rare earths and improve the availability of data specific to neodymium. While there is evidence in the literature that these steps are being taken, a thorough assessment of the long term effects of material availability on the deployment of electric vehicles and wind turbines still requires a much improved understanding of the potential for, and the economic implications of, expansion in both the production and recycling of lithium and neodymium.

Glossary

AER	All-electric range
BDC	Brushed DC motor
BEV	Battery-electric vehicle
BHmax	The maximum energy product of a magnet (magnetic flux multiplied by magnetic field intensity), measured in Mega Gauss Oersteds (MGOe).
Coercivity	Measure of intensity of magnetic field that would need to be applied to a magnet to reduce its magnetisation to zero.
DC	Direct current
DOE	US Department of Energy
Electric drivetrain vehicle	Road vehicles that are fully or partly propelled by electricity, via electric motors. The electricity can be drawn by the electricity grid and stored on board in batteries, or generated onboard using either a hydrogen fuel cell or an internal combustion engine (ICE), and regenerative braking. Hence electric drivetrain vehicles include the following categories: battery electric vehicles (BEVs), hydrogen fuel cell vehicles (FCVs) and internal combustion engine plug-in hybrids (PHEVs) and hybrids (HEVs). In this report electric drivetrain vehicles are referred to as electric vehicles (EV) for the sake of brevity.
EV	Electric vehicle
FCV	Fuel-cell vehicle
GDP	Gross domestic product
HEV	Hybrid electric vehicle
ICE	Internal Combustion Engine
IM	Induction motor
IEA	International Energy Agency
LCV	Low carbon vehicle
Li	Lithium

Li-ion	Lithium ion
Material intensity	The amount of material demanded in the manufacturing of a unit of a given product.
MGOe	Mega Gauss Oersteds
Nd	Neodymium
NiMH	Nickel-metal-hydride
NVH	Noise, vibration and harshness
OEM	Original equipment manufacturer
PEM FC	Polymer electrolyte membrane, or proton exchange membrane fuel cell
Permanent magnets (PM)	Any object or device made from a material that is inherently magnetised and creates its own magnetic field. In the twentieth century several permanent magnets were discovered and manufactured into magnets for various applications (electric motors and generators, computer memory, audio speakers and microphones, magnetic resonance imaging, and mobile phones). This report focuses on the neodymium-iron-boron (NdFeB) magnet, currently the most used magnet in these applications due to its high maximum energy product, a key figure of merit for magnetic materials (Gutfleisch et al. 2011).
PHEV	Plug-in hybrid electric vehicle
PMG	Permanent magnet generator
PV	Photo-voltaic
R&D	Research and development
REE	Rare earth element
Reserves	See Annex 3
Resources	Defined by the USGS as “a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible”.
RPM	Revolutions per minute

SRM	Switched reluctance motor
UKERC	UK Energy Research Centre
USGS	United States Geological Survey
Well to Wheel	Analysis of energy consumption and CO_2 emissions associated with the whole cycle of production, transportation and use of road transport fuels. The analysis includes all energy used and CO_2 emitted directly when producing, transporting and using the fuel in a road vehicle, but excludes the energy used and CO_2 emitted when manufacturing and disposing of the fuel production and delivery infrastructure as well as the vehicle itself.

Units

Wt%	Weight percentage
W	Watts. Used in conjunction with prefix multipliers.
Wh	Watt hours. Used in conjunction with prefix multipliers.
t	Tonnes. Used in conjunction with prefix multipliers.
V	Volts.
Ah	Ampère hours
g	Grams. Used in conjunction with prefix multipliers.
m	Metres. Used in conjunction with prefix multipliers

Prefix multipliers

k	Kilo; x 10^3
M	Mega; x 10^6
G	Giga; x 10^9

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1 Introduction

1.1 A UKERC series on materials availability and low carbon energy

The availability of resources to support the growth and development of human populations forms a contentious debate which has occupied society for at least two centuries. The nature of this debate is broad, and there is little consensus. Through its course focus has been drawn to agricultural productivity and population growth (Malthus 1798), coal availability and the industrial revolution (Jevons 1865), and the potential of a peak in global oil production (Hubbert 1956; Sorrell et al. 2009). More recently focus has been drawn to the availability of certain metals which have been classified as 'critical' or 'strategic' materials in recent literature (Angerer 2009a; Moss et al. 2011). One interesting aspect of this for energy research is the apparent correlation between the materials identified in the literature as critical, and their use in low carbon energy technologies (DOE 2010; DOE 2011; Moss *et al.* 2011).

The UK Energy Research Centre (UKERC) is currently conducting a review of the evidence surrounding the availability of critical materials for low carbon technologies, forming the latest in a series of evidence based reviews of contentious energy topics[1]. In April 2011 the UKERC Technology and Policy Assessment (TPA) theme published a working paper which investigated the issues surrounding the availability of indium and tellurium for the manufacture of thin film PV technologies. This working paper is the next in that series.

1.2 An electric vehicles case study

Transport emissions are a significant component of global CO_2 emissions, responsible for about 25% of global energy-related CO_2 emissions in 2007 (IEA 2009b). More than half of transport energy is used in road passenger transport (IEA 2009b), with cars the dominant mode used. Historically there has been a strong correlation between GDP per capita and car ownership (Chamon *et al.* 2008), suggesting that global passenger vehicle demand is likely to grow significantly in the future as a result of GDP growth in countries such as China and India. The decarbonisation of passenger vehicles is therefore a significant challenge for the decarbonisation of the global economy.

Electric vehicles (EVs) have the potential to significantly reduce the Well-to-Wheel emissions of road vehicles, through the use of low carbon electricity in efficient electric motors and batteries. However, the increasing debate on the availability of critical materials raises questions regarding the feasibility of manufacturing batteries and electric motors at scale (DOE 2010; Kara et al. 2010; DOE 2011). This may have implications for the future decarbonisation of the transport sector, given the high reliance on these technologies in common 2050 energy scenarios (CCC 2008; UKERC 2009b; IEA 2010).

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[1] http://www.ukerc.ac.uk/support/tiki-index.php?page=TPA+Overview&structure=TPA+Overview

We use the term EVs to indicate all those road vehicle types that have an electric drivetrain; these include hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and fuel cell vehicles (FCV). This definition is expressed fully in the glossary and in Box 2.1.

This working paper investigates the various issues surrounding EV batteries and electric motors, and the supply of materials critical to their manufacture. We focus on two particular metals, neodymium and lithium. These materials were chosen because: a) they are discussed repeatedly in both the academic and grey literature (Yaksic and Tilton 2009; Tahil 2010; Moss et al. 2011; Chen 2011a) and media (Blas 2009; Gorman 2009b; Dombey 2010); and b) they represent materials with different characteristics which helps to explore the full range of relevant issues, including their use in batteries and electric motors, and their extraction, production and refining.

Section 2 examines the issues of demand. First we review the literature which estimates future electric vehicle demand, presenting the range of future penetrations of the various low carbon vehicle types. The section then investigates the issues associated with material intensity in electric vehicles, deriving the range of potential weights of lithium and neodymium per vehicle.

In Section 3 we look at the issue of neodymium demand for wind turbines, another low carbon technology which also uses neodymium and may influence the findings for that material.

Section 4 examines the issues of supply. We deal with lithium and neodymium in turn, first discussing the issues of extraction and production, then examining the estimates of future production potential.

In Section 5 we bring the information in previous sections together, illustrating the implications of this evidence, before finally concluding in Section 6.

2 Understanding demand: electric vehicles and material intensity

2.1 Introduction

The demand for materials in manufacturing depends on a range of factors. Understanding these factors is central to exposing the relationship between resources and low carbon technologies. In this section we explore both the issues surrounding demand for electric vehicles, and the variables which define the quantity of material needed in their manufacture.

Global demand for electric vehicles is driven by a number of factors including the global decarbonisation agenda, the need to improve air quality particularly in urban areas, the response to rising fossil fuel prices, global population growth and rising GDP per capita in developing countries. Several scenario reports have been published which estimate future EV growth in response to these drivers. These issues and the results of these scenarios are discussed in Section 2.2.

Deriving the implications of electric vehicle uptake for future lithium and neodymium demand is also complex. In Section 2.3 we investigate the literature which discusses the weight of lithium or neodymium in vehicle batteries and motors, and explore the relationship between material weight and battery or motor performance. We also consider the potential for this relationship to change over time, and the potential for substitution of these materials with other materials with lesser availability concerns.

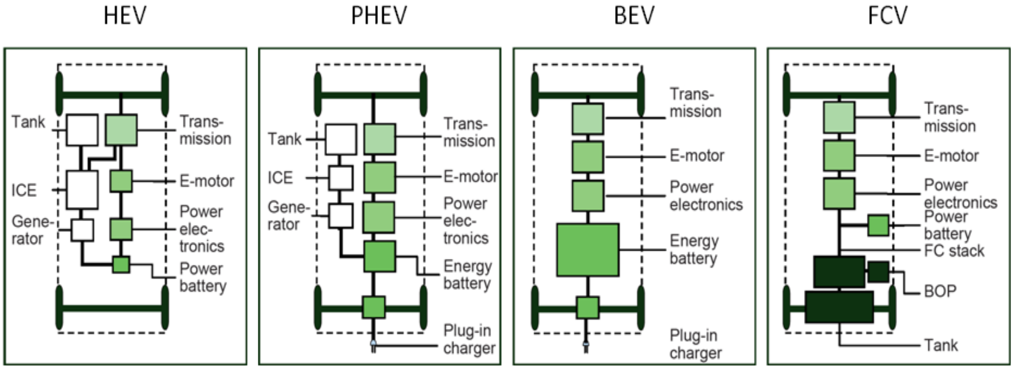
Box 2.1: Four types of electric vehicle

In this report we consider four types of electric vehicle:

- Hybrid Electric Vehicles (HEV)
- Plug-in Hybrid Electric Vehicles (PHEV)
- Battery Electric Vehicles (BEV)
- Fuel Cell Vehicles (FCV)

This classification is broad and does not accurately represent the variety of different vehicle architectures. It is however practical for this report for two reasons: 1) the literature often classifies vehicle technology in a similar way; and 2) these vehicle types all make use of batteries and electric motors. The generic architecture of these vehicles is illustrated below in Box Figure 2.1.

Box Figure 2.1. Schematic of HEV, PHEV, BEV and FCV drive-trains.



- **Parallel hybrid** configuration of electric and ICE drive; also known as hybrid electric vehicle (HEV)
- **ICE is primary mover** of the vehicle with support from small electric motor
- **Small battery** charged by the ICE
- Fully electric driving only **at low speed for smaller distances (<5 km)**
- **Better fuel economy** than conventional ICE

- **Series hybrid** configuration of electric and ICE drive3
- **Smaller battery capacity** than BEV, (Li-ion)
- Vehicle can be **plugged-in** to charge from the grid
- **Small ICE-based** generator for larger range ('range extender')
- **Short range: typically** 40-60 km electric driving.

- **Purely electric drive**
- Large battery capacity, Li-ion technology
- Only charging of battery **from the grid while** stationary1
- **Short range: typically** 150-250 km

- **Series configuration of fuel** cell system and electric drive
- **Fuel cell stack based on** PEM technology
- Hydrogen tank pressure typically 350 or 700 bar
- **Medium range: typically** 400-600 km

Source: Adapted from McKinsey & Co. and EU Powertrain Coalition (2010)

2.2 Global demand for electric vehicles

The current market for EVs is relatively small. Approximately 75 million vehicles were manufactured in 2010, while ~ 2.5 million HEV PHEV and BEVs were sold globally over the decade to 2011 (International Energy 2011)[2]. Sales of EVs to date consist mainly of HEVs and, to a lesser extent, BEVs (Reuters 2010)[3]; lead markets for these technologies are Japan and the US in particular[4] (International Energy 2011). The FCV market is still negligible, with a small number of vehicles available through lease schemes in limited areas of the US and Japan, although leading car OEMs are planning to start mass commercialisation of these vehicles by 2015 (FCB 2009).

To illustrate the range of future electric vehicle uptake scenarios found in the literature we compare several studies in Figure 2.1. This figure compares five studies, disaggregated by vehicle type and over a range of time horizons, the earliest beginning in 2008 and the longest projecting to 2050 (DCM 2009; McKinsey 2009; Angerer *et al.* 2009b; IEA 2010; Marcus *et al.* 2010).

In the Cleantech Insight report "A Cleantech Resource Crisis?" Marcus et al (2010) present a scenario taken from the PricewaterhouseCoopers (PwC) Autofacts report (PWC 2009). This scenario projects annual sales of both BEVs and PHEVs between 2009 and 2015. The results of this are shown in Figure 2.1 (green line) and appear in the BEV and PHEV charts only. This scenario is towards the bottom of the range of future scenarios examined, with 401,000 BEV sales in 2015, and 189,000 PHEV sales in the same year. The work conducted by PWC is industry– focused and is not based on climate change constraints or CO_2 targets.

In the 2009 report "Roads towards a low carbon future" McKinsey (2009) present potential development paths for the automotive sector, covering Internal Combustion Engine (ICEs), HEVs, PHEVs and BEVs. This includes three separate scenarios: an "Optimised ICE" scenario where ICE manufacturers improve the emissions and fuel efficiency of these vehicles, and they maintain a dominant share of the market, 99% in 2030; a "Mixed Technology" scenario, where all EVs increase their market share over time, with ICEs taking a 58% share in 2030; and a "Hybrid and Electric" scenario, described as relatively aggressive, with hybrid and electric vehicles rapidly gaining market share. The scenario data is presented for the years 2010, 2020 and 2030, and is presented in the three blue shades in Figure 2.1 in the BEV, HEV and PHEV charts. The three scenarios cover development paths from bottom to centre of the range of scenarios examined, with 2030 sales of BEVs, HEVs and PHEVs totalling 7 million, 22 million and 25 million respectively for the Hybrid and Electric scenario. Again, this scenario is driven by market factors and not CO_2 constraints.

Investment firm Dundee Capital Markets (DCM 2009) present four separate vehicle sales scenarios in their report "Lithium – Hype or substance". The "Low", "Medium", "High" and "Aggressive" scenarios forecast BEVs, HEVs, and PHEVs from 2009 to 2020 and present increasingly rapid uptake rates for each of the vehicle types. In the aggressive scenario HEVs

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[2] See www.oica.net

[3] Other estimates placed the rate of vehicle adoption in 2009 at 4,250 for PHEV and 3,950 for BEV (Marcus *et al.* 2010).

[4] HEVs and BEVs constitute 9% of the new vehicle sales market in Japan and 2% in the US market

are estimated to have 15.5 million vehicle sales in 2020, half of all EV vehicle sales in that year. BEVs reach 5 million vehicle sales in 2020, while PHEVs reach 9.3 million sales in the same year. Again this estimate has no explicit acknowledgment of climate targets.

While the three studies above present estimates over shorter timeframes, and provide only a limited number of discrete years of data, the remaining two sources present per year scenario data out to 2050. The first of these is published by the German research organisation Fraunhofer ISI (Angerer et al. 2009b). In the work "Lithium für Zukunftstechnologien" (translated as lithium for future technologies) the authors present two scenarios of vehicle sales for HEVs, PHEVs and BEVs: a balanced scenario entitled "Pluralism", where ICE technologies maintain approximately half of future vehicle sales in 2050; and a "Dominance" scenario, where BEVs and PHEVs progressively erode ICE market share, eventually taking nearly 75% of annual vehicle sales in 2050. These are defined by the authors as estimates of the maximum and minimum demand cases for batteries in small passenger vehicles, and are not defined by any carbon constraint. In the report, vehicle shares for ICEs, HEVs, short range BEVs (labelled as "City BEVs"), and an aggregate group of both PHEVs and BEVs are estimated out to 2050. These shares are then applied to the global vehicle scenario found in the report "Mobility 2030" (WBCSD 2004). In our presentation of this data we have disaggregated the PHEV and BEV shares by assuming that they each represent half of their aggregate total in the report (Hoenderdaal 2011). We then add City BEV data to the overall BEV shares. These short range City BEVs are unlikely to have identical battery and motor configurations as long range BEVs. However, the share that these vehicles take is small (less than 3% in 2050 in the Dominance scenario) and is unlikely to alter findings significantly[5].

Finally the IEA provide a scenario entitled "BLUE Map". This scenario models future vehicle sales for a range of vehicle types, including HEV, PHEV, BEV and FCV. This scenario is provided in the Energy Technology Perspectives (ETP) report (IEA 2010). An important feature of the scenario is that it is consistent with a 50% reduction in global emissions by 2050 and is modelled in conjunction with a wide range of other technologies. The scenario suggests that PHEVs, BEVs and FCVs will take an increasing share of vehicle sales to 2050 with market shares for these vehicles approximately 34%, 26% and 18% of the total passenger car market respectively (IEA 2010).

In addition the IEA present a scenario they call BLUE EV Shifts. This scenario is similarly motivated by CO_2 targets, but envisages a world where BEVs become the preferred mode of decarbonising transport, taking an increasing share of vehicle sales in 2050 above that of the BLUE Map scenario. This preference for BEVs reduces the demand for other vehicle types in 2050, and eliminates FCV demand. A single data point representing this scenario is presented as a yellow box in Figure 2.1.

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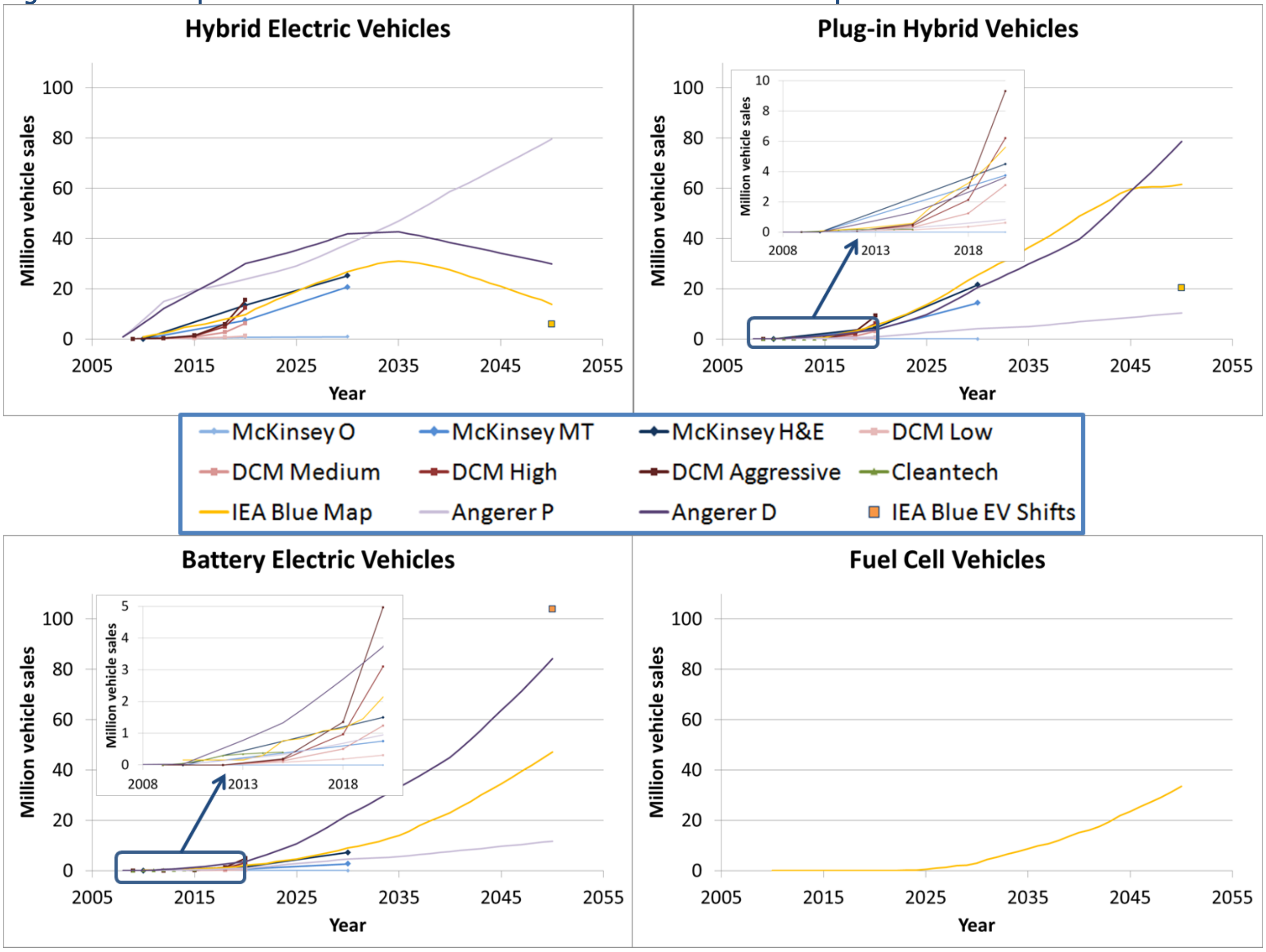
[5] This is compounded by the fact that battery and motor sizes in these vehicle types is likely to be relatively small.

Figure 2.1: Comparison of scenarios of future annual electric vehicle production.



Source: IEA (2010); Angerer et al (2009b); DCM (2009); Marcus (2010); McKinsey (2009)
Note: Click here or the figure above to download a larger version. Some of the data above was extracted from figures using the computer program Engauge Digitizer.

Whilst the estimates presented Figure 2.1 provides an illustrative range of future electric vehicle sales the IEA scenarios are of specific interest for the following reasons:

1. They provide estimates of vehicle sales in 2050, a key year in terms of climate goals.
2. They are based on a 50% reduction in CO_2 emissions by 2050 compared with 2005 levels. According to the Intergovernmental Panel on Climate Change (IPCC 2007) this is the minimum necessary to maintain temperature rises to within 2°C to 3°C.
3. They include estimates of future FCV sales.

The implications for 2050 based on the IEA scenarios are summarised in Table 2.1.

Table 2.1: Annual vehicle sales (millions) in 2050 under the IEA Blue Map and Blue EV shifts scenarios

	HEV	PHEV	BEV	FCV
Blue Map	14	62	47	34
Blue EV shifts	6	20	104	0

Source: IEA (2010)

2.3 Deriving material intensity

Batteries and electric motors are two essential components of electric drivetrain vehicles. Current electric vehicle designs commonly use Li-ion batteries (Rosenberg and Garcia 2010). Current EV designs also commonly include permanent magnet electric motors, which utilise neodymium as a component of their high strength magnets. Both of these metals have been discussed in the literature as potentially critical materials for which future supply may not be able to keep pace with growing demand, particularly demand arising from global decarbonisation goals and the deployment of low carbon technologies (Yaksic and Tilton 2009; Kara et al. 2010; Kleijn and van der Voet 2010; Gruber et al. 2011). In this section we address batteries and electric motors in turn, discussing the associated technological issues, the material intensity of lithium and neodymium, the potential variation of these over time, and the translation of these issues into total demand.

The essential parameters needed to derive material intensity for both batteries and motors are listed below. Estimating the amount of lithium in batteries (Section 2.3.1) and the amount of neodymium in permanent magnet motors (Section 2.3.4) is not straightforward, and the estimate is complicated by differences in battery chemistry (Box 2.2) and magnet manufacturing complexities (Box 2.4). Moreover, material intensity tends to change (either increase or decrease) over time due to technology improvements. We address these complexities and the prospects for future material intensity to decrease in the following sections.

For lithium-ion batteries, deriving material intensity ideally requires knowledge of:

- the nominal voltage of the battery (volts, V);
- the specific capacity of the battery chemistry (Ampère-hours per gram, Ah/g); and
- the concentration of lithium in the active materials of the battery when this is assembled (weight percent, wt%).

For permanent magnet motors, parameters needed to derive material intensity are:

- the summed weight of the permanent magnets in the motor (kg);
- the power rating of the motor (kilowatts, kW); and
- the concentration of neodymium in the final magnet (wt%).

Furthermore, in estimating the potential demand for lithium and neodymium for vehicle applications (Sections 2.4.1 and 2.4.2 respectively), knowledge of the market share (%) of lithium-ion batteries and permanent magnet motors in the future is needed.

2.3.1 Material intensity of batteries

Rechargeable batteries are electrochemical devices that convert electrical energy into chemical energy, store it and then release the necessary power when required by reversing the process. Batteries are an essential component of BEV or PHEV powertrains, because they allow the onboard storage and release of electrical power previously drawn from the electricity grid. Batteries are also needed on board HEVs and FCVs, where they allow the storage of energy generated on board via regenerative braking or other onboard charging, releasing it when required. Small batteries of the order of 1 kWh are therefore generally sufficient for these vehicle types (see Table 2.2). If we assume HEVs and FCVs sold in 2050 continue to utilise 1.3kWh and 1.4kWh batteries respectively and PHEVs and BEVs were equipped with 16 kWh and 35 kWh[6] batteries respectively, 2050 lithium demand from HEVs and FCVs would be 2.4% of total EV lithium demand. In addition, current HEV vehicles often use NiMH batteries. While it is expected that in future NiMH batteries will be replaced by Li-ion batteries, supercapacitors may also be adopted as a NiMH substitute due to the need for very high power density and for comparatively low energy density (Burke 2010), further reducing future lithium demand. Therefore we exclude HEVs and FCVs from our analysis of the demand for lithium in electric vehicles.

Table 2.2. Key technical specifications of selected Internal Combustion Engine (ICE) hybrids currently on the market and of pre-production Proton Exchange Membrane Fuel Cell (PEM FC) hybrids.

HEV model	Battery capacity (kWh)	Battery type
Honda Jazz Hybrid 2011	0.6	NiMH
Honda Civic Hybrid 2012	0.6	NiMH
Honda Insight 2011	0.58	NiMH
Toyota Prius 2011	1.3	NiMH
Ford Fusion hybrid 2012	1.3	NiMH
Audi Q5 Hybrid 2011	1.3	Li-ion
Lexus RX450H	1.9	NiMH
FCV model	**Battery capacity (kWh)**	**Battery type**
Toyota FCHV 2008	1.3	NiMH
Honda FCX Clarity 2011	NA	Li-ion
Mercedes Benz B Class F-Cell 2011	1.4	Li-ion

Source: OEM websites

The amount of lithium contained in an EV battery is a function of the size and chemistry of the battery, its construction and rated performance. As discussed below, it is impossible to define with certainty the amount of lithium that each individual electric vehicle will require. Nevertheless, we discuss each of the main factors influencing the amount of lithium

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[6] See Section 2.3.2 for discussion of battery specifications

required in an individual EV battery in turn. On this basis we identify a range of values for lithium demand per vehicle which is then combined with the global EV demand projections discussed in Section 2.2 in order to estimate future global demand for lithium for the EV market.

The calculation of the global lithium demand for EVs in year y ($D_{Li,y}$) can be summarised by the following equation:

$$D_{Li,y} = (M \times S \times I)_{BEV} + (M \times S \times I)_{PHEV} \tag{2.1}$$

Where M is the market size (annual vehicle sales) of BEV/PHEV in year y, S is the average size (kWh) of a BEV/PHEV battery in year y, and I is the average intensity (amount of lithium per unit energy capacity (kWh) of a BEV/PHEV battery in year y.).

A similar approach has been taken implicitly or explicitly in a number of relevant studies reviewed here (Table 2.5). In the following sub-sections we discuss average battery sizes and average amounts of Li per unit energy stored in turn.

2.3.2 Average battery sizes for BEVs and PHEVs

The battery rated energy, expressed in kWh, is one of the main parameters determining the all-electric range (AER) of a BEV or PHEV. The rated energy is a parameter declared by the manufacturer and as such its relationship with the lithium content is not transparent. The actual energy stored in an EV battery (and hence its true lithium content) is usually significantly higher than its rated energy would suggest, for reasons discussed below. Here we will focus on the average rated energy of EV batteries, which we will refer to as battery size.

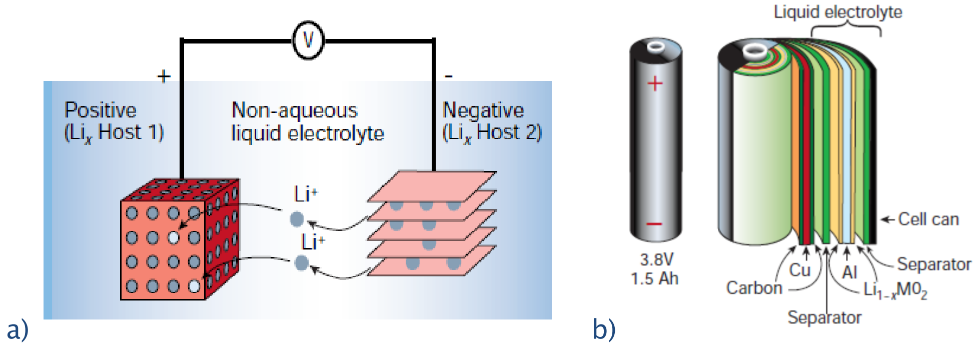
In principle there is no standard battery size for BEVs and PHEVs, and automotive Original Equipment Manufacturers (OEMs) may decide to manufacture different types of BEV or PHEV with very different AER capabilities and therefore different battery sizes. In reality trade-offs exist between AER on one hand and cost, weight and volume of the battery on the other. This constrains the extent to which battery size can vary across different models of BEVs and PHEVs. As for PHEVs in particular, recent research carried out at Imperial College London reinforces this point by demonstrating that from a pure economic perspective the optimum battery size is to be found in a relatively narrow range (5-15 kWh) regardless of the size of the car and intended drive patterns (Contestabile et al. 2011).

Box 2.2: Brief history of Li-ion batteries

Lithium (Li) is an anode material for high energy density batteries, because it is the lightest and most electropositive (-3.04V versus standard hydrogen electrode) metal. Li metal anodes were first demonstrated in the 1970s in high energy, high power primary (i.e.: non-rechargeable) batteries. However, using Li metal anodes in rechargeable batteries proved problematic, as dendrites tend to form on the surface of the electrode upon cycling which eventually lead to internal short-circuits, thermal runaway and possibly explosions (Armand and Tarascon 2008).

Li metal was then replaced with so-called Li insertion or intercalation compounds. These compounds accept Li+ ions (charge) and release them (discharge) by changing their oxidation state as they do so, but without the formation of metallic Li. The Li-ion battery concept (Box Figure 2.2a), was first demonstrated in the lab in the 1980s (Lazzari and Scrosati 1980) and commercialised by Sony in 1991 (Ozawa 1994). The Sony cell was based on a carbon anode, a $LiCoO_2$ cathode and an organic solvent containing a Li salt as electrolyte. Although Li-ion cells can be constructed in different shapes and forms, they generally consist of a coil of thin electrode films deposited on metallic current collectors and with a polymer separator in between (Box Figure 2.2b).

Box Figure 2.2: Illustration of Li-Ion battery processes (a) and battery structure (b)



a) b)

Note: Using Li insertion compounds both at the anode and at the cathode, Li+ ions ‘shuttle’ between the electrodes without Li metal formation.

Source: Adapted from Tarascon and Armand (2001)

Since 1991 Li-ion batteries have rapidly established themselves as the standard in portable electronics, thanks to their high energy density, high power capability, long cycle life and lack of memory effects (Scrosati and Garche 2010). In the meantime, many new electrode materials have been researched and new Li-ion battery concepts developed, such as the plastic battery and Li-polymer battery (Tarascon and Armand 2001). However, until recently the composition of the active materials used in commercial Li-ion cells for the portable electronics market has not deviated much from that of the original Sony battery (Scrosati and Garche 2010).

Renewed interest in alternative Li-ion battery materials has recently been driven by the possible use of Li-ion batteries on board electric vehicles, for which the conventional $C/LiCoO_2$ chemistry is not adequate (Scrosati and Garche 2010). Advancements in nanomaterials have also opened up new avenues for research (Armand and Tarascon 2008). The result is that new anode and cathode materials are now emerging in commercial Li-ion batteries, in order to reduce costs, improve safety or increase power density. Examples of new materials are the $LiFePO_4$ cathode and the $Li_4Ti_5O_{12}$ anode, used in commercial Li-ion batteries for power tools, HEVs and PHEVs (Scrosati and Garche 2010).

In order to significantly improve energy density, especially for use on BEVs, chemistries such as Li-sulphur (Li-S) and Li-air are currently also being researched. While neither is new, recent advances in Li battery material science (nanomaterials in particular) hold promise for their commercial development. Relatively encouraging lab results have been obtained for Li-S batteries in particular, while the road ahead for Li-air batteries appears significantly more uncertain (Scrosati et al. 2011).

BEV models currently being, or about to be, commercialised generally use Li-ion batteries capable of storing in the region of 16-35 kWh, depending on the size of the car, which allow them to achieve ranges in the order of 130-180 km (see Table 2.3). While not addressed in our quantitative analysis of global lithium demand in EVs, the effect of major technological breakthroughs will be qualitatively discussed in Section 2.4.

Table 2.3. Key technical specifications of BEV models on the way to commercialisation in 2011-2012 in the UK (source: OEM websites, Car Magazine website).

BEV model	Battery capacity (kWh)	Battery type	Range (km)	Max Speed (km/h)
Smart fortwo electric drive	16.5	Li-ion	135	100
Citroen C-Zero	16	-	130-160	130
Puegeot iOn 2010	16	Li-ion (Mn)	150	130
Tata Indica Vista EV 2011	26.5	Li-ion	180	120
Mitsubishi i-MiEV 2012	16	Li-ion	160	130
Nissan Leaf 2012	24	Li-ion	160	145
Chevrolet Spark EV 2013	NA	Li-ion	-	-
Ford Focus electric 2012	23	Li-ion	-	-
AC Propulsion eBox 2007	35	Li-ion	-	-
Mini E 2010	35	Li-ion	-	-
Tesla Roadster 2011	53	Li-ion	-	-

Today's plug-in hybrid vehicles (PHEVs) also use Li-ion batteries, however, compared to BEVs, their size varies significantly across vehicle models. This is due to the fact that different powertrain architectures are possible, which are suited to using different modes of operation and to achieving different all-electric ranges. In particular, the Toyota Prius plug-in has been designed to have limited all-electric operation capabilities and hence has a small battery pack (in the order of 4.3 kWh). On the other hand, range-extended electric vehicles such as the Chevrolet Volt are capable of delivering high performance while operating in EV mode and hence have a significantly larger battery pack (16 kWh, see Table 2.4)

Table 2.4. Key technical specifications of PHEV models which are on the way to commercialisation in 2011-2012 in the UK (source: OEM websites, Green Car Congress website).

Vehicle model	Max EV speed (km/h)	EV range (km)	Battery energy (kWh)
Toyota Prius Plug-in Hybrid	100	20	4.3
Chevrolet Volt	190	60	16
Vauxhall Ampera	N/A	60	16
BYD Auto F3DM	N/A	60	20

2.3.3 Lithium content per unit of energy stored in batteries for BEVs and PHEVs

The amount of lithium required per kWh of battery is an important determinant of total demand for lithium in electric vehicles. However, its estimation is far from straightforward, contributing to the wide range of figures reported in the literature (Table 2.5). There are different methods used to derive these estimates, each with its own limitations. Here we discuss the main factors affecting these estimates, following an approach similar to a number of existing studies (Rade and Andersson 2001; Angerer 2009a; Tahil 2010; Gruber et al. 2011; Kushnir and Sandén 2012). We also discuss the main differences between our approach and others.

As already mentioned, estimating material intensity in batteries requires knowledge of the voltage that the battery is capable of delivering while in operation, its specific capacity and the chemical composition of each one of its components. However, this information is only readily available to the battery manufacturers. One way of estimating material intensity (labelled 'A' in the methodology column of Table 2.5) is to quote industry data where available. This is done in several of the studies cited in Table 2.5. Alternatively, in principle it is possible to measure voltage and specific capacity of a battery, then disassemble it and analyse its composition in a laboratory; this process (labelled 'B'), sometimes referred to as "reverse engineering", is often not practical as it is expensive and results obtained for one particular type of cell would not be of general validity. The two remaining options are: to use published data for battery voltage and specific capacity and then make assumptions on its composition (labelled 'C'); or to estimate the amount of Li required by starting from the theoretical value required under ideal conditions and then adding to it in order to take into account real operation conditions (labelled 'D'). In the following discussion we take the latter approach.

There are three key factors which vary and must be accounted for in an assessment of lithium intensity in Li-Ion batteries:

1. Variation in chemistry
2. Variation in losses
3. Variation in over-specification

These are dealt with in turn below.

First, the amount of lithium used per kWh depends on the stoichiometry of the electrochemical reaction for the battery considered[7] and on its corresponding electromotive force (E_0)[8]. Based on Faraday's laws, the theoretical Li demand per kWh can be calculated as:

$$I = \frac{m.10^3}{E_0 ac} \tag{2.2}$$

Where *I* is the lithium intensity in g/kWh, *m* is the molar mass of lithium in g/mol, E_0 is the electromotive force in volts, *a* is the fraction of lithium available and *c* is the charge of 1 mol of lithium ions in Ah/mol.

Using appropriate values we get:

$$I = \frac{6941}{E_0 a.\frac{96{,}485}{3{,}600}} \tag{2.3}$$

Let us now illustrate the use of this formula we have derived on the conventional Li-ion chemistry as used in the battery originally commercialised by Sony. This is based on the following redox process:

$$6C + LiCoO_2 \leftrightarrow Li_{0.5}C_6 + Li_{0.5}CoO_2 \qquad E_0 \approx 4\ V \tag{2.4}$$

Where the cathode material $LiCoO_2$ can only exchange roughly half of its lithium content, hence the fraction of lithium available as in the formula above would be 50%. Entering these values in the formula the theoretical amount of Li needed per kWh of a conventional Li-ion battery would be 129.5g[9].

Let us now consider the case of a battery which uses a $LiFePO_4$ cathode and a $Li_4Ti_5O_{12}$ anode, which could improve battery safety based on the properties of the electrode. The electromotive force (E_0) of this system is ≈ 2V. If we assume that 100% of the Li contained in $LiFePO_4$ and 75% of the Li contained in $Li_4Ti_5O_{12}$ can be made available[10], the theoretical amount of Li needed per kWh would be 172.6g. It can be seen from this example that Li intensity is not the same for different chemistries.

Calculating Li/kWh in this way provides a theoretical minimum. Actual lithium intensity will be higher than the theoretical value for a variety of reasons discussed below. However, starting from the theoretical value is useful, not least because it shows that lithium intensity

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[7] The degree to which the anode and cathode materials can make available the Li that they contain is a factor which should be accounted for as not all material contained will be available to the reaction.

[8] For more detail on these and other electrochemistry concepts, refer to relevant textbooks (Hamann et al. 2007; Atkins 2009).

[9] Or 689g of lithium carbonate, see Annex 1.

[10] These are commonly made assumptions based on the structure of the material and its ability to release all the lithium contained without being structurally affected.

changes from one battery chemistry to another simply as a result of the different electrochemical processes involved.

One key reason why lithium intensity significantly deviates from the theoretical value is that the voltage of the battery when operating is significantly lower than its electromotive force E_0, the difference being a result of resistance within the battery. When the cell is operating, its actual voltage ΔV (the difference in potential between the electrodes) can be expressed as:

$$\Delta V = E_0 - (iR_I) \tag{2.5}$$

Where i is the current being drawn from the cell and R_I is the internal resistance of the cell. R_I is the result of the ohmic resistance of the electrolyte and electrodes as well as the resistance due to the kinetics of charge transfer at the interface between electrodes and electrolyte. In summary the difference between E_0 and ΔV, usually referred to as overpotential, is a function of both how the cell is operated (i.e. how fast the cell is discharged) and how it is constructed (i.e. chemical composition of the electrodes, their density, thickness and size of the particles of active material; the concentration of the lithium salt used as electrolyte and the chemical composition of the solvents used). Hence if we substitute E_0 with ΔV in equation (2.2), Li demand per kWh will be higher than the theoretical value because ΔV is always smaller than E_0. The variation between E_0 and ΔV is too complicated to be estimated theoretically from first principles, making it difficult to estimate without examining batteries directly.

Finally, manufacturers often 'over-specify'[11] batteries, typically for two reasons: to offset the expected degradation through use; and to improve the rated cycle life, which is typically calculated as the number of charge-discharge cycles achievable before energy capacity falls below 80% of the rated value. In many cases the over-specification of the battery is quite substantial, and the depth of charge-discharge cycles is constrained to avoid full discharge and resulting degradation[12]. The extent to which the battery is over-specified and the level to which discharge depth is constrained can vary greatly across manufacturers, chemistry and intended use of the battery. As a consequence the actual amount of Li present in the battery can increase by as much as a factor of two[13].

In Table 2.5 we present several estimates of lithium intensity in EVs as found in the literature. The range varies widely between 50g/kWh and 562g/kWh. Not all of the estimates in this list have the same merit. First, not all methodologies labelled 'A' are actual industry sources, as many are quoted in the media or in corporate presentations without reference to either public or proprietary industry data. We discount a number of these

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[11] i.e. to manufacture batteries with greater specification than the rated values.

[12] Fully discharging the battery mechanically stresses the electrode materials and generally results in faster degradation.

[13] See for example Eberle and von Helmolt (2010), where the authors report that despite the 16kWh nominal energy of the battery of the new Chevrolet Volt PHEV,it is operated at 50% maximum depth of discharge and hence the actual usable energy is only 8kWh.

estimates on this basis, as well as for values lower than theoretical limits (Engel 2007; DCM 2009). Methodology 'C' is valid, although the study using it (Gaines and Nelson 2009a) does not disclose justifications or references for the assumptions used therein. Within the studies employing methodology 'D', Tahil (2010) includes conceptual errors in adjusting theoretical values for practical operating conditions, resulting in overestimation of lithium intensity, Angerer (2009a) uses theoretical values making no adjustments for operating conditions, and the estimate of Gruber et al (2011) makes some assumptions regarding practical conditions, but results in lower values. Finally, a number of studies do not disclose the full details of their assumptions or methods (Neubauer 2011; Kushnir and Sandén 2012). These observations make it difficult to judge the value of many estimates in Table 2.5. For this reason we use a range (190g/kWh to 380g/kWh) to provide illustrative ranges of lithium demand in 2050 (Section 2.5.1).

Based on the evidence presented above it is fair to conclude that the only way of knowing with certainty the actual demand of lithium used per kWh for a given model of battery is to rely on industry data, where they are available. Failing this, estimates such as those made by Tahil (2010) and Gaines & Nelson (2009a) are useful albeit affected by significant uncertainty.

In conclusion, we have discussed values for the amount of Li needed per kWh of battery which can now be used to derive illustrative ranges of future lithium demand from BEVs and PHEVs in Section 2.5. We have so far implicitly assumed that lithium-based chemistries will dominate the BEV and PHEV markets from today until at least 2050, and that no substitution with non-lithium based battery chemistries will occur. This assumption is discussed in Section 2.4.1.

Table 2.5. Estimates of Lithium Carbonate (Li_2CO_3) usage per kWh found in the literature.

Source	**Vehicle Application**	**Material intensity (kg Li/ kWh)**	***Methodology*** [a]
Chemetall GmbH (Engel-Bader 2010)	EV (25 kWh)	0.165	A
	PHEV (16 kWh)	0.176	
	HEV (1 kWh)	0.375	
Meridian International Research (Tahil 2007)		0.300	A
Meridian International Research (Tahil 2010)		0.563	D
Kushnir and Sanden (2012)	Average for four chemistries	0.160	D
Rade and Andersson (2001)	Li-ion (Mn)	0.140	D
	Li-ion (Ni)		
	Li-ion (Co)		
Argonne National Laboratory (Gaines and Nelson 2009a)	HEV4 (1.2 kWh)	0.308	C
	PHEV20 (6 kWh)	0.244	
	PHEV40 (12 kWh)	0.246	
	EV100 (30 kWh)	0.246	
Gruber et al (2011)	Li-ion (Co, Mn, Ni)	0.114	D
Evans (2009)		0.113	A
Evans cited by Reuters (Rosenberg and Garcia 2010)	Chevrolet Volt (16 kWh)	0.158	A
Engel (2007)		0.050	A
Fraunhofer ISI (Angerer 2009a)	$LiCoO_2$	0.180	D
	$LiFePO_4$	0.120	
Dundee Capital Markets (DCM 2009)		0.080	A
National Renewable Energy Laboratory (Neubauer 2011)	HEV (1.7 kWh)	0.100	Internal modelling study (C or D)
	PHEV12 (5.6 kWh)	0.108	
	PHEV35 (17.5 kWh)	0.110	
	BEV75 (29.5 kWh)	0.112	
	BEV150 (67kWh)	0.112	

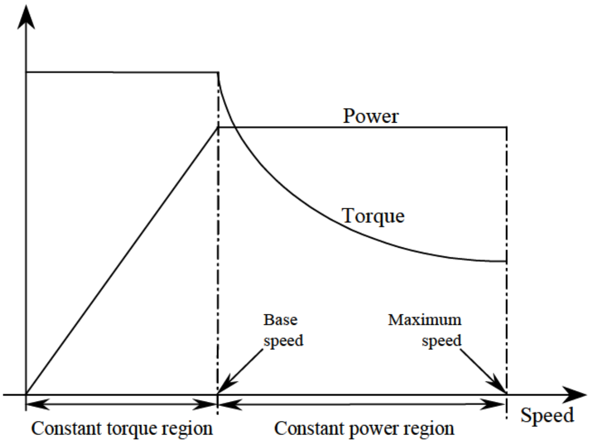
Notes:

a. For a list of methodologies see page 9.

2.3.4 Motors

Electric motors are another central component of electric vehicles, providing traction to the wheels for movement in a variety of different driving situations, including start-up and acceleration phases, and hill-climbing and cruising phases (Xue et al. 2008). To meet these requirements the electric motor needs to operate at a very wide range of speeds (measured in rotations per minute, RPM) and to provide constant power throughout as much of the speed range as possible (Zeraoulia et al. 2006). In addition, an electric motor needs to provide high torque when operating at low speeds in order to provide traction for starting and climbing (Chan and Chau 2001). These two principal requirements—a 'constant torque' region at low motor speeds, and a 'constant power' region at high motor speeds—are illustrated graphically in Figure 2.2 (for more on the relationships between motor speed, power and torque, see Annex 2)

Figure 2.2. Typical expected characteristics of electric vehicle motors

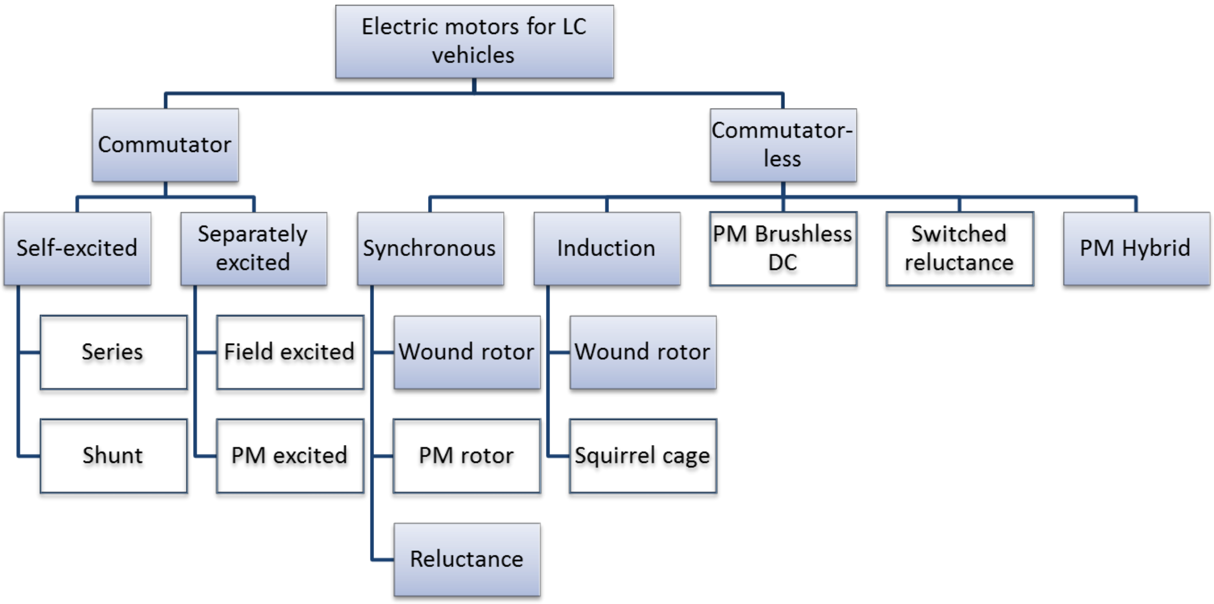


Source: Zeraoulia et al (2006)

2.3.5 Motor types

Electric motor technologies come in various types as shown in Figure 2.3. These can be classified in various ways although it is common to distinguish between those that use a *commutator* and those that do not. A commutator is a simple electromechanical device that reverses the flow of electrical current between the rotor—the moving part of the motor—and the external circuit in order to regulate torque. In the past, the device consisted of copper brushes: though these are no longer used, the term "brushed" motor persists. Modern day motors use carbon-based commutators, electronic switches or no commutation at all. The motor types used in recent commercial vehicles are shown in Figure 2.3 highlighted in white.

Figure 2.3. Types of electric motors for electric vehicles.



Source: Adapted from Chen & Chau (2001)

There is considerable disagreement and obfuscation in the literature regarding motor classification. For example, the terms ‘PM brushless DC’ and ‘PM synchronous AC’ are used interchangeably although they are different motors (Figure 2.3) with some similar characteristics. “Induction motors” are also often referred to as “asynchronous motors” (Schüler et al. 2011). In addition, some authors group synchronous PM motors with PM brushless DC motors and PM hybrid motors (Zeraoulia et al. 2006), although these are not equivalent technologies (Chan and Chau 2001). There are arguably various misnomers and differences in the detailed designs of motors (Chan and Chau 2001; Hodkinson and Fenton 2001) that contribute to the divergence among sources in their classification.

In light-duty electric and hybrid vehicles there is some consensus that motor technologies consist of four types (Hodkinson and Fenton 2001; Zeraoulia et al. 2006; Xue et al. 2008). In this report we group synchronous PM and PM brushless DC and consider the four main electric vehicle motor types as:

- Brushed DC motors (BDC)
- Induction motors (IM)
- Synchronous PM and PM brushless DC motors (PM)
- Switched reluctance motors (SRM)

Brushed DC motors have been prominent in vehicle applications, but are now being replaced due to their low efficiency and reliability and need of frequent maintenance (Zeraoulia et al. 2006). They are also unsuitable in motor sizes of over 40 kW[14] (Hodkinson and Fenton 2001). Induction motors and PM motors are at similar stages of maturity and are often cited as the two main candidate technologies (Zeraoulia et al. 2006; Gutfleisch et al. 2011).

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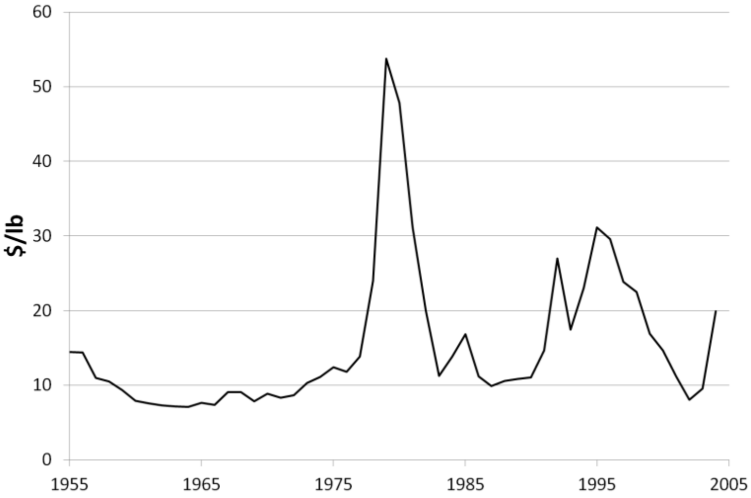
[14] Most commercial BEVs, PHEVs and FCVs use motors larger than 40 kW (see Table 2.7).

Switched reluctance motors may be suitable in some vehicle designs due to their simple construction and ability to provide constant power over a large range of speeds. They are potentially competitive with induction and PM motors if magnet costs increased (Hodkinson and Fenton 2001).

Box 2.3: Out of the frying pan: a brief history of neodymium magnets

Until the early 1980's samarium-cobalt was the strongest permanent magnet alloy available. It was therefore the ideal choice for magnets for high power or space constrained applications. During the 1970's 50% of global cobalt production was produced in Zaire (now the Democratic Republic of Congo). But by 1978, production from key cobalt mines in Zaire ceased due to a combination of industrial action and civil unrest. Production in Zaire resumed in 1979, but the new uncertainty in the market resulted in an escalating cobalt price, which increased some 800% over a period of months. Two types of responses were precipitated. First, the market sought more supply security, developing new mines and organising cobalt stock piles. Second, a new R&D effort began, seeking viable alternatives to cobalt. One such effort, a collaboration between General Motors (GM) and Japan's Sumitomo Corp, produced the Neodymium Iron Boron alloy (NdFeB) a new magnetic alloy which produced stronger permanent magnets than achieved with previous samarium cobalt alloys. Today NdFeB magnets are the high power magnet standard, and are used extensively. This highlights the potential power of substitution as a reaction to price signals. However, in this case the substitute, the NdFeB magnet, has generated its own material supply concern and it is currently unclear whether a similar price signal will illicit an equivalent substitution response.

Box Figure 2.3: Price of cobalt between 1955 and 2005



Source: USGS

A point-grading system is often adopted to rank and evaluate motor types. Typically cost, efficiency, weight and other factors are assessed on a scale of 1 to 5 where five marks the optimum. The points for each factor are then added up without weighting and the sum is used for ranking. Different studies use different factors for ranking motors — some consider only three factors while others use six factors, or divide costs into two parts — and due to this divergence it is difficult to systematically compare results. Table 2.6 shows the summed rankings of 3 recently published studies and personal communication with low-carbon vehicle experts.

Table 2.6. Ranking of motor types from various studies.

Zeraoulia et al (2006)	Xue et al (2008)	Chan and Chau (2001)	Clague and Howey (2011)
1. IM	1. SRM	1. IM	1. IM
2. PM	2. PM	2. PM	2. PM (tie)
3. SRM	3. IM	3. SRM (tie with PM hybrid)	2. BDC (tie)
4. BDC	4. BDC	4. BDC	4. SRM
Note: 'Tie' indicates an equal aggregate score for two motor types. In the Chan and Chau study a fifth motor type, the PM hybrid motor (discussed in Section 2.4.2), is considered in the ranking.			

From the comparison of rankings it appears that there is not complete agreement on a 'best' motor technology. Switched Reluctance motors are ranked first in one study and last in another, mainly due to the fact that the latter considers noise, vibration and harshness (NVH) characteristics to be a "showstopper" while the former does not consider NVH. IM's are ranked first in three studies, due to high reliability, low cost, and low maintenance requirements. Permanent magnet motors have the highest power density and efficiency of all four motor types, but are placed second in all four studies due to high magnet cost and motor performance shortfalls due to the presence of permanent magnets. There is consensus that brushed DC motors are the poorest candidate in terms of performance, though they may remain in use in some applications due to their low cost.

The comparison of rankings suggests that there will be increased competition among the remaining three motor types: induction motors, PM motors and switched reluctance motors. Though there are no estimates of the exact share of permanent magnet motors in the present or future low carbon vehicle market, this is expected to be significant. Chan and Chau (2001) explain in their ranking that "when the cost and maturity of PM brushless motors (including ac or dc) have significant improvements, these motors will be most attractive." Hodkinson and Fenton (2001) argue that there is "general consensus" that PM motors will be used today and in the future. In fact, there is a dominance of the PM motor in currently commercial BEV, PHEV, HEV and FCEV vehicles as shown in Table 2.7. This may not continue, and various pressures may result in manufacturers switching to induction motors (The Economist 2011). Due to the lack of data on future PM market share, we estimate a range of neodymium demand for electric vehicles using several illustrative future market shares in Section 2.5.

Table 2.7. Motor size and type of current and near-production electric vehicles

BEV model	Motor size	Motor type
Smart fortwo electric drive	30 kW	PM motor
Citroen C-Zero	47 kW	PM motor
Puegeot iOn 2010	47 kW	PM motor
Tata Indica Vista EV 2011	55 kW	PM motor
Mitsubishi i-MiEV 2012	66 kW	PM motor
Nissan Leaf 2012	80 kW	PM motor
Chevrolet Spark EV 2013	85 kW	PM motor
BMW Active E 2012	125 kW	PM motor
Ford Focus electric 2012	130 kW	PM motor
AC Propulsion eBox 2007	150 kW	Induction motor
Mini E 2010	150 kW	Induction motor
Tesla Roadster 2011	185 kW	Induction motor
PHEV model	**Motor size**	**Motor type**
Toyota Prius PHEV 2012	60 kW	PM motor
BYD F3DM	50 kW + 25 kW	2 PM motors
Chevrolet Volt 2011	111 kW	PM motor
HEV model	**Motor size**	**Motor type**
Honda Jazz Hybrid 2011	10 kW	PM motor
Mercedes S400 Blue Hybrid 2011	15 kW	PM motor
Honda Civic Hybrid 2012	17 kW	PM motor
Porsche Panamera S Hybrid 2012	34 kW	PM motor
Toyota Prius 2011	60 kW	PM motor
Ford Fusion hybrid 2012	79 kW	PM motor
Lexus RX450H	123 kW (front) + 50 kW (rear)	2 PM motors
FCV model	**Motor size**	**Motor type**
Toyota FCHV 2008	90 kW	PM motor
Honda FCX Clarity 2011	100 kW	PM motor
Mercedes Benz B Class F-Cell 2011	100 kW	PM motor

Source: OEM websites

2.3.6 Neodymium content

The permanent magnets used in PM motor technologies are often called rare earth permanent magnets, neodymium-iron-boron (NdFeB) magnets or simply “neo” magnets. The basic purpose of these magnets in a motor is to provide magnetic flux. In motor applications, permanent magnets need to be light and to resist demagnetisation from the electric circuit and from high operating temperatures. These two requirements are measured respectively by the maximum energy product[15] (BH_{max}) which is linked to the remanent

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[15] The maximum energy product BH_{max} is the product of magnetic flux (B), measured in Gauss (G), and magnetic field intensity (H), measured in Oersteds (Oe). It indicates a magnet’s energy density and is commonly measured in Mega Gauss-Oersteds (MGOe) or the SI unit equivalent, kilojoules per cubic metre (kJ/m^3).

magnetisation[16], and the coercivity[17] (H_c), both of which are extremely important to motor applications (Gutfleisch et al. 2011).

As shown in Figure 2.4, NdFeB magnets were developed in the early 1980s, following the cobalt shortage of 1978 (see Box 2.3) and are now very widely used due to their high energy density (BH_{max}). While the standard chemical formula for these magnets is $Nd_2Fe_{14}B$, quantities of other elements are sometimes alloyed to improve specific properties. In electric and hybrid vehicle applications dysprosium (Dy) substitutes part of the Nd in order to improve the magnet's coercivity at high temperatures[18]. Nd-Fe-B alone is not a good candidate for motor applications due to its instability at high temperatures (NIMS 2010; Gutfleisch et al. 2011). In recent years $(Nd_{10}Dy_4)Fe_{80}B$ magnets have instead been developed for such applications (Gutfleisch et al. 2011). Hono et al (2011) demonstrate other compositions for hybrid and electric vehicles, both commercial and in development. In addition, cobalt, copper, gadolinium may be added to improve corrosion resistance (E-Magnets UK 2011), though the extent to which these additives are used in vehicle motor applications is unclear.

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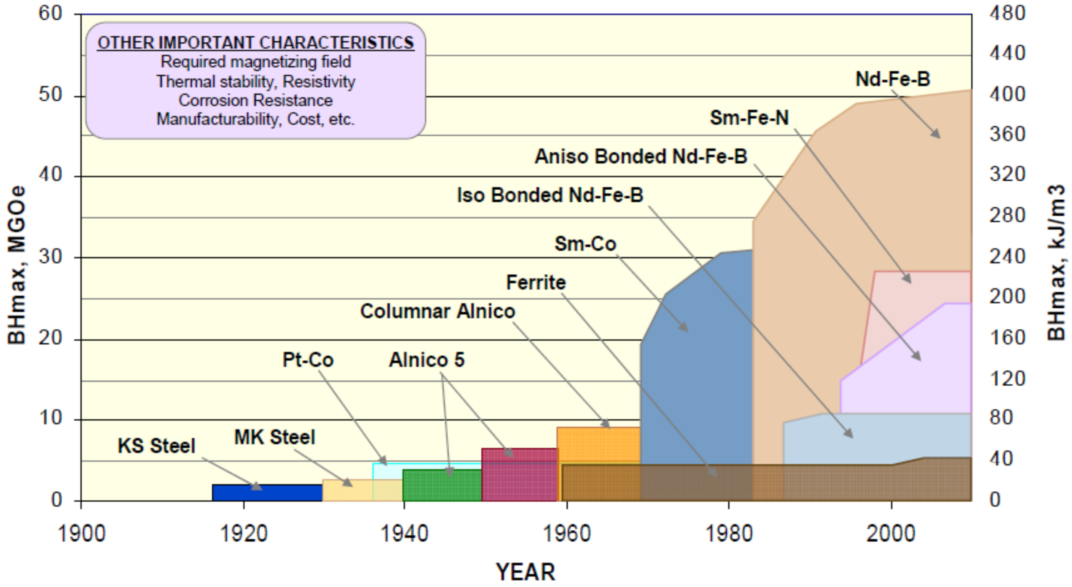
[16] Remanent magnetisation (B_r) or remanence is another figure of merit for magnets (Gutfleisch et al 2011), This is because remanence is known to be affected by a number of compositional and crystal alignment factors (Brown et al 2002), and the subsequent effect of these factors on maximum energy product BH_{max} is even larger, since BH_{max} is proportional to the square of remanence.

[17] Coercivity is defined as the ability of a magnet to resist demagnetisation from the electric or magnetic circuit and from high operating temperature. Magnet coercivity is measured using two parameters, *intrinsic* coercivity ($_iH_c$) and *normal* coercivity (H_c) (Gutfleisch et al. 2011).

[18] This is often called the 'Curie' temperature, the temperature above which a PM becomes demagnetised.

Figure 2.4. Development in magnet energy density (BH_{max}, at room temperature) in the past century.



Source: Constantinides (2010)

Determination of Nd content in a single vehicle requires knowledge of the total amount of permanent magnets in the motor(s), and the atomic or weight composition (at% or wt%) of each magnet. However, the composition of produced permanent magnets varies greatly from one factory to another, and from one application to the next, resulting in various ‘grades’ of neodymium magnet. These are normally labelled with ‘N’ and a two-digit number indicating maximum energy product in MGOe[19], and at times a one- or two- letter suffix (M, H, SH, UH, EH, VH) to indicate increasing intrinsic coercivity, e.g. N50M. Magnet manufacturers often do not disclose data on magnet compositions, as these are considered proprietary. Table 2.8 lists the various compositions of permanent magnets for motor applications found in the published literature.

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[19] Mega Gauss Oersteds. See footnote 15 on the previous page.

Table 2.8. Estimates of NdFeB magnet composition by weight found in the literature.

Composition of NdFeB magnets used in motor applications (wt%)								
Source	*Neodymium (Nd)*	*Iron (Fe)*	*Boron (B)*	*Dysprosium (Dy)*	*Aluminium (Al)*	*Niobium (Nb)*	*Praseodymium (Pr)*	*Terbium (Tb)*
Gutfleisch et al 2011	21.77	67.44	0.98	9.81				
Shin-Etsu 2010[a]	29	66	1	3				
E-Magnets UK 2011	29 - 32	64.2 - 68.5	1.0 - 1.2	0.8 - 1.2	0.2 - 0.4	0.5 - 1		
Credit Suisse 2009	25			8				
Hykawy et al 2010	29.7	68	1	4				
DOE 2010	31			5.5				
DOE 2011	31			4.5 - 6.0			< 5	

Note:

a. Cited in Kara et al (2010). Shin-Etsu notes that terbium (Tb) can replace Dy, but Tb supply is even more limited. Praseodymium (Pr) can also substitute Nd by using a mixed grade Nd/Pr alloy (75%/25%).

Neodymium content ranges from 22–32% and dysprosium from 0.8–9.8%. This variance is due to the complexities in tailoring the manufacturing process to achieve desired magnet properties (see Box 2.4 for a technical description). A magnet with lower dysprosium content does not necessarily imply an equal amount of increased neodymium because other metals may substitute Nd and Dy. Additives such as dysprosium, cobalt and others tend to improve one desired property while degrading another, and the alloying method as well as the quantity of additives further complicates this effect; further additives can be used to offset the performance reduction caused by main additives such as Dy. Different magnet manufacturers address these complexities in different ways, leading to a largely non-uniform 'recipe' for NdFeB magnets found in the literature (E-Magnets UK 2011).

Box 2.4. Complexities in NdFeB magnet manufacturing.

NdFeB magnets can be manufactured via processes known as sintering, bonding or hot deforming. In the case of EV motor magnets, sintered NdFeB magnets provide the strongest magnet (or highest BH_{max}) and are therefore favoured. Sintering involves a process of forming solid dense magnets from metallurgical powders produced by the coarse grinding and jet milling of cast ingots (Brown et al. 2002). The final sintered magnet includes three phases: a dominant hard magnetic phase at stoichiometric ($Nd_2Fe_{14}B$) composition, a 'soft' magnetic phase rich in boron and iron, and a neodymium-rich phase used as an aid in the liquid phase sintering process to allow the magnet to reach full density (Holc et al. 1990; Harris 2011).

Current commercial sintered NdFeB magnets have a BH_{max} of about 56 MGOe (Gutfleisch et al. 2011), which is still lower than the theoretical BH_{max} of 64 MGOe for the stoichiometric 'pure' magnetic material, $Nd_2Fe_{14}B$ (Honshima and Ohashi 1994). Creating sintered NdFeB magnets based on the pure stoichiometric compound leads to a number of problems and barriers, however. One such problem is that the NdFeB powder can be oxidised in surrounding air to form small quantities of neodymium oxide (Nd_2O_3), which consumes neodymium, resulting in raw material wastage, and lowers the magnetic properties of the final product, making it difficult to achieve stoichiometric $Nd_2Fe_{14}B$ at commercial scale (Honshima and Ohashi 1994). As a result, research efforts are focused on reducing oxygen concentration in final sintered magnets. Another problem is iron precipitation in the form of alpha-iron dendrites (α-Fe) (Brown et al. 2002), which may adversely affect the magnet's intrinsic properties and maximum energy product if excessive (Holc et al. 1990; Yan et al. 2011).

Thus, research efforts aimed at improving magnet performance attempt to resolve these issues while reaching the high BH_{max} offered by the stoichiometric $Nd_2Fe_{14}B$ composition. A new strip casting technique is now used in the initial ingot casting to limit iron precipitation, and allow magnets with lower rare-earth content to be produced (Brown et al. 2002). Additives may also be used to improve one performance parameter, but their unwanted effect on another parameter may need to be resolved using further additives (see Annex 4 for the uses and effects of elemental additives for Nd-Fe-B magnets).

An equally wide range of estimates exist for the weight of permanent magnets in EV motors, between 1 and 3.6 kg per vehicle as shown in Table 2.9. The most widely cited figure in the media and industry reports is 1 kg Neodymium per vehicle, an unpublished figure from an independent consultant (Gorman 2009a; Reuters 2010). Most sources state either the weight of the magnet or the weight of neodymium contained per vehicle, often not giving their assumed magnet composition. Moreover, due to the lack of quantitative information we have neglected here the use of Nd in the numerous other (non-traction) electric motors in a vehicle, such as electric power steering, electric brakes, audio speakers, transmission, ignition coil and other components (Hitachi 2010). The Nd content of these other vehicle components is estimated as negligible in most studies (Hykawy et al. 2010). Thus there is inherent difficulty in estimating a single figure for vehicle neodymium content. Note that the lowest material intensity is based on a laboratory report and highest material intensity is for electric motors placed in the wheel hub of the vehicle—this is a rarely used technology currently (Zeraoulia et al. 2006; Xue et al. 2008). In Section 2.5 we present lowest and highest material intensities to illustrate metal demand from the low-carbon vehicle sector.

Table 2.9. Estimates of material intensity of electric and hybrid vehicle motors found in the literature.

Estimates of the quantity of Rare Earth Permanent Magnets in electric and hybrid vehicles					
Source	**Cited in**	**Motor type**	*PM weight (kg)*	*Nd (kg)*	*Dy (kg)*
Dudley Kingsnorth, Industrial Minerals Company of Australia (IMCOA)	Kara et al (2010)	Toyota Prius		0.9 - 1.8	
Jack Lifton, Technology Metals Research	Reuters (Gorman, 2009)	Toyota Prius		1.0	
Toyota	Gutfleisch et al (2011)	Toyota Prius	1.3		
US Dept of Energy	DOE (2010)		1.0 - 2.0	0.31 – 0.62	0.055 – 0.110
Avalon Rare Metals	Bubar (2011)		1.0 - 2.0		
Arnold Magnetic Technologies	Constantinides (2010)		1.25		
Ames Laboratory (US Dept of Energy)	Campbell (2008)	Sintered NdFeB	0.650		
Byron Capital Markets: Equity Research	Hykawy et al (2011)	Toyota Prius (55 kW)	0.650[a]	0.193	0.024
Technology Metals Research	Hatch (2011)			1.0[c]	0.1 - 0.2
IFRI Centre for Asian Studies	Seaman (2010)	Mercedes S400		0.5	
Industrial Simulations, St. Pölten University of Applied Sciences	Schrefl (2011)[b]		2		

Less Common Metals Ltd.	Kennedy (2011)[b]		2		
Magnet Motor GmpH	Muller (2011)[b]	40 kW wheel hub motor	2.3		
Magnet Motor GmpH	Muller (2011)[b]	50 kW wheel hub motor	3.6		
Credit Suisse: Equity Research	Credit Suisse (2009)	50-100 kW motor	1.0	0.25	0.08
Fraunhofer ISI	Angerer et al (2009a)		1.5 - 4.5	0.5 - 1	

Notes:

a. value for PM weight cited in Hykawy et al (2011) is based on laboratory report by Campbell (2008)
b. cited in Hoenderdaal (2011) based on personal communication with Fraunhofer ISI
c. includes an unspecified amount of praseodymium (Pr)

2.4 Estimating future material intensity

2.4.1 Batteries

The focus of research and development in lithium-ion batteries is currently aimed at increasing safety, lowering cost, increasing energy density and improving cycle life, with a long-term view towards low environmental impact (Ritchie 2004; Armand and Tarascon 2008). Raw lithium contributes only 1-2% of final battery cost (Kushnir and Sandén 2012). Accordingly, little discussion about reductions in lithium content can be found in the literature. Rade and Andersson (2001) provide the only estimates of future lithium intensity of Li-ion batteries based on the improvement of active material utilisation (the amount of lithium content in the anode and cathode that can be made available in the reaction) from a current 50% to 60-80% depending on chemistry, leading to intensity reductions of 21-34%. It is worth noting that this is an illustrative scenario only, and it is unclear whether these developments will actually occur. Additionally, from the discussion of complexities of lithium intensity in current batteries (Section 2.3.1) it appears unlikely that intensity may be reduced in a straightforward manner.

It is unclear whether future development in lithium-based batteries will reduce material intensity. The two lithium-based batteries that are currently being developed as Li-ion are lithium-air (Armand and Tarascon 2008) and lithium-sulphur, which has recently received renewed attention (Hassoun et al. 2012). Both of these technologies have higher energy density and thus ability to dramatically improve the driving range of electric vehicles. It is worth pointing out that the improvements associated with these technologies may increase both the market share of lithium batteries as well as the average size (kWh) of an automotive lithium battery, resulting in an overall increase in annual demand for lithium as shown in Equation (2.3).

Thus it appears that the principal option for a straightforward reduction in lithium intensity in the case of future supply shortages is the total substitution of lithium in automotive batteries. We review the prospects for this substitution and relevant battery technologies below.

2.4.1.1 Potential for substitution

Early BEVs such as the GM EV1 used lead acid batteries and more recently the Think City used Sodium/Nickel Chloride (also known as ZEBRA) batteries. However, lithium batteries have significant advantages over these two battery types and it is unlikely that they will be used in future BEVs and PHEVs. Since lithium is the lightest metal and has an extremely negative electrode potential, lithium-based batteries have much higher gravimetric energy density than lead-acid batteries, allowing EVs to achieve acceptable ranges without imposing a high weight penalty. Unlike ZEBRA batteries which use molten Sodium at 300-350°C, lithium batteries operate at room temperature and because they don't need preheating they are always available for use, which is a very desirable characteristic for vehicles with no fixed usage patterns such as passenger cars. These favourable characteristics, together with the high power density and long cycle life, explain why Li-ion batteries are the technology of choice for BEVs and PHEVs. Moreover, lithium batteries are a much younger technology than lead acid batteries, and as such it is expected that they still have significant margin for improvement.

Other non-lithium chemistries are being researched at present which may, if successfully developed, offer high enough energy density and other favourable characteristics to compete with lithium-based batteries. The choice in terms of materials that can replace lithium is quite limited though, because prospective systems need to have high energy density and hence research efforts are focused on light metals such as Sodium, Magnesium and Aluminium.

Battery systems currently under investigation include Magnesium/Sulphur and Aluminium/Graphite Fluoride. However, the practical viability of these systems has not been demonstrated and their future use in electric vehicles depends on the occurrence of significant technological improvement (Armand and Tarascon 2008). Metal air chemistries such as sodium air and zinc air are also possible alternatives to lithium air. Sodium air batteries in particular have the potential to mitigate some of the problems of Li/air technology but significant technological improvement is still needed before this technology may be considered for practical applications (Peled et al. 2011).

To summarise, alternatives to lithium-based batteries exist. However in the short to medium term lithium-based chemistries seem favoured, while in the long term other options may become competitive, giving rise to potential substitution. However alternative technologies are currently far from mature and technological improvement is still needed. It is possible that the current research focus on Li-Ion may constrain the funding for research and development in non-lithium alternatives, slowing their technological development.

2.4.2 Motors

Published estimates of future Neodymium content per vehicle are not available in the literature. The values reported in Table 2.9 are used as static values in all modelling and projections of future neodymium demand from electric and hybrid vehicles. It is possible, however, that neodymium content per vehicle will decrease as the metal's price increases and the technologies mature, as has been demonstrated more clearly in the case of photovoltaics (Candelise et al. 2011; Speirs et al. 2011). Toyota and General Electric have also initiated a programme aimed at reducing Neodymium content per vehicle or altogether replacing it in some models (Elmquist 2011).

Essentially, reducing Neodymium content per vehicle requires "shedding weight", or increasing the energy density of the magnets. In a review of magnetic materials developments to date, Gutfleisch et al (2011) explain that the search for novel magnets and materials with higher energy density and remanent magnetisation has "somewhat stagnated and no further breakthrough is in sight." This is however a general observation and does not imply that material intensity reductions cannot be achieved. In fact, Gutfleisch et al (2011) note that there are major research efforts in reducing the dysprosium content of permanent magnets, mainly due to the high price of dysprosium relative to neodymium[20]. Since dysprosium is used to improve magnet performance at high temperatures, reducing the need for dysprosium could be achieved by improving motor cooling in order to reduce operating temperatures (Fromer et al. 2011).

Several suggestions have been made on reducing material intensity for permanent magnets, but most of these are focused on at least partial substitution, and many are not currently being pursued. Schuler et al (2011) examine some of the motor types discussed in Section 2.3.4 and conclude that:

- Induction motors are a viable substitute;
- Samarium cobalt magnets (SmCo) may re-enter the market if the relative cost of NdFeB rises; and
- Hybrid PM motors have high potential for the future.

The third point is most relevant to the discussion of material intensity reduction. Hybrid PM motors that combine principles of PM motors with switched reluctance motors require less neodymium than the PM motors currently used in commercial vehicles. Although hybrid PM motors are still in the R&D phase (Schüler et al. 2011) their uptake may represent a future scenario of reduced neodymium demand from the electric mobility sector.

In addition, Fromer et al (2011) provide several suggestions on material intensity reduction along with estimates of their reduction potential, shown in Figure 2.5. The suggestions include both Neodymium and dysprosium, and focus more on the latter. Reductions between 10 and 30% can, according to the report, be achieved in magnet manufacturing. Up to 50% reductions can come from recycling, reducing dysprosium content and using magnetic gearing systems to improve power density while reducing material intensity. The

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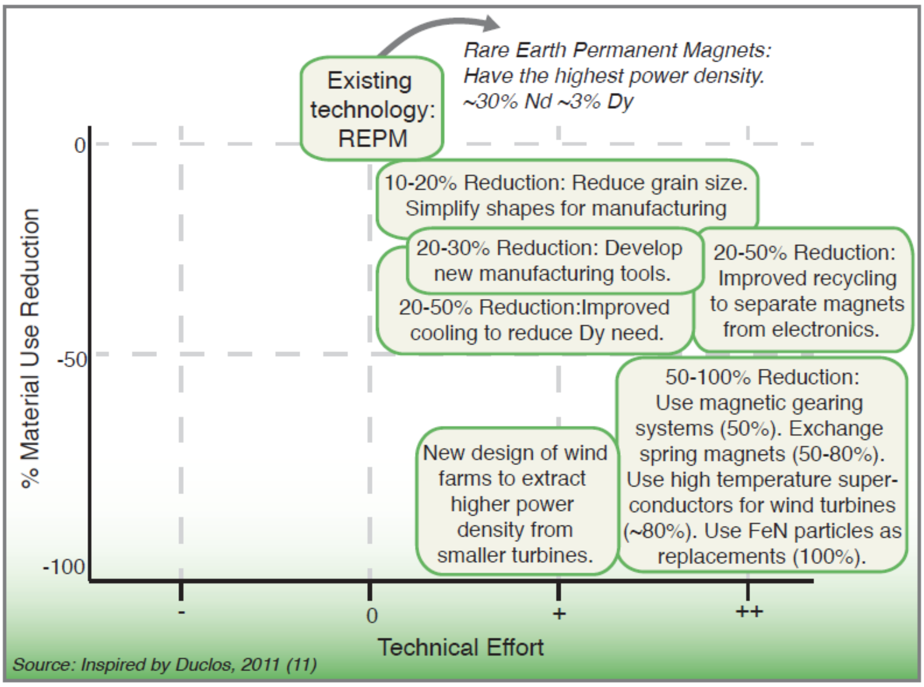
[20] In 2011, neodymium prices ranged from about \$90/kg to \$460/kg, dysprosium prices ranged from approximately \$350/kg to \$3500/kg (DOE 2011).

largest reductions (51–100%) come exclusively from substitution. Iron nitride ($Fe_{16}N_2$) can be a potential substitute for rare earth permanent magnets if a small particle size is developed. This has already been demonstrated at laboratory scale in the “Rare Metal Substitute Materials Development Project” at the Japanese New Energy and Industrial Technology Development Organisation (NEDO) (Tomioka and Monozukuri 2011). However, it is unlikely to be commercial before 2025 (Fromer et al. 2011).

Figure 2.5. Suggestions for material reduction in permanent magnets for motors and wind turbines.



Source: Inspired by Duclos, 2011 (11)

Source: Fromer et al (2011)

Thus, discussion of material intensity reduction in electric motors in the literature tends to focus on substitution rather than NdFeB technology improvement. In addition to the substitution efforts above, the US Department of Energy’s Advanced Research Projects Agency–Energy (ARPA–E) funds several ongoing projects in search of non–rare earth permanent magnets: McCallum (2010) reports on research in Iron–cobalt (FeCo) as well as Alnico (Aluminium, Nickel, Cobalt) magnets with copper and titanium additions; Anderson (2011b) reports on FeCo with tungsten (W) additions and yttrium (Y) substituting dysprosium in magnets with equal performance improvements. Another potential permanent magnet substitute material identified at Oak Ridge National Laboratory (involved in the same project) is hafnium cobalt (HfCo), although various treatments and production methods are still being investigated to optimise its performance (McGuire 2011). It is unclear from a resource perspective whether hafnium would be a useful substitute for Nd: data on hafnium supply, demand and consumption are very limited. However, hafnium is a by–product of zirconium and can be produced at 2% of zirconium production at most (Graedel 2011). This estimate places Hf production only slightly higher than current Nd production. Finally, nanocomposites combining NdFeB and FeCo nanoparticles could be an ideal solution in terms of rare earth content and performance. Related research is funded extensively by ARPA-E, but their manufacture and control of magnetic properties has been described as an ‘engineering nightmare’[21] (Jones 2011).

While material intensity reductions can be achieved in the near-term, the rare earth-free magnetic materials options described above are still the subjects of early research. According to Jones (2011), many of the leading magnetic researchers worldwide admit that completely eliminating rare earths from permanent magnets is extremely challenging.

It is difficult to quantify future Nd usage in electric vehicle motors because no estimate of future material intensity per-kW or equivalent exists in the literature. Table 2.10 presents possible options for material intensity reduction and material substitution along with the evidence base for their effect and potential. In the following section we apply the findings here to derive ranges of material demand in EVs.

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[21] Nevertheless, a number of research initiatives for the manufacture of nanocomposite magnets, funded by ARPA-E are currently underway at the University of Delaware, Ames Laboratory at Iowa State University, the University of Texas at Arlington, and General Electric.

Table 2.10. Prospects for future material intensity of permanent magnets and their potential

Options for Material Intensity Reduction in Permanent Magnets for Vehicles	
Improving energy density of NdFeB magnets - "shedding weight"	No information available Development appears stagnant
Manufacturing improvements: reducing grain size, simplifying shapes, new manufacturing techniques	Little information available 10-30% reduction [a] Manufacturing technologies not disclosed
Recycling during manufacturing and from end-of-life magnets	See recycling efforts in Section 4.2.4
Reducing Dy content	May result in poorer motor performance [b,c] Does not positively affect Nd demand
Using Nd-Cu to replace Dy in magnets without performance losses	Still in R&D phase [d] Implies greater Nd concentrations [d]
Using PM hybrid motors	Reduction in Nd use not well quantified Technology not fully commercialised [e,f]
Options for Material Substitution in Permanent Magnets for Vehicles	
Induction motors	Lower efficiency and higher weight [b,e] Most likely option
Samarium Cobalt (SmCo) magnets	Currently more expensive than NdFeB [b] Prone to supply risks (see Box 2.3)
Iron nitride	Demonstrated but not yet commercial [g]
Alnico magnets with Cu and Ti additions	Still in R&D phase
Iron-cobalt (FeCo) and tungsten (FeCoW)	
Hafnium Cobalt (HfCo)	Limited information on Hf supply
Nanocomposite magnets	R&D in the US and Japan [h] Energy product possibly twice that of NdFeB[i] Rare earth content of ~5 wt% [i] Extremely difficult to manufacture [h]

Source: [a] (Fromer et al. 2011) [b] (Gutfleisch et al. 2011) [c] (E–Magnets UK 2011) [d] (Sepehri–Amin et al. 2010) [e] (Schüler et al. 2011) [f] (Xue et al. 2008) [g] (Tomioka and Monozukuri 2011) [h] (Jones 2011) [i] (Skomski and Coey 1993)

2.5 Illustrative ranges: future EV demand for lithium and neodymium.

2.5.1 Batteries

In Table 2.11, a range of demand for lithium for BEV and PHEV batteries is presented. This range is represented by a ‘low’ and ‘high’ material intensity case. Due to the complexity in estimating the lithium content of batteries, only indicative figures for lithium intensity (g Li/kWh) from the discussion in Section 2.3.1 are used here. Different assumptions about battery size are used in the low and high intensity cases. The ‘low material intensity’ uses an average of 9 kWh in both BEV and PHEV (Yaksic and Tilton 2009), the lowest value found in the literature. The 'high material intensity' case uses indicative figures from today's BEVs and PHEVs (see Table 2.3 and Table 2.4).

The annual sales figure is that projected in the IEA's BLUE Map scenario detailed in Table 2.1. Two estimates of demand were produced, one for 2030 and another for 2050. An estimate of lithium demand for the current vehicle market was not made since the current situation represents a niche market and the use of Li-ion batteries on commercial light-duty vehicles is a recent trend.

Table 2.11. Illustrative ranges of lithium demand for battery electric and plug-in hybrid vehicles in 2030 and 2050 markets.

Variable	Low material intensity	High material intensity
Battery Size (kWh) – PHEV [a]	9	16
Battery Size (kWh) – BEV [a]	9	35
Intensity (g Li/kWh) [b]	190	380
2030 BLUE Map market		
Annual sales (million units/yr) – PHEV	25	25
Annual sales (million units/yr) – BEV	9	9
Market share of Li-ion batteries	100%	100%
Range of demand (kilotonnes Li/yr)	**57.4**	**268**
2050 BLUE Map market		
Annual sales (million units/yr) – PHEV	62	62
Annual sales (million units/yr) – BEV	47	47
Market share of Li-ion batteries	100%	100%
Range of demand (kilotonnes Li/yr)	**184**	**989**

Notes:

a. Battery size used in the lowest material intensity case is the average used in Yaksic and Tilton; the values in the highest material intensity are illustrative.

b. Based on an illustrative range for lithium carbonate intensity of 1 – 2 kg/kWh.

Using these assumptions, the lithium demand for electric and hybrid vehicles increases by a large factor (~3.2 - 3.7) between 2030 and 2050. This is mainly due to the large growth in annual vehicle sales between the two estimates, and the changing ratio between PHEV and BEV sales, which have different battery sizes (kWh) in the high material intensity case. The scale of future demand is also very large, with almost one million tonnes of lithium demanded annually in the 2050 market, high intensity case. These figures point to the fast-growing lithium demand in 2030 and 2050, and are compared with present and estimated future lithium supply in Chapter 4.

2.5.2 Motors

In Table 2.12, a range of demand for neodymium for electric motors is presented. Due to the complexity in predicting an exact magnet composition and thus Nd content the lowest magnet weight and the least Nd-rich composition reported in current estimates (Section 2.3.4) is combined with a 30% reduction from improved manufacturing technologies (Fromer et al. 2011) to form a *low material intensity* estimate. The highest weight and the most Nd-rich composition currently reported form the basis of a *high material intensity* estimate.

In the case of electric motors, material intensity is not reported on a per-kW basis, because most sources do not specify the motor type in their material intensity estimate (Table 2.9). As a result, the amount of Nd is assumed to be the same in all PM EVs. This results in a large uncertainty in the estimates of demand presented below, and the similar future demand projections found in all of the sources cited in Table 2.9.

Using these assumptions, the neodymium demand for electric and hybrid vehicles increases dramatically (a factor of ~120) between the current market and the market in 2050. This is mainly due to the growth of the electric and hybrid vehicle fleet in this period and the 50% market share of PM motors in 2050, which is an illustrative scenario only. Material intensity scenarios also show a large variance, with neodymium demand in the high intensity estimate about 7.5 times larger than in the low intensity estimate. These figures, while much lower than those estimated for lithium (Table 2.11 above), are nevertheless indicators of the strongly growing neodymium demand in the outlook to 2050, and are compared with present and estimated future neodymium supply in Chapter 5.

Table 2.12. Illustrative ranges of neodymium demand for electric and hybrid vehicles in current and 2050 markets.

Variable	**Low material intensity**	**High material intensity**
PM weight (kg) [a]	1	3.6
Nd content (wt%)	21.8%	32.0%
Reduction due to manufacturing improvements	30%	N/A
Current market		
EV/PHEV/HEV/FCV annual sales (million units/yr)	0.73	0.73
Market share of PM motors [b]	90%	90%
Range of demand (kilotonnes Nd/yr)	0.10	0.76
Range of demand (kilotonnes Nd_2O_3/yr)	**0.12**	**0.89**
2050 BLUE Map market		
EV/PHEV/HEV/FCV annual sales (million units/yr)	157	157
Market share of PM motors [b]	50%	50%
Range of demand (kilotonnes Nd/yr) [c]	11.96	90.43
Range of demand (kilotonnes Nd_2O_3/yr)	**13.95**	**105.48**

Notes:

a. PM weight is assumed equal in all types of vehicles and all motor sizes. This is unlikely to be true in reality, however information is not available on the correlation between motor size (kW) and PM weight (kg).

b. The market share of PM motors in the current market is assumed as 90% as an approximation of electric motors used in commercial vehicles produced in 2008-2013 (see Table 2.7). The market share for the 2050 market is an illustrative scenario only as forecasts of PM motor shares in this period are not available.

c. Neodymium supply is most often quoted in units of neodymium oxide (Nd_2O_3), for this reason we have converted neodymium demand figures to neodymium oxide. For a list of conversion factors used here, see Annex 1.

3 The case of wind

Neodymium magnets, discussed in Section 2.3.4, are also components of direct-drive wind turbines. Though this report focuses on electric vehicles, wind turbine deployment may also prove an important driver of rare earth metal demand from low carbon technologies. It is important therefore to understand the technology, its estimated future development and its potential to compete with electric vehicles for potentially scarce resources in the future. In this chapter we examine the case of wind turbines and their relationship to neodymium.

As with the electric vehicle components discussed in Chapter 2, the relationship between wind turbines and future neodymium demand can be broken down into several key variables. These are:

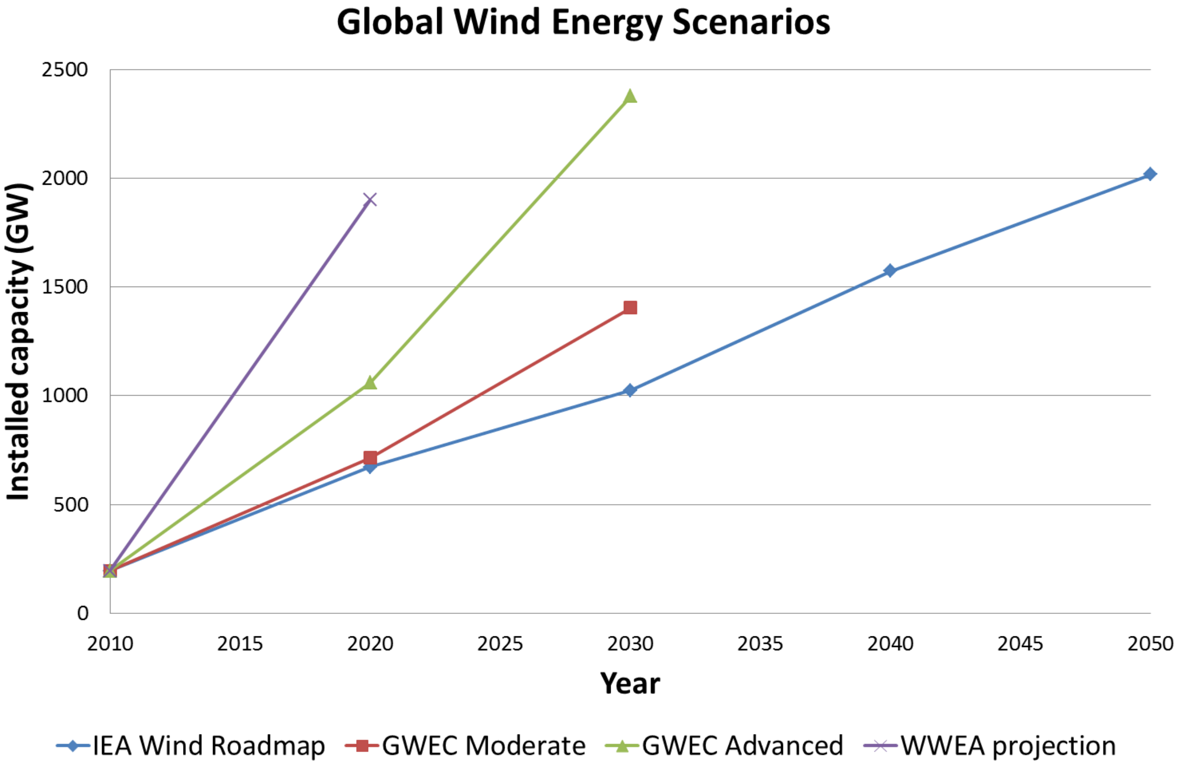
- the future deployment of wind turbines, expressed in GW;
- the proportion of these wind turbines utilising magnets;
- the material intensity of neodymium in a wind turbine magnet, expressed in kg/MW; and
- the future potential to reduce the weight of neodymium in turbine magnets.

We begin by discussing the first of these issues, the future capacity of the wind energy market. We then discuss the market share of turbine technologies and the range of potential demand for neodymium from the wind sector. We list prospects for reduction in material intensity as well as partial or complete material substitution, concluding by presenting an illustrative range of demand for neodymium for wind turbines. This range is added to the demand from electric vehicles (Table 2.12) and compared to current and estimated future supply in Chapter 5.

3.1 Global demand for wind energy

Wind energy is a comparatively mature renewable energy technology with an installed capacity of about 240 GW estimated at the end of 2011 (WWEA 2011). Four global wind scenarios (GWEC 2008; IEA 2009a; WWEA 2010) are compared in Figure 3.1, presenting a range of installed wind capacity between 1024 GW and 2376 GW in 2030. The IEA's wind energy roadmap has a wind installed capacity target of 2 TW by 2050. The IEA forecasts are notably more conservative compared to those of the GWEC or WWEA, although they are more appropriate for this report, since they are based on the IEA's Blue Map scenario consistent with a global 50% emission reduction by 2050.

Figure 3.1. Global scenarios for wind energy, 2010-2050.



Note: All scenarios adjusted to an initial installed capacity of 195 GW in 2010 (IEA 2011).
Source: (GWEC 2008; IEA 2009a; WWEA 2010)

Global demand for wind turbines is expected to rise in the coming decades, with installed capacity reaching ~3 – 10 times current size by 2020, and ~5 – 12 times current size by 2030. This could imply a non-negligible future demand for neodymium and possibly dysprosium metal. To translate installed capacity into an estimate of annual manufacturing rate we assume a compound growth rate between the 2040 and 2050 data points, giving an annual rate of ~50GW/y by 2050.

3.2 Direct drive wind turbines

Until the 1990s most manufacturers built constant speed turbines of less than 1.5 MW, using a squirrel cage induction motor (see Section 2.3.4) and a gearbox (Polinder et al. 2005). Subsequently, variable speed turbines were developed for higher power ratings, using the so-called doubly-fed induction generator (DFIG), which use low-cost power converters (de Vries 2010). More recently, direct drive turbines have been developed and commercialised.

The direct drive wind turbine (shown in Figure 3.2) is an increasingly adopted turbine concept using a rotor directly connected to the generator in place of the more conventional geared design. With the elimination of the gearbox, a direct drive wind turbine has no high-speed mechanical or electrical components[22], reducing turbine downtime[23] and maintenance

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[22] It is *synchronous*, which means that the rotor and generator rotate at identical speeds.

from gearbox failures (Polinder et al. 2005). Gearboxes are frequently identified as the most common cause of turbine downtime (Ribrant and Bertling 2007), although more recent studies attribute most downtime to converter and generator issues (Wilkinson 2009). Reduced maintenance and improved reliability are especially important to offshore wind applications, where maintenance is a more costly issue (Faulstich et al. 2011). Direct drive turbines were developed starting in 1991 using electrical excitation, although the generators used in these turbines made them heavier than geared designs of equivalent power rating (de Vries 2011) and prone to excitation losses[24] (Polinder et al. 2005). Recent direct drive turbines using permanent magnet generators eliminate excitation losses and are substantially lighter than electrically excited designs (Spooner et al. 2005).

In addition to increased reliability, direct drive wind turbines have a significantly smaller number of moving parts, improving reliability and reducing the need for maintenance (Siemens 2011). However, direct-drive turbines require heavy and bulky large diameter multi-pole ring generators (de Vries 2011), and costly power electronics needed for power conversion and grid connection (Polinder et al. 2005). The first issue has been addressed by the aforementioned replacement of external field excitation with substantially lighter permanent magnet generators (PMGs): the ‘head mass’[25] of the latest direct drive PMG turbines is now reportedly lower than geared designs (Bubar 2011a), having been 15–30% heavier in the 1990s (de Vries 2011).

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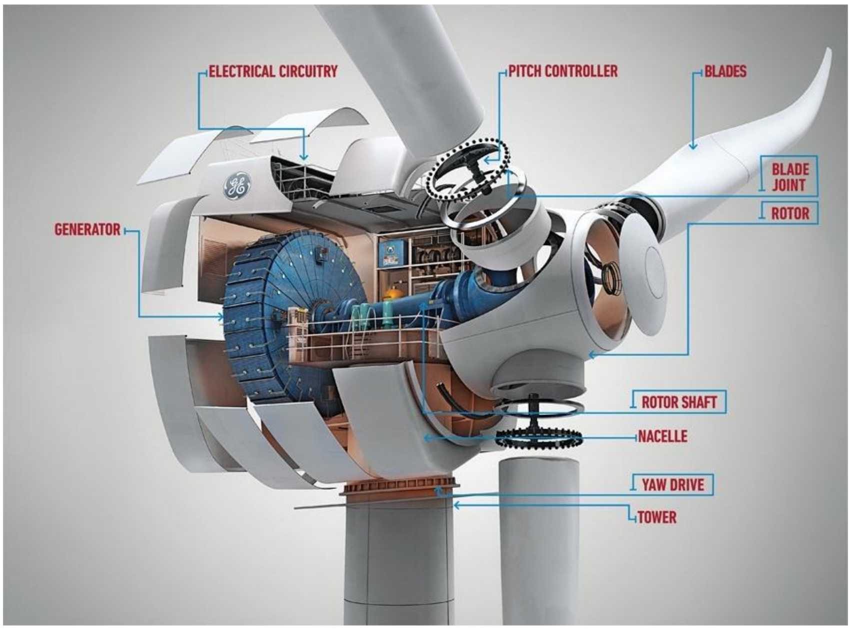
[23] Defined as the period of time in which a wind turbine is not operating due to failure or maintenance, and commonly measured in hours per year or lost kWh.

[24] Electrically excited wind turbines, both geared and direct drive, require external electric excitation to generate a magnetic field. The electricity comes from the grid, and can reduce the power output of the turbines, particularly at low speeds. The permanent magnet generator does not require external excitation, and thus the power required from the grid for excitation is saved (Salo 2009).

[25] Defined as the combined mass of the turbine rotor and the nacelle, the cover housing the generator and drive train (see Figure 3.2).

Figure 3.2. Diagram of the components in General Electric's new 4MW PMG direct drive offshore turbine.



Source: Pacella (2010)

There is still notable disagreement on the near-term wind turbine technology mix. At the end of 2009, 3.14% of installed wind capacity consisted of direct drive turbines (Kara et al. 2010). Although it is clear that direct drive turbines are currently gaining market share, the extent to which this will continue is uncertain. Manufacturers are mostly concerned with dependence on the rare earths. De Vries (2011) explains that the rising price of rare earth elements used in the PMGs has caused a major increase in manufacturing costs that may limit the future market penetration of direct drive turbines. Non-permanent magnet technologies, which occupied 86% of the market in 2009 (Moss et al. 2011). They are still subject to much technological improvement, particularly DFIG technology with a gearbox, which was estimated by Polinder et al (2005) to have the highest ratio of energy yield to total cost among five turbine drive train technologies. Philipp (2011) of Repower Systems defends the geared design, noting that its reliability has greatly improved over the past decade—a recent study places gearbox failures at less than 5% of annual downtime (Wilkinson 2009). Philipp also lists a number of disadvantages for PMG designs: a larger number of electrical components, lack of a track record in wind applications, dependency on costly rare earths and other uncertainties. Though these individual points may be disputed, Repower’s argument serves to demonstrate that a portion of the wind turbine industry may continue its endorsement of the geared design, and that PMGs may never fully replace it. Accordingly, projections of the future market share of direct drive PMG wind turbines to 2020 and 2030 range from 12.5% to 35% in 2020 and 10% to 30% in 2030 (EWEA 2011; Hatch 2011; Moss et al. 2011) No estimates for 2050 were found. For our estimation of illustrative ranges of neodymium demand from wind turbines in 2050 (Section 3.3.2) we assume that these will be exclusively used on offshore turbines, where reduced maintenance and lower weight are most crucial (Spooner et al. 2005; Kleijn and van der Voet 2010; de Vries 2011; Faulstich et al. 2011), and thus the IEA Blue Map projected market share of offshore wind turbines in 2050 (~32%) is assigned to direct drive PMG technologies.

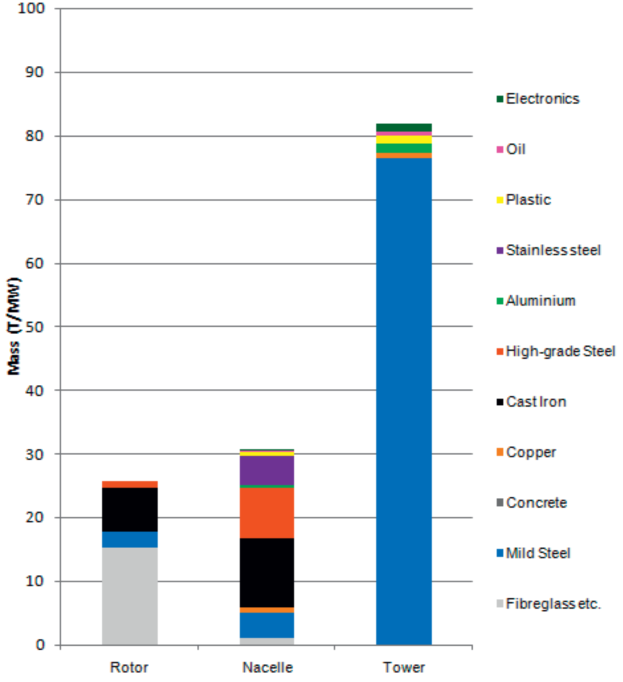
3.3 Material intensity of wind energy

Wind turbines tend to increase in power rating and thus size over time, and are generally highly material intensive. Most turbine designs utilise large quantities of steels, fibreglass, copper, resins and plastics (Figure 3.3) and a number of studies have reported these as potential concerns (DOE 2008; Kleijn and van der Voet 2010; Valpy 2010; Moss et al. 2011). In this report, however, we are concerned with the turbines' permanent magnet neodymium (and dysprosium) content. As such, we focus on PMG direct drive turbine designs. Estimating the amount of neodymium per megawatt turbine capacity can be done in a way similar to that for vehicle motors. The parameters of interest are:

- turbine rated power,
- permanent magnet weight, and
- neodymium weight percentage (wt%) in the magnet.

Other factors may also play a role. Moss et al (2011) note that the generator speed determines permanent magnet weight, and that high and medium-speed PMGs can use magnets almost 10 times lighter than low-speed PMGs, However, high and medium speed generators are not yet competitive, and PMG direct-drive turbines more commonly use low-speed generators, with high-speed generators commonly termed 'hybrids' (de Vries 2011) and addressed in the next section.

Figure 3.3. Material intensity (tonnes/MW) in a conventional geared wind turbine.



Source: Valpy (2010)

While the non-magnet material intensity of wind turbines is generally well understood and quantified (Moss et al. 2011), the rare earth content is less well documented. The evidence base for the weight composition of NdFeB permanent magnets used in wind turbines is similar to that reported for motors in Table 2.8, though different magnet compositions may be used in each application (Gutfleisch et al. 2011). A US Department of Energy report (DOE 2011) highlights this point by assuming a smaller range for dysprosium in turbines than in EVs[26] (4.5–6.0% range for EVs to 2–4% for turbines). Less dysprosium is needed in wind turbine generators since they operate at lower temperatures than electric vehicle motors. Estimates of permanent magnet or Nd weight in wind turbines are listed in Table 3.1. While there are a number of estimates, many of these are cited in the media based on ‘industry sources’, while others are cited in company presentations, private communications or peer-reviewed literature without direct reference. None of these estimates is directly linked to a publicly available turbine manufacturer’s specifications. Note that several sources appear more than once on the table, citing different estimates. Overall, there is a wide variance of estimates for permanent magnet weight per megawatt turbine capacity from 250–1000 kg/MW, demonstrating the uncertainty in estimating turbine material intensity.

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[26]

Table 3.1. Estimates of the material intensity of PMG direct drive wind turbines.

Source	**Cited in**	**Direct drive turbine type**	*PM weight (kg/MW)*	*Nd (kg/MW)*	*Dy (kg/MW)*
US Dept of Energy	DOE (2010)	-	400 - 600	124 - 186	22 - 33
US Dept of Energy [a]	DOE (2011)	-	200 - 600	62 - 186	4 – 24
European Commission Joint Research Centre	Moss et al (2011)	-		40.6	2.8
Avalon Rare Metals	Bubar (2011a)	General Electric 4MW PMG turbine	500 - 750		
Avalon Rare Metals	Kara et al (2010)	5 MW turbine	400		
Arnold Magnetic Technologies	Constantinides (2010)	-	250 - 600		
Zenergy Power	Zenergy Power (2011)	-	250		
Technology Metals Research	Lifton (2009)	-	700 - 1000		
Technology Metals Research	Hatch (2011)	-		150-200 [b]	20-35
Dexter Magnetic Technologies	Hatch (2008)	Scanwind 3500 DL 3.5MW turbine	571		
Polinder et al (2005)		3 MW PMG direct drive turbine	567		
Gutfleisch et al (2011)		3 MW direct drive turbine	500		
Siemens	Bartos (2011)	Siemens PMG direct drive turbines	650	25 - 30 wt% rare earths	
Roskill Rare Earths Conference	Hudson Resources Inc (2009)	New 7MW turbine	500		
IFRI Centre for Asian Studies	Seaman (2010)	Siemens 3 MW direct drive turbine	667	200	
Less Common Metals Ltd.	Kennedy (2011) [c]	-	500		

Chinese Society of Rare Earths	Zhanheng (2011) [c]	-	1000		
Great Western Minerals	McDonald (2011) [c]	-	667		
Vestas	Holm (2011) [c]	Vestas direct drive turbines	550		

Notes:

a. The range presented by DOE (2011) includes material intensity for hybrid drive wind turbines, which use less rare earths (Section 3.3.1).

b. Includes an unspecified amount of praseodymium (Pr)

c. Cited in Hoenderdaal (2011) based on personal communication with Fraunhofer ISI

3.3.1 Estimating future material intensity

The options for material intensity reduction via technology improvements, partial and complete substitution are shown in Table 3.2. Many of these are similar to those for electric motors (Table 2.10) while other turbine-specific options are listed. Notably, the use of a ‘hybrid’ system, combining a PMG direct drive train and a gearbox, can achieve an 80% reduction in rare earth content (de Vries 2011; Winergy 2011). Material substitution possibilities include a return to geared designs (de Vries 2011; Philipp 2011) as well as superconductors (Zenergy Power 2011) though the latter is not yet commercial and little information is available.

Table 3.2. Prospects for material intensity reduction and material substitution in wind turbines.

Options for Material Intensity Reduction in Permanent Magnets for Wind Turbines	
Options	**Prospects**
Improving energy density of NdFeB magnets - "shedding weight"	Development appears stagnant [a]
Manufacturing improvements: reducing grain size, simplifying shapes, new manufacturing techniques	Little information available 10-30% intensity reduction [b] Manufacturing technologies not disclosed
Recycling during manufacturing and from end-of-life magnets	See Nd recycling efforts in Section 4.2.4
Reducing Dy content	May result in poorer motor performance [a,c] Does not positively affect Nd demand
Using hybrid turbines	80% reduction New concept
Options for Material Substitution in Permanent Magnets for Wind Turbines	
Geared designs	Reliability issues, increased maintenance [d,e]
Second generation (2G) superconductors	Use only 2 kg rare earths per MW [f] Demonstrated but not yet commercial [b]
Samarium Cobalt (SmCo) magnets	Currently more expensive than NdFeB [a] Prone to supply risks (see Box 2.3)
Iron nitride	Demonstrated but not yet commercial [g]
Alnico magnets with Cu and Ti additions	Still in R&D phase
Iron-cobalt (FeCo) and tungsten (FeCoW)	
Hafnium Cobalt (HfCo)	Limited information on Hf supply
Nanocomposite magnets	R&D in the US and Japan [h] Energy product possibly twice that of NdFeB[i] Rare earth content of 5 wt% [i] Extremely difficult to manufacture [h]

Source: [a] (Gutfleisch et al. 2011) [b] (Fromer et al. 2011) [c] (E–Magnets UK 2011) [d] (Siemens 2011) [e] (Polinder et al. 2005) [f] (Zenergy Power 2011) [g] (Tomioka and Monozukuri 2011) [h] (Jones 2011) [i] (Skomski and Coey 1993)

3.3.2 Illustrative ranges of neodymium demand for wind turbines

Table 3.3 presents illustrative ranges of demand for neodymium for PMG direct drive wind turbines for the current market and the IEA's BlueMAP scenario market in 2050. The latter market is relatively conservative as shown in the comparison of future scenarios (Figure 3.1).

Despite this relatively low increase in annual installed capacity between current and 2050 markets, the demand for neodymium in 2050 shows a large (~13.5x) increase over current levels. This is due to the market share of PMG direct drive turbines, for which we assume

3.14% at present (Kara et al. 2010) to 32.3% in 2050. The latter figure is an illustrative estimate due to the paucity of information regarding PMG direct drive turbine market penetration. We assume here that due to relatively high costs, PMG direct drive designs are exclusively used in offshore turbines, which represent 32.3% of the BLUE Map wind market in 2050 (IEA 2010). This may be a conservative estimate (de Vries (2011) suggests that if PMG prices are competitive the entire wind industry could switch to this technology), but it allows for the uncertainty regarding drive train technology competition and possible future breakthroughs.

Table 3.3. Illustrative ranges of neodymium demand for wind turbines in current and 2050 markets.

Variable	**Lowest material intensity**	**Highest material intensity**
PM weight (kg/MW)	200	1000
Nd content (wt%)	21.8%	32.0%
Reduction due to manufacturing improvements	30%	N/A
Current market		
Annual installed capacity (GW/yr) [a]	37.47	37.47
Market share of PMG direct drive turbines [b]	3.14%	3.14%
Range of demand (kilotonnes Nd/yr)	0.036	0.376
Range of demand (kilotonnes Nd_2O_3/yr)	**0.042**	**0.44**
2050 BLUE Map market		
Annual installed capacity (GW/yr) [a]	49.53	49.53
Market share of PMG direct drive turbines [b]	32.30%	32.30%
Range of demand (kilotonnes Nd/yr)	0.49	5.12
Range of demand (kilotonnes Nd_2O_3/yr)	**0.57**	**5.97**

Notes:

a. The annual installed capacity for the current market is as reported by GWEC (2010). The annual installed capacity for the 2050 BLUE Map market is interpolated between cumulative installed capacity forecasts from the IEA (2010).

b. The PMG direct drive turbine market share for the current market is that stated for annual installed capacity in 2009 in Kara et al (2010).The market share for 2050 is unavailable in the literature and is an illustrative scenario that assumes that PMGs are exclusively used in offshore turbines.

c. Neodymium supply is most often quoted in units of neodymium oxide (Nd_2O_3), for this reason we have converted neodymium demand figures to neodymium oxide. For a list of conversion factors used here, see Annex 1.

These estimates, while uncertain and possibly conservative, demonstrate that wind turbines may represent a significant source of demand for neodymium by 2050. This demand is relatively low in comparison with the demand from electric and hybrid vehicles (Table 2.12), for which the IEA Blue Map scenario is more aggressive in 2050. In Chapter 5 we combine neodymium demand for both of these low-carbon technologies and comment on the implications for supply.

4 Supply of lithium and neodymium

In this chapter we address the supply side of material availability for electric vehicles. We discuss lithium and neodymium in turn, examining how they are extracted, the rates of their historical production, and their main end uses. This is followed by a discussion of the estimates of future lithium supply found in the available literature.

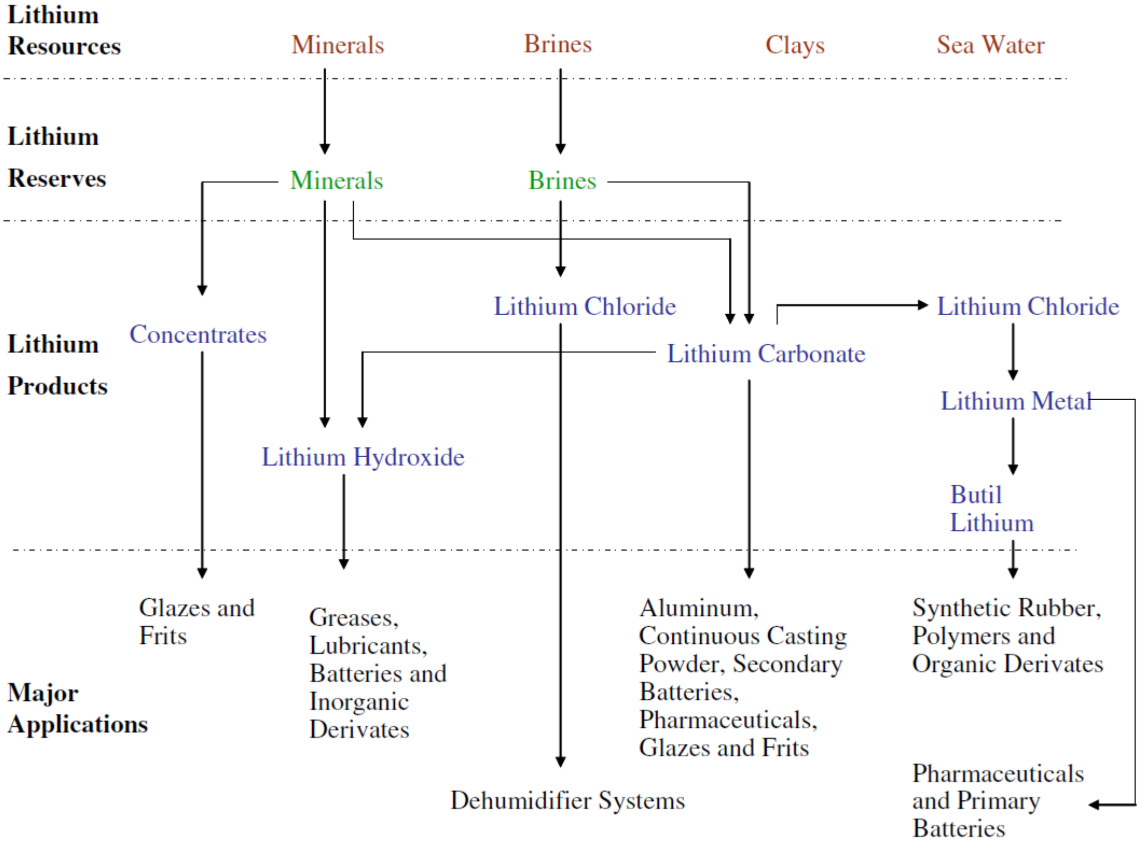
4.1 Lithium

4.1.1 Extraction, refining and processing

Lithium is an alkali group metal, and is the lightest metal in the periodic table. Lithium metal is highly reactive, and corrodes on contact with moist air. Due to this reactivity, lithium metal never occurs freely in nature, and is instead found in four main deposit types: Minerals, brines, sedimentary rocks and seawater. Two of these, minerals and brines, constitute the world's source of lithium today. Lithium containing minerals are typically coarse-grained intrusive igneous rocks known as pegmatites, such as spodumene, petalite, lepidolite, amblygonite and eucryptite (Gruber et al. 2011) . Brine deposits are currently the largest and cheapest sources of lithium (Yaksic and Tilton 2009) and are mostly found in dry lakes such as the Salar de Aracama in Chile, as well as geothermal deposits and oil fields. The third source of lithium is in sedimentary rocks, notably clays such as hectorite and lacustrine evaporates such as the newly discovered jadarite (Clarke and Harben 2009; Gruber et al. 2011). Finally, lithium is found in diffuse but very large quantities in seawater—according to Yaksic and Tilton (2009), 44.8 billion tonnes are recoverable from seawater. The economic viability of the latter two sources is uncertain.

Lithium is not mined in its elemental form but is produced as lithium carbonate, lithium hydroxide, lithium chloride and other forms shown in Figure 4.1. Different forms of lithium are used in different applications. The three forms used in batteries are lithium metal (not mined but produced from lithium chloride by electrolysis), lithium hydroxide and lithium carbonate, which are used in Li-ion battery manufacture.

Figure 4.1. Sources and chemical forms of lithium and their major applications.



Source: Yaksic and Tilton (2009)

Of the major producers of lithium by content (see Figure 4.2) Chile and Argentina both produce Lithium Carbonate from brine, while Australia produce lithium in minerals recovered from spodumene deposits. China's production is split between mineral production and lithium carbonate production from brine, with lithium minerals containing 35% of China's reserves while brines contained 65% of lithium reserves.

4.1.1.1 Ores

Lithium containing spodumene ores are recovered by quarrying or open cast mining of veins of the ore, which are often only a few meters thick. Concentration of the ore can be carried out by hand-sorting of raw ore. Further separation of ore mineral from waste material is achieved by froth flotation.

The ore is first roasted, which improves milling into the powder required for the flotation process. Roasting is carried out at 1050-1100˚C for 15-30 minutes. When cool the material is crushed to a grain size less than 0.1 mm. This powder is fed to floatation tanks containing anionic fatty acids in alkaline solution or sulphonated oils in acid. Concentration by 70% is achieved.

The powder is treated with an excess of 93% sulphuric acid at elevated temperature in a lined rotary furnace. Lithium sulphate solution is produced which is leached out of the remaining inert solids with hot water. The liquor is treated with soda lime to remove calcium, magnesium and iron, filtered then neutralised with more sulphuric acid. The liquor is then transferred to an evaporation vessel and concentrated to 200-250 g/L Li_2SO_4. Lithium is often converted to $LiCO_3$ by addition of sodium carbonate.

In turn lithium carbonate can be used to produce lithium metal. The carbonate is re-dissolved in hydrochloric acid. The chloride solution is concentrated in a vacuum evaporator and dried. The product, mixed with potassium chloride to lower the melting point, is fused in an electrolytic cell similar to the Downs cell used for sodium production. Electrolysis produces lithium metal and chlorine gas. The metal is used in sacrificial anodes in lithium batteries. (Averill and Olson 1978; Bale and May 1989).

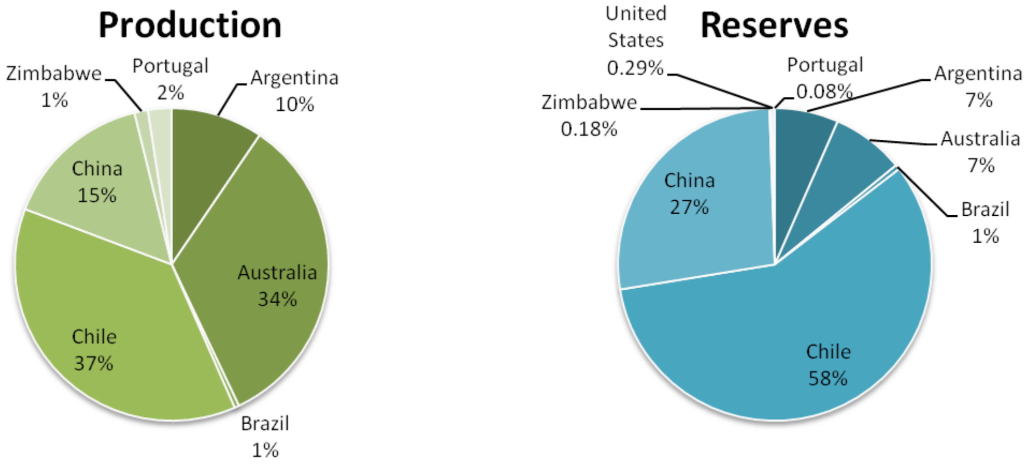
4.1.1.2 Brines

Economically treatable brines are found in South America, particularly Argentina, Bolivia and Chile also in the USA and China. Production of lithium carbonate from brines begins with the concentration of brine, often through solar evaporation. This increases the concentration of lithium chloride and precipitates out certain impurities. The concentration process is particularly effective because lithium chloride is highly soluble. Yields are reduced, however, because of the presence of other metals, particularly magnesium. The magnesium can be removed during concentration by treatment with lime. However, this leads to loss of a proportion of the lithium content. The concentration of lithium in lithium chloride liquor rises to about 6% at which point it is treated with soda ash to precipitate lithium as the carbonate. As above in this form the lithium metal can be produced by electrolysis. (Averill and Olson 1978).

4.1.2 Production and Reserves

Known reserves of lithium exist and are produced in a number of countries, the relative distribution of which is presented in Figure 4.2. The largest share of both production, and reported reserves occur in Chile, which recovers lithium from brine pools located in salt flats throughout the Andes mountain range. We now discuss the production of lithium before discussing the available data on reserves and resources.

Figure 4.2: Distribution of lithium production and reserves in 2011.



Source: USGS (2012)

Note: USGS do not disclose US production data

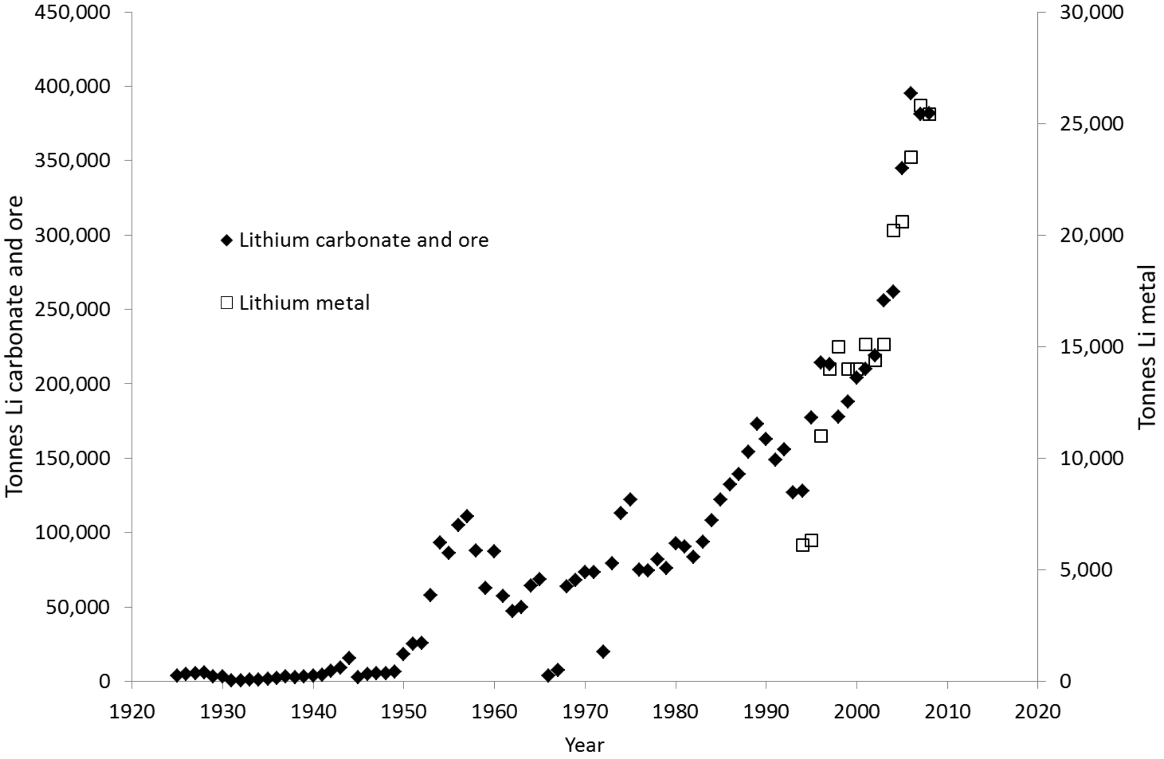
The USGS provide the most commonly available production data for many elements including lithium. USGS lithium production data has taken several forms over the last eight decades. In Figure 4.3 we present two different sets of production data published by the USGS and its predecessor the US Bureau of Mines.

The first set of data (the black diamonds in Figure 4.3), from 1925 to 2008, represents tonnes of lithium carbonate and ore, and is presented against the primary vertical axis. The data is compiled by the USGS from its "Minerals Yearbook" report and its predecessor published by the US Bureau of Mines "Mineral Resources of the United States." Historically the definitions of this global lithium resource have changed. Between 1925 and 1967 the data represents 'gross product of lithium minerals and brine,' and for the remainder of the time series this referred to 'ore and ore concentrate from mines, and lithium carbonate from brines.' As such, the lithium metal content in this data would represent only a proportion of the total weight reported, the remainder being carbon and oxygen, and other ore constituents in ore and ore concentrates. Calculating the metal content accurately is problematic given the unknown composition of ore and ore concentrate (see Annex 1).

The USGS also provide data on global production of lithium metal (white squares in Figure 4.3), which can be compiled from successive issues of the USGS 'Minerals Commodities Summaries.' This is presented against the secondary vertical axis. This data is available between 1994 and 2011.

Despite inconsistencies in data, Figure 4.3 appears to presents a resource which is being exploited through an exponential phase of production, and displays no indication of a slowing production rate.

Figure 4.3: World annual lithium production, 1925–2011



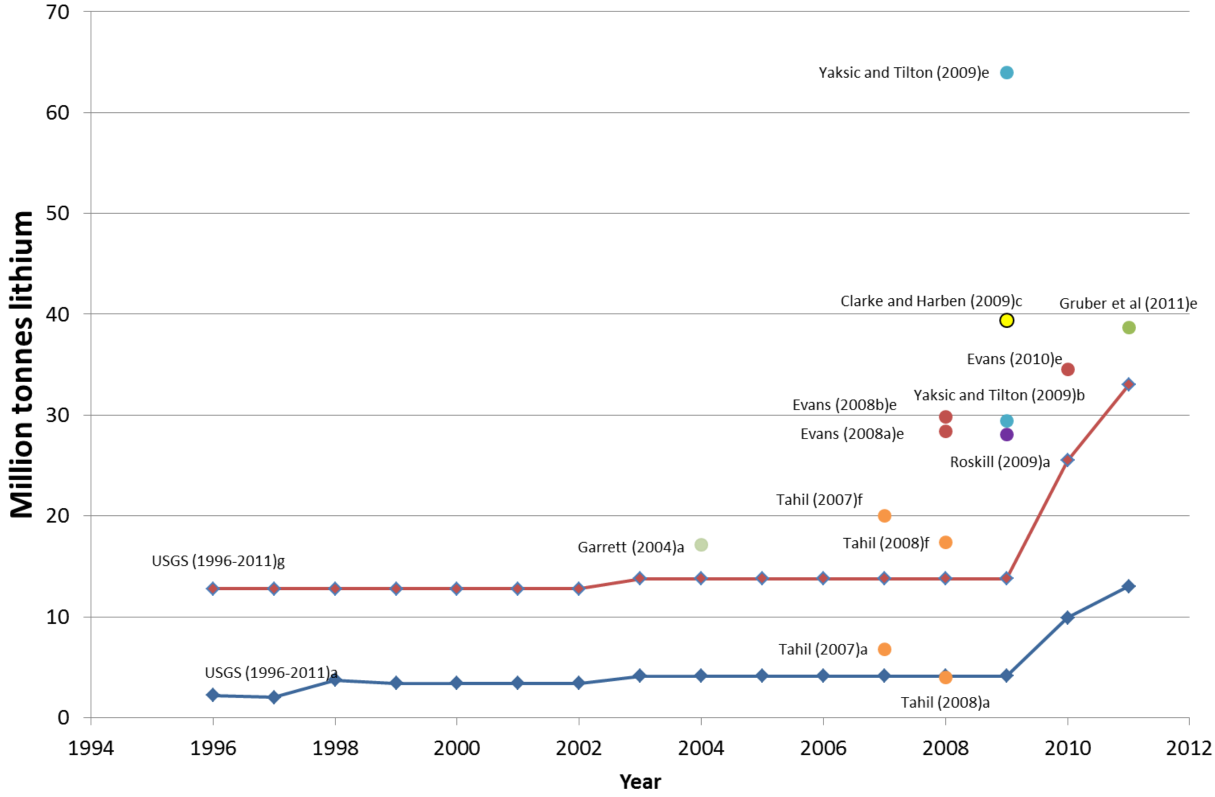
Source: USGS

Notes: No US data after 1954. No data for Rhodesia (Zimbabwe) and other African countries between 1966 and 1967

In Figure 4.4 we present several different lithium reserve and resource estimates. This figure presents a number of different classifications of resources, and these are acknowledged in the notes below. A description of the reserve classification is presented, where available, in Annex 3. It is important to note that where reserve classifications differ estimates are not directly comparable. This issue is compounded by the fact that explicit descriptions of reserve classifications are not always provided by authors.

The USGS present figures for reserves and reserve base, though reserve base reporting was discontinued after 2009. Roskill (cited in Engel-Bader (2010)) also present reserve data for 2009. In 2004, disaggregate reserve figures are presented by Garrett (2004). Reserve and reserve base estimates from Tahil (2007; Tahil 2008) are presented in years 2005 and 2007. In year 2008 reserve and 'in situ' data from Evans (2008a; Evans 2008b) are presented. Finally Yaksic and Tilton (2009) provide estimates of recoverable resources and in situ resources in 2009, which are also included. This data presents a considerable range of estimates, with the largest estimate in 2009 over 700% greater than the smallest. This can in part be explained by the differing natures of reserve classifications, but this also reflects the range of opinion regarding the future prospects for lithium production. It is also worth mentioning that the USGS refer to additional "resources" for several countries, including Bolivia, which as yet has no recorded production or reserves, but the USGS (2012) estimate it to have 9 million tonnes of resources. What prevents any of these resources from being reported as reserves by the USGS is unclear. The USGS (2012) estimate world resources at 34 million tonnes, over twice the reserve estimate in the 2012 issue of the Mineral Commodity Summaries but still less than half the in situ estimate in 2009.

Figure 4.4: USGS annual reported reserves and other available estimates from existing literature



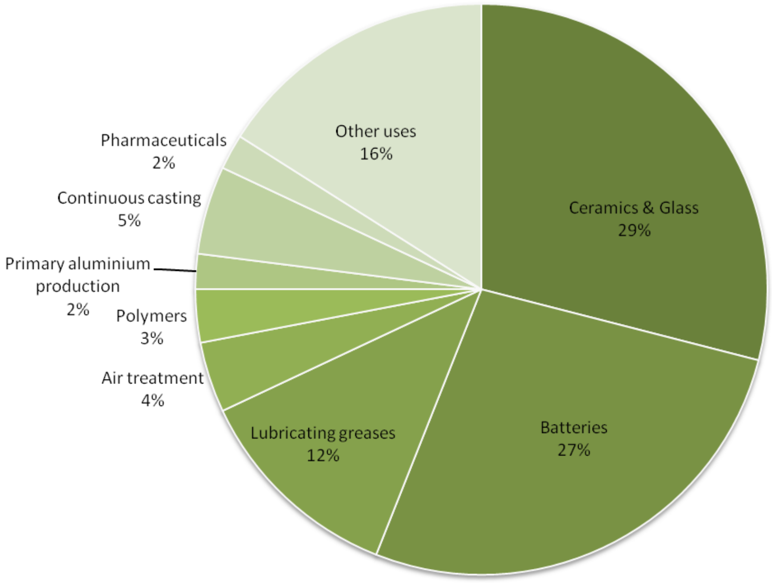
Notes:

a. Reserves
b. Recoverable resources
c. Broad based reserves
d. Reserve base
e. In Situ resources
f. Ultimate global reserve base
g. Identified Resources

4.1.3 End-use

The USGS estimates of global lithium market share are presented in Figure 4.5. While batteries are not yet the dominant end use for lithium, this is expected to change in the coming years as the use of lithium ion batteries in a range of applications increases significantly.

Figure 4.5: Distribution of end-uses for lithium in 2011.



Source: USGS (2012)

4.1.4 Recycling

Historically, recycled lithium has been insignificant (USGS 2011). the United Nations Environment Programme estimates lithium end-of-life recycling rates at less than 1% (UNEP 2011a). However, there has been an increase in use recently due to battery applications, and in particular the laws regulating the disposal of waste batteries: in Europe, Member States are obliged to collect 25% of end-of-life batteries by 2012 and 45% by 2016 (European Parliament 2006). This legislation does not necessarily imply nor mandate the recycling of lithium metal content; in fact, the recent Umicore battery recycling facility in Belgium recycles cobalt and nickel hydroxides but not lithium, which instead is removed as slag (Buchert et al. 2009).

Nevertheless, the potential for recycling of lithium from end-of-life batteries is estimated to be significant. Gaines and Nelson (2009a) estimate that over 40,000 tonnes of contained lithium could be recycled in the US by 2050, assuming 100% recycling rates and a 10-year battery life. In the modelling study by Gruber et al (2011), recycled lithium constitutes between 50 and 63% of cumulative demand over the 2010-2100 period, assuming recycling rates of 90-100%. Buchert et al (2009), however, note that while the large growth in battery production implies a significant recycling potential, there is currently a lack of economic incentive to recycle lithium given its relatively low price[27].

A primary issue in recycling lithium from end-of-life batteries is the sorting of collected waste batteries. Not all collected batteries will be Li-ion batteries, e.g. in the automotive sector many will still be NiMH, and not all Li-ion batteries have the same chemistry. In order to develop an efficient recycling process, it is necessary to know the composition of the

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[27] Lithium price is often reported as the price of lithium carbonate. In 2011, the average price of lithium carbonate was approximately $4.3/kg (Jevons 1865).

batteries to be treated (Contestabile et al. 1999). A number of automatic sorting systems have now been developed for waste batteries, using magnetic or electrodynamic sensors, photo recognition of the label and x-ray imaging, all resulting in varying levels of purity in the separated fractions (Bernardes et al. 2004).

There are a number of existing lithium-ion battery recycling processes, mostly hydrometallurgical (Bernardes et al. 2004), although many of these are primarily focused on recycling cobalt due to its high concentration and price incentive (Lain 2001; Sloop 2008). Other metals are also recycled due to flammability or toxicity concerns (Castillo et al. 2002; Bernardes et al. 2004). For example, the Sony process, named after the company to which the patent is assigned, does not recover lithium (Lain 2001; Bernardes et al. 2004). On the other hand, the Toxco process (McLaughlin 1994) uses cryogenic processes followed by mechanical shredding and mixture with water to produce lithium hydroxide as a main product. This is then converted to lithium carbonate. More recently, processes have focused on lithium and lithium carbonate recovery (Castillo et al. 2002; Kondás et al. 2006). Xu et al (2008) review the processes available for recycling Li-ion batteries, and list six treatment methods for the processing of Li-ion cathode materials, further divided into two distinct groups. Physical treatment methods are mechano-chemical, thermal or dissolution processes, while chemical processes involve acid leaching, bioleaching or solvent extraction (Xu et al. 2008). If future lithium availability constraints were to arise, processes that recover lithium (Toxco) are likely to be favoured over those that do not (Sony).

The recovery of lithium from spent batteries remains a niche market (Buchert et al. 2009), and the battery industry does not currently produce batteries using recycled material (Kotaich and Sloop 2009). For recycled lithium to contribute half of future supply as suggested by Gruber et al (2011) appears to be difficult and will require more targeted legislation or a clear economic incentive.

In addition, it has been proposed that automotive Li-ion batteries could be reused after their useful life in electric vehicles. The National Renewable Energy Laboratory (Neubauer and Pesaran 2011) is investigating the potential revenue and BEV/PHEV cost reductions achievable through the use of end-of-life electric vehicle batteries in secondary applications for utility energy storage, such as storage for wind and solar power. However, this form of recycling would extend the delay in availability of recycled material for new EV battery manufacture.

4.1.5 Estimates of future supply

Both production and reserve estimates are likely to change over time and several authors have tried to account for these changes within estimates of future production or availability. Figure 4.6 presents estimates of both future production and future availability. These estimates are in the order of ~60 to ~110 kt/y of lithium metal production in 2020 and ~2 to ~20 Mt of lithium metal available over the century to 2100 or over all time. The methods used to calculate these values and the values themselves are discussed below.

The future production chart in Figure 4.6 contains estimates from three sources. A fourth source (Yaksic and Tilton 2009) estimates future production of lithium metal in 2100 at 330 kt/y. This datapoint has been omitted given its long time horizon.

A report by Dundee Capital Markets (DCM 2009) presents their projection for lithium supply to 2020. This data is subdivided into lithium production from brines, lithium production from spodumene minerals, and lithium from new production capacity forecast to come onstream from 2012. These data are represented by the red bars in Figure 4.6, and forecast lithium production of ~110kt/y. Anderson (2011a) presents a similar supply forecast to 2020, with slightly more conservative lithium production figures of ~75kt/y. Finally Tahil (2008) presents two spot estimates for future lithium production, estimating 44kt/y in 2015 and 58kt/y in 2020.

Based on the evidence presented in Figure 4.6 production of lithium in 2020 may be between 58kt/y and 110kt/y.

The future availability chart in Figure 4.6 presents estimates from six sources. Tahil (2008) provides an estimate of the lithium he considers producible. This figure is based on the USGS reserve figure for lithium in that year. This can therefore be viewed as a conservative estimate since reserves estimates are likely to increase for a range of reasons (Clarke 2010). As presented in Figure 4.4 USGS reserve estimates have grown in more recent years, and by 2011 reserves were estimated at 13Mt, over three times the Tahil (2008) estimate.

In an earlier report Tahil (2007) estimated future availability by calculating an Ultimately Recoverable Resource (URR)[28] of lithium at 35Mt of lithium carbonate (or 6.6Mt of lithium metal). This figure is derived by applying a 50% recovery factor to estimates of lithium resource to arrive at a value of 33.55Mt lithium carbonate which is rounded up to 35Mt. This figure excludes any sodumene ore deposits which the author describes as 'not economically or energetically viable for LiIon batteries'.

Ebensperger (2005) presents two estimates of future availability, 3.4Mt and 9Mt, both taken from Crowson (2001). These are presented in Figure 4.6, with the higher of the two estimates represented by the black outline.

Andersson and Rade (2001) present a low and high estimate of future availability, 1.5Mt to 17.34Mt, which represents a significant range. This value is derived by assuming a quantity of metal available from the earth's crust, adding the availability from future recycling of lithium, and subtracting the lithium used by markets competing with the BEV market. As such this estimate represents the material available to automotive battery markets, and not the total metal available. This is a relatively sophisticated methodology for calculating future availability, though the range presented covers a large proportion of the range of all estimates in Figure 4.6.

Gruber et al (2011) present a figure for the minimum recoverable resource of 19.34 Mt. This is derived by summing the in-situ resources from known brines, pegmatites and sedimentary rock deposits, and applying a 50% recovery factor. This provides one of the largest estimates in Figure 4.6.

Finally, Yaksic & Tilton (2009) present a cumulative availability curve for lithium. This curve presents a range of marginal resources, their estimated weight, and the price of lithium needed to make them economic. This therefore presents an increasing weight of lithium available as the price of lithium increases. This curve describes a low cost and a high cost scenario which give a narrow range of lithium price per unit weight. Given a lithium price of $2/lb lithium carbonate the curve suggests a lithium availability of ~22Mt. However, the

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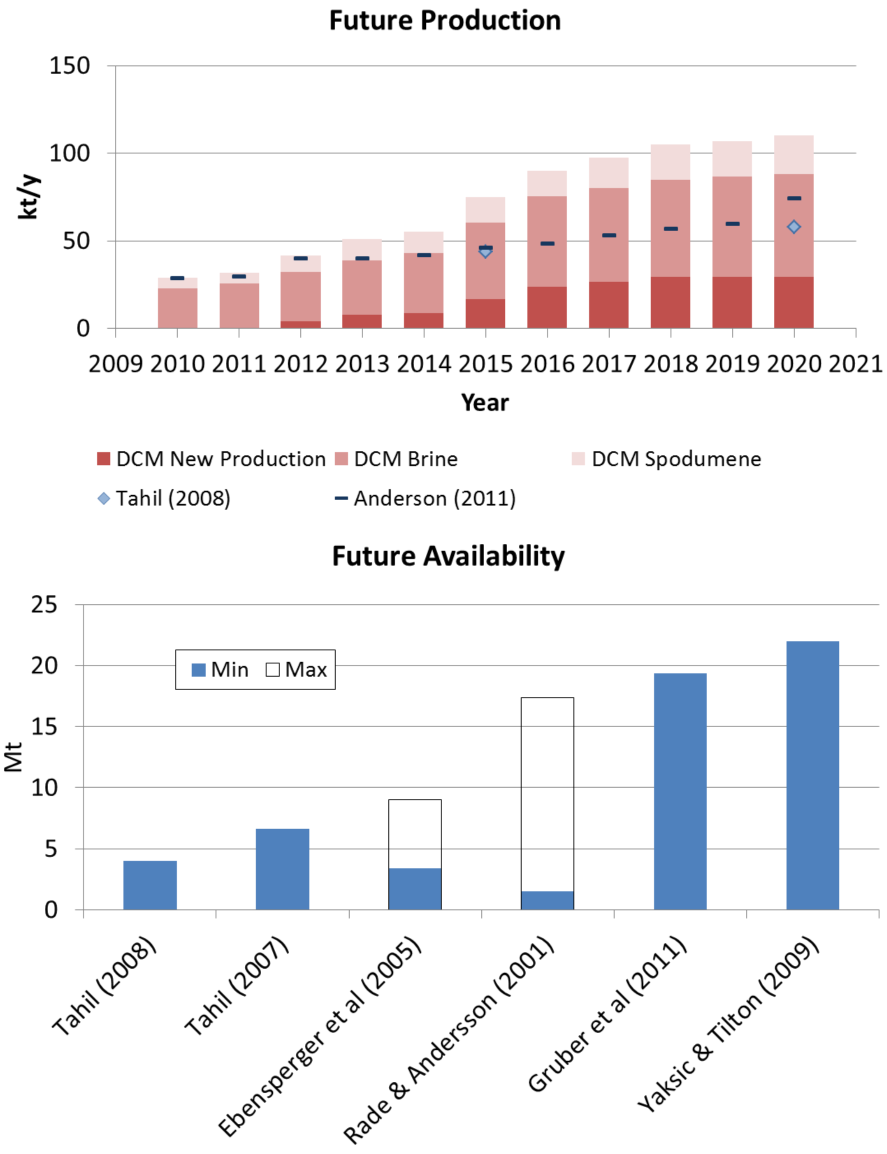
[28] The concept of URR is described in UKERC (2009a)

curve also suggests that at higher prices, the availability increases significantly. If the lithium carbonate price rose to $7.20 about 44.8Mt of lithium would become available according to the authors[29]. This, they suggest, is an unlimited supply for all practical purposes.

Figure 4.6: Available estimates of future annual production and future cumulative availability of lithium



Given the conservative nature of common reserve estimates, and the resulting behaviour that these estimates typically increase over time, it is practical to assume the latest reserve estimate as a lower bound for estimates of future lithium availability. Given the current USGS lithium reserve estimate of 13Mt it is reasonable to discount those estimates in Figure 4.6

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[29] At this price the authors estimate that lithium extraction from seawater will become economic, producing the high estimate.

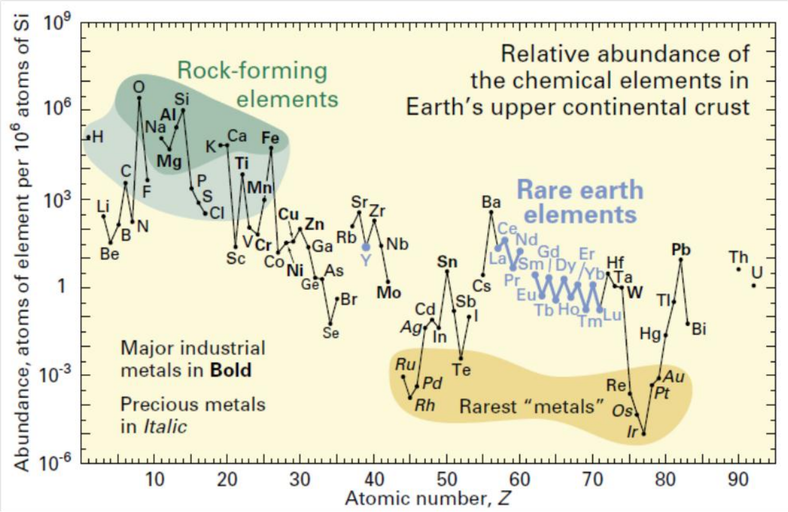
with estimates lower than 13Mt. This leaves the upper estimate provided by Rade and Andersson (2001), the Gruber et al (2011) estimate, and the Yaksic & Tilton (2009) estimate. This gives a range of 13Mt to 22Mt[30] for future availability of lithium.

4.2 Neodymium

4.2.1 Extraction, refining and processing

Neodymium is one of 17 rare earth elements[31] (REE), which are typically coproduced together from several ore bodies including bastnäsite, monazite, xenotime, rare earth laterite, apatite, cheralite, eudialyte, loparite, phosphorites, rare-earth-bearing (ion adsorption) clays and spent uranium solutions. Neodymium is also one of the lanthanides (or lanthanoids), which includes the 15 metals of the lanthanide series[32].
The rare earth elements are not in fact particularly rare. For example neodymium is more abundant than lead. It is the 32nd most abundant element in the earth's crust (see Figure 4.7).

Figure 4.7: Relative crustal abundance of the elements.



Source: USGS (2002)

The 17 REEs have very similar arrangements of electrons which in turn creates similar chemical properties. This similarity makes separation of the individual elements from each other difficult. During the Second World War, successful separations by ion exchange were achieved on small quantities of radioactive fission products, particularly of cerium, praseodymium, neodymium, promethium and yttrium. Later improvements were made to

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[30] Based on the assumption that lithium carbonate remains around $2/lb.

[31] This group is typically defined to include 15 lanthanide elements, with the addition of yttrium and scandium, which are commonly found in the same ores

[32] The lanthanides are usually separated on representations of the periodic table. REEs include all lanthanides plus scandium and yttrium.

the process by use of a strong complexing ion such as chelating agent. This is an organic molecule that bonds strongly to the rare earth ions.

Another consequence of their similarity is that the elements are found together in ore bodies albeit in differing concentrations. The principal minerals containing neodymium are monazite and bastnäsite. Currently most neodymium is recovered from bastnäsite ore and purified using solvent extraction techniques.

Bastnäsite occurs in USA (California), Burundi, Madagascar and Mongolia in the People's Republic of China. It is a fluorocarbonate with rare earth content up to 75%, and neodymium content of 12-18% typically. Monazite occurs in the heavy minerals of coastal sands in Australia, Brazil, India, Malaysia, Nigeria and Zaire. It is a phosphate mineral with rare earth content of up to 65% and neodymium content of 15-17%. Mining of monazite often occurs as an activity secondary to mining of other minerals such as ilmenite, zircon and cassiterite. Therefore to some extent the amount mined depends on demand for the main product.

Ore extraction is by open cast mining, often by blasting. The ore is crushed and milled to a fine powder. Separation of valuable minerals from gangue in the powder is carried out by froth flotation, heavy medium separation and magnetic separation.

To extract the valuable metals from the ore leaching with strong alkali or acid solution is carried out at raised temperature. Alkaline leaching produces RE Hydroxides which can then be dissolved in concentrated acid. Treatment of ores with sulphuric or hydrochloric acid converts the metals to soluble salts directly.

Separation of the rare earth elements is challenging because of the close similarities in the chemical properties of the elements. A preliminary step is separation into groups of elements with the greatest similarity. The two main methods for this process are ion exchange and liquid-liquid separation (McGill 2000). Ion exchange tends to be used for small quantities of very pure elements. Liquid-liquid separation is now the process favoured for most purposes (McGill 2000). One liquid is the acidic extract from the leaching process (described above), the other is organic, often containing two or more constituents, one of which is a chelating agent, which is strongly bonding and causes transfer of RE elements to the organic phase. The other is present as a solvent for the first. The two phases are circulated counter current to each other in the extraction plant. The organic phase becomes loaded with RE metals that form the most stable chelate bonds while those less strongly bonded stay in the aqueous phase. The two phases are separated and the RE content of the organic phase is washed out, that is, it is removed from the organic phase which is reused while the separated RE fraction is processed further to a high purity refined product. Repeated extraction and removal of the metals causes progressive separation, first of the groups of rare earths with greatest similarity and then of individual metals within the groups.

High purity refining (>99.99% purity) is achieved through ion exchange techniques. Before 1950, double nitrate crystallisation techniques were used but were superseded due to improved efficiency and purity achievable through more modern techniques (McGill 2000).

4.2.2 Production and Reserves

Known reserves of rare earth ores exist in several countries throughout the world, the relative geographical distribution of which is presented in Figure 4.8, which also presents the distribution by country of global production of rare earth oxide (REO) in 2010. China largely dominates current supply of rare earths, due to a number of factors including low labour and regulatory costs, continued expansion of electronics and other manufacturing in Asia, the favourable number, size, and heavy rare earth element (HREE) content of Chinese deposits, and the on-going environmental and regulatory problems at the Mountain Pass mine in California, which was the single source of most global rare earth production between 1965 and 1985 (USGS 2002).

According to Figure 4.8, China also holds almost half of global reserves, with the remainder found in the US, the Commonwealth of Independent States (CIS), Australia, India, and other countries. This distribution of reserves from the USGS (2011) differs greatly from the distribution of reserves presented by the Chinese Society of Rare Earths (Chen 2011a; Chen 2011b) which places Brazil as the principal reserve-holding country, with 32% of global reserves while China has 22%. Other major reserve-holding countries presented in this data include Vietnam (9.1%), Australia (8.25%), USA (7.23%), Greenland (3.01%), and Canada (2.70%).

Data on production and reserves for neodymium are more difficult to acquire than that of lithium. Data for the 17 rare earth metals are reported as a single figure in most available sources, and disaggregated data is not commonly available. However, by taking the USGS time series for historical production of rare earth oxides, assuming a weighted percentage content of neodymium oxide[33], and then calculating the neodymium metal content, the historical production data presented in Figure 4.9 was derived. While there are clear inadequacies with assuming a fixed proportion of neodymium content across all countries and over all time, this process should provide a reasonable approximation of historical trend in neodymium production.

Figure 4.9 shows an approximate exponential growth phase associated with the early phase in the production of a non-renewable resource (UKERC 2009a). There is no apparent indication that the production rate might be slowing or tending towards a peak.

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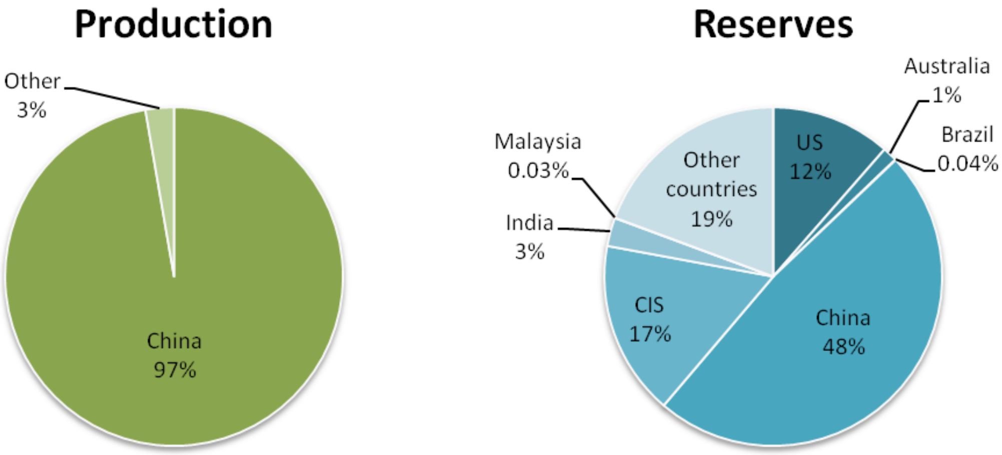
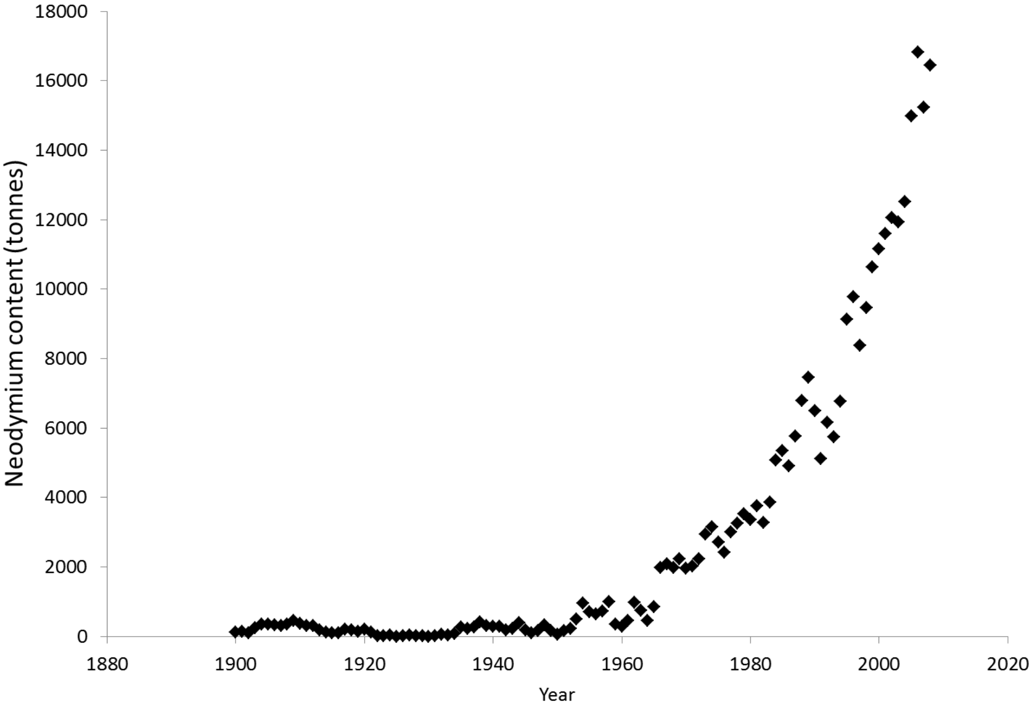
[33] The weighted percentage of neodymium oxide content in total rare earth oxide production was taken as 14.42% from supporting information presented in Du and Graedel (2011a), where a table of compositions of eight major mines is given. These mines have provided almost all of global supply since the 1990s, although it is unclear which proportion of supply they provided before then. Thus the assumed 14.42% value may not provide an exact description of historical supply before the 1990s.

Figure 4.8. Distribution of production and reserves of rare earth oxides by country in 2011.



Source: USGS (2012)

Figure 4.9. World annual neodymium oxide production, 1900–2011.

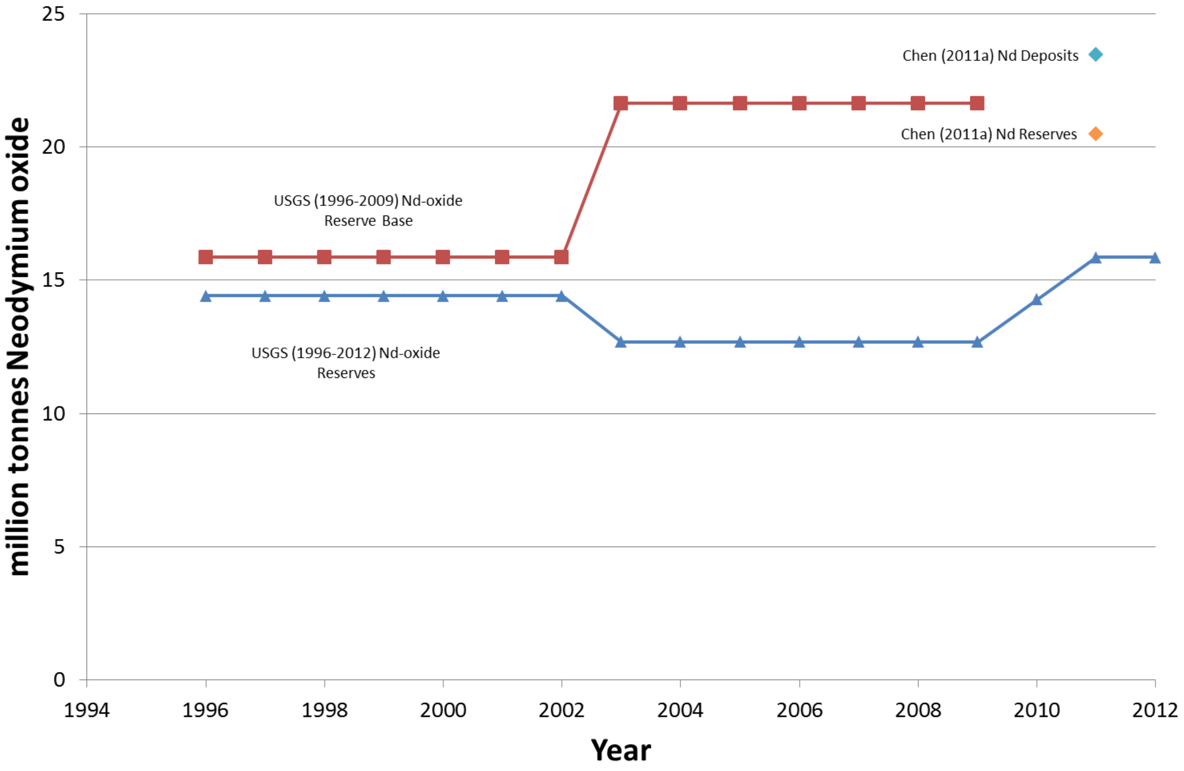


Source: USGS

Notes: A fixed weighted percentage of neodymium content in total rare earth oxide (REO) production was assumed to adjust this data series, originally presented in tonnes REO, to tonnes neodymium oxide. See footnote 33.

Data on neodymium reserves is also complicated by issues of aggregate reporting. While ore bodies for each country are known, and neodymium content for many ore bodies has been measured, reserves are still reported for all rare earth oxides. By applying the same weighted average used to calculate neodymium production we can estimate levels of neodymium reserves and reserve base in recent years (Figure 4.10). This weighted percentage is also applied to data from the Chinese Society of Rare Earths (Chen 2011a), whose estimates are shown on the same graph.

Figure 4.10. Estimates of neodymium resources found in the literature.



Notes: A fixed weighted percentage of neodymium content in total rare earth oxide (REO) production was assumed to adjust this data series, originally presented in tonnes REO, to tonnes neodymium oxide. See footnote 33 on page 59. No definition is provided by Chen for ‘deposits’.

Again, the assumptions used in Figure 4.10 can only provide an indication of magnitude and trend in Nd reserve estimates. The data does, however, indicate a period of stable reserve figures, with little in terms of reserve additions over that time period.

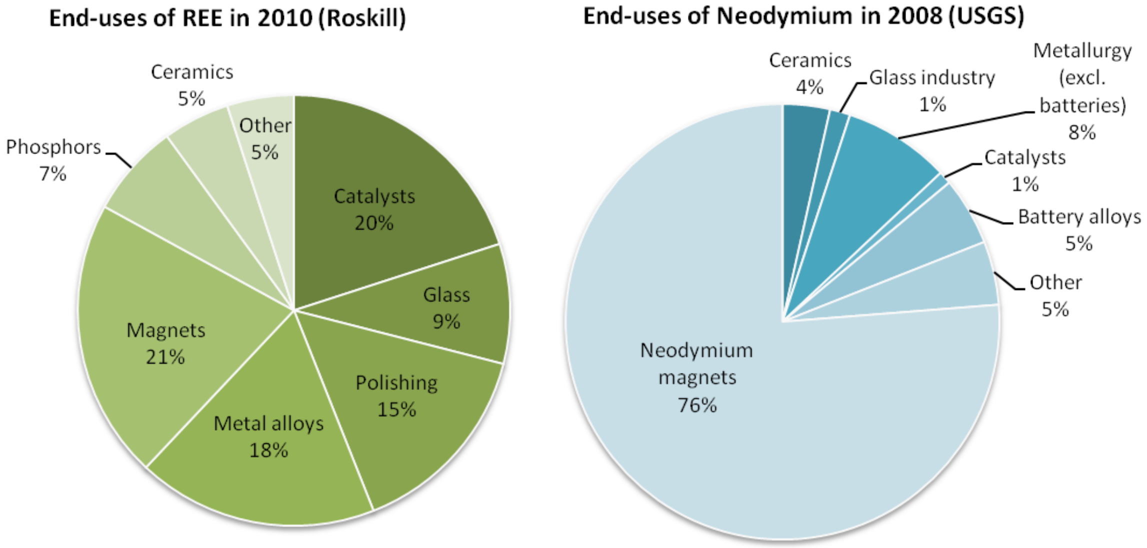
As with the USGS data used in section 4.1.2, various reporting anomalies should be acknowledged. Reserve base figures have no longer been reported since 2009, and US production has been reported as zero, while sources suggest that the Mountain Pass mine in California has been producing rare earth oxide since 2008 from stockpiled ores previously mined there (Molycorp 2011).

Neodymium’s primary demand is in manufacturing of permanent magnets, of which there are many uses, including computer hard drives, medical equipment such as MRI scanners, loud speakers and permanent magnet motors used in power tools, compressors, and electric vehicles. Neodymium is also used in laser designs, to tint glass products, and as a material in catalytic converters. Of these markets, neodymium use in permanent magnets and in catalytic converters is expected to continue growing significantly.

4.2.3 End-uses

As is the case for production and reserve data, the main applications of rare earth elements are usually reported as an aggregate. Little information is available on the specific end-uses for neodymium only, however, the most recent studies have begun to disaggregate end-uses and life cycles by element (Goonan 2011; Du and Graedel 2011a; Du and Graedel 2011b; Du and Graedel 2011c). Figure 4.11 presents the end-uses of rare earths in 2010 as reported by Roskill (Chegwidden and Kingsnorth 2011), and the end-uses of neodymium in 2008 as reported by the USGS (Goonan 2011). While the classification terminology of end-uses is not exactly the same in the two sources, the end-uses of Nd are distinct from those of all REEs: demand is dominated by magnets, Nd is not used in phosphors, and negligible amounts are used for glassmaking.

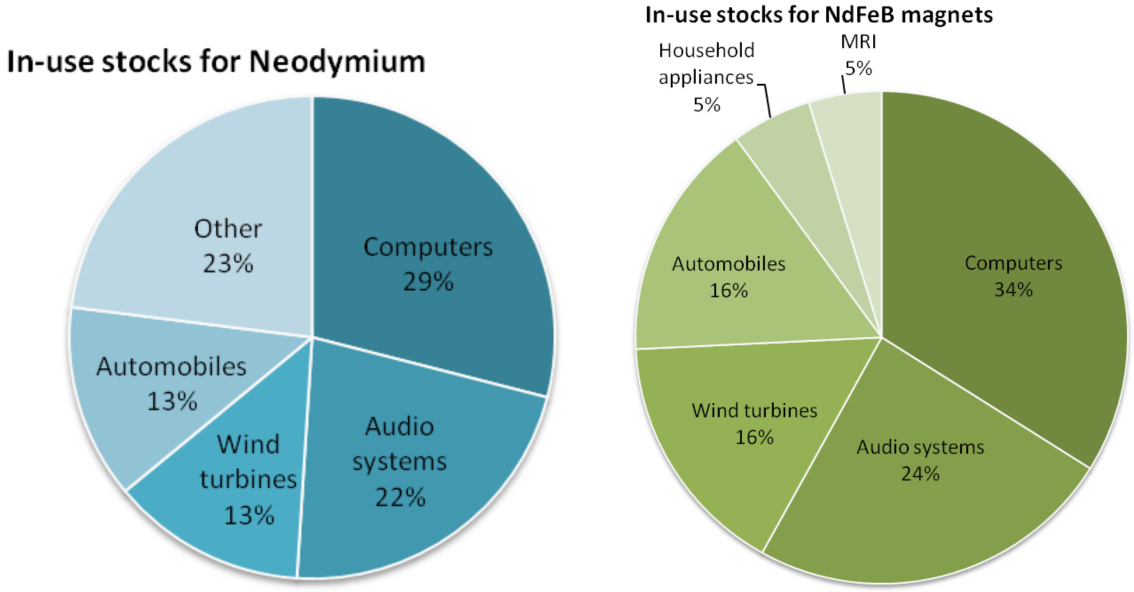
Figure 4.11. Distribution of end-uses of rare earths in 2010 and of neodymium in 2008. 'Other' includes chemicals, military weapons and delivery systems and satellite systems (Goonan 2011).



Sources: Roskill (Chegwidden and Kingsnorth 2011); USGS (Goonan 2011)

Because rare earths are used in a number of new high-growth technologies (phosphors, ceramics, battery alloys and magnets) the proportions of these end uses changes from year to year (Gutfleisch et al. 2011; Du and Graedel 2011b). It is useful to examine the consumption of Nd throughout recent years in order to understand its principal uses. Du and Graedel (2011a) provide the first estimates of the global *in-use stocks* between 1995 and 2007, shown in Figure 4.12. Computers, audio systems, wind turbines, and automobiles are all applications using NdFeB magnets, demonstrating that this has been the largest use of Nd in recent years. In another paper, Du and Graedel (2011b) provide a further estimated breakdown of global in-use stocks of neodymium in NdFeB magnets by application (Figure 4.12), showing that automobiles and wind turbines represent 16% each, while computers (hard drives, CD/DVD drives) occupy the largest segment.

Figure 4.12. Global in-use stocks for neodymium (left), 1995–2007, and for NdFeB magnets (right), 1983–2007. Other includes Glass additives, NiMH batteries, family appliances, magnetic resonance imaging, and fertilisers.



Source: adapted from Du and Graedel (2011a); (2011b)

4.2.4 Recycling

At present there is no significant amount of recycling of the rare earth elements. Due to difficulties associated with handling permanent magnets, or with recovering more diffuse neodymium from other recyclates, most feedstock material is imported as primary metal, with used magnets being disposed of as scrap (Takeda et al. 2006). A small amount of pre-consumer recycling is thought to exist within magnet manufacturing (Du and Graedel 2011c). Global end-of-life (post-consumer) recycling rates are estimated at less than 1% (UNEP 2011a), and recent consumption breakdowns and material flow analyses show no recycling at all for REEs (Goonan 2011; Du and Graedel 2011c).

Historically, a small amount of REEs may have been recovered from end-of-life nickel metal hydride (NiMH) batteries, which mostly contain lanthanum (La) and smaller amounts of neodymium (Goonan 2011). The recycling of NiMH batteries has in the past focused on recovering nickel and cobalt (Sabatini et al. 1994; Tenório and Espinosa 2002) including some amount of REE recycling, although the recycled output was in forms such as fluorides, hydroxides or mischmetal[34] which were impractical for recycling purposes (Xu et al. 2000) and had limited markets (Sabatini et al. 1994). More recently, processes have focused on recovering REEs (Bertuol et al. 2006; Rodrigues and Mansur 2010; Rhodia 2011).

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[34] Rare earth mischmetal is an alloy of rare earths found in naturally occurring proportions. It contains approximately 50% cerium and 25% lanthanum, with smaller amounts of other REEs. Mischmetal is difficult to purify, and, in its impure state is soft, brittle and inferior in magnetic, optical and electric properties.

However, the potential for REE recycling is significant, particularly in the case of magnets. Xu et al (2000) showed that the average composition of scrap NdFeB included 18.0 wt% Nd, 1.82 wt% Pr and 5.3 wt% Dy. In a series of studies aimed at estimating global in-use stocks of rare earths by element and by end-use, Du and Graedel (2011a; Du and Graedel 2011b; Du and Graedel 2011c) estimate that the in-use stocks of these elements in NdFeB magnets in the period 1983-2007 are almost four times the annual extraction rate of the individual elements in 2007, and thus could provide a valuable supplement to geological stocks. Not all end-uses provide equivalent recyclability, as shown in Table 4.1.

A number of rare earth recycling processes exist today, such as molten salts, hydrometallurgical processes for NiMH batteries, treatment of Nd with liquid metals, melt spinning for magnets, glass slag method for REE alloys, and electroslag remelting for bulk magnet scrap. Kara et al (2010) note that the patents for most of these processes were registered in the 1990s and that little has changed in this industry for the last fifteen years. Activity has resumed in the last two years, in which Umicore and Rhodia developed a process based on high temperatures (UHT) and refining (Rhodia 2011), and Hitachi, partly funded by the Japanese government, developed a proprietary process for rare earth recycling from spent air conditioning compressors (Clenfield et al. 2010).

The recycling of REEs seems feasible both in the short term, as a source of supply in the case of shortages and subsequent price increases, and in the long term, as global in-use stocks grow substantially. While the exact economics of this process, and the neodymium price necessary for expansion of this market are unknown, it seems likely that rising commodity prices and European regulatory trends will incentivise this market.

Table 4.1. Recyclability of neodymium (and other REEs) by end-use as reported by the USGS.

End-use sector	Recyclability of Nd and other REEs
Catalysts	Spent catalysts generally considered hazardous and incur high disposal costs. REEs not currently recovered, but very small amounts can be recycled within processes that recycle platinum group metals in automotive catalytic converters.
Glass	Small amounts of Nd are used in the production of yttrium-aluminium-garnet (YAG) lasers, but there is no recycling at present.
Metallurgy (excl battery alloys)	The use of REEs in metal alloys is generally dissipative; slag containing REEs is used as construction aggregate or landfilled.
Ceramics	Recycling is achievable using current technology, but little actually occurs since the cost of REE separation is higher than the potential value of the metals.
NdFeB magnets	Can be recycled, remanufactured and reused. No recycling until recently, but Hitachi has developed recycling technologies and is currently scaling them up (Clenfield et al. 2010).
Battery alloys	NiMH batteries can and are being recycled (Kotaich and Sloop 2009), although primarily for nickel and cobalt.

Source: (Goonan 2011)

4.2.5 Estimates of future supply

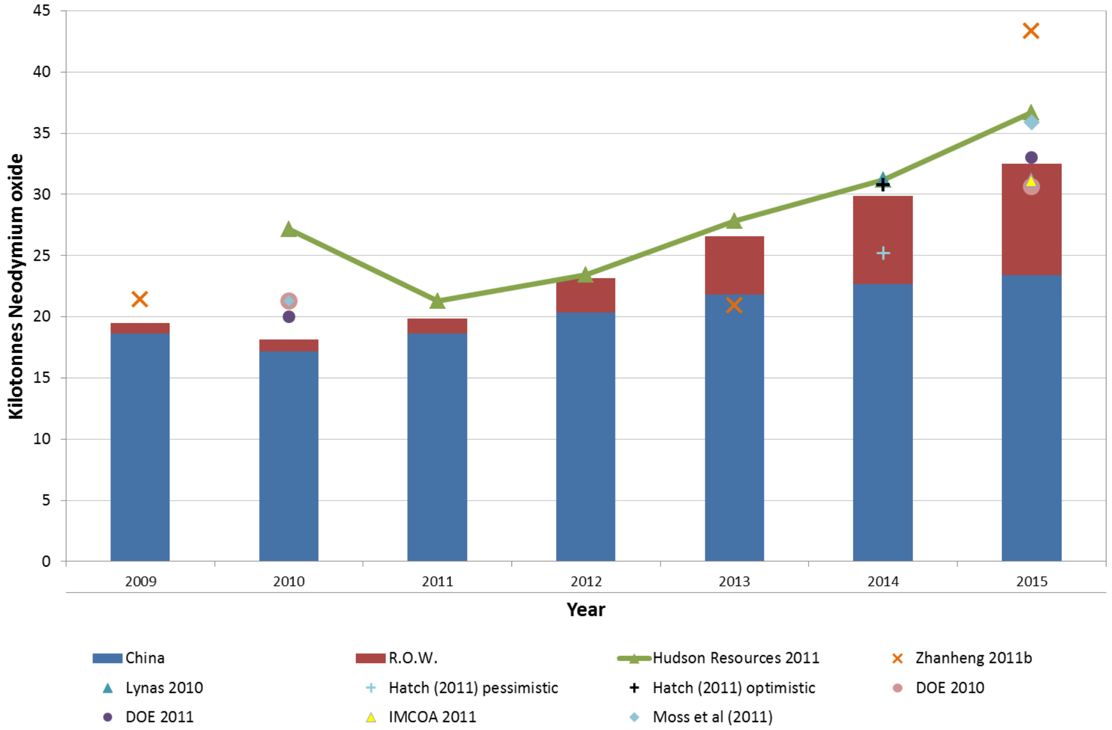
Various estimates of future rare earth supply can be found in the literature, and these are presented in Figure 4.13. Most of the supply concerns regarding rare earths focus on the short and medium term, e.g. 2010–2020. This is due to China's dominance of global supply at present, its tightening export quotas, and the relatively slow commencement of REE production in other countries. While there were over 300 new REE mining projects identified in 2010 (Chegwidden and Kingsnorth 2011), most of these are still in the feasibility study or pre-commercial phase (Curtis 2007; Bubar 2011b), and the economic viability of many deposits remains unclear.

The estimates presented in Figure 4.13 aim to show the available supply up to 2015 as non-Chinese production comes online. Most of these estimates were presented as aggregate rare earth oxide (REO), and a number of assumptions (shown in the Figure notes) were made to convert this into neodymium oxide (Nd_2O_3).

The Roskill forecasts assume that approximately 39% of global 2015 production will be from non-Chinese (rest of the world, R.O.W.) sources (Chegwidden and Kingsnorth 2010). By contrast, Zhanheng (2011b) from the Chinese Society of Rare Earths, forecasts a much higher total production figure in 2015, and assumes that R.O.W. production will be 64%. Hudson Resources Inc. (2011), a prospective rare earths mining company in Greenland, also provides high figures for neodymium production in all years; it is unclear whether this is an explicitly higher supply estimate or if it is due to higher assumptions about the percentage of neodymium in total REE supply (see Figure 4.13 caption). In 2014, there is consensus among four sources about the global production of neodymium (Chegwidden and Kingsnorth 2010; Hatch 2011; Hudson Resources Inc 2011; Schüler et al. 2011), due to a number of non-Chinese sources of supply expected to begin production by then (e.g. Smith (2010)).

Few estimates of rare earth (and thus Nd) production beyond 2015 can be found in the literature, those that have been identified here are shown in Figure 4.14. Hatch (2011) presents projections for 2017 production of neodymium oxide ranging from 26.6 – 32.3 kilotonnes (kt); and the JRC (Moss et al. 2011) estimate Nd_2O_3 production in 2020 at 52.8 kt. Kara et al (2010) provide three scenarios to 2030 for rare earth production, which have been adjusted here for neodymium content. The latter scenarios are used in Chapter 5 to compare with estimated demand ranges for 2050, where their validity is discussed.

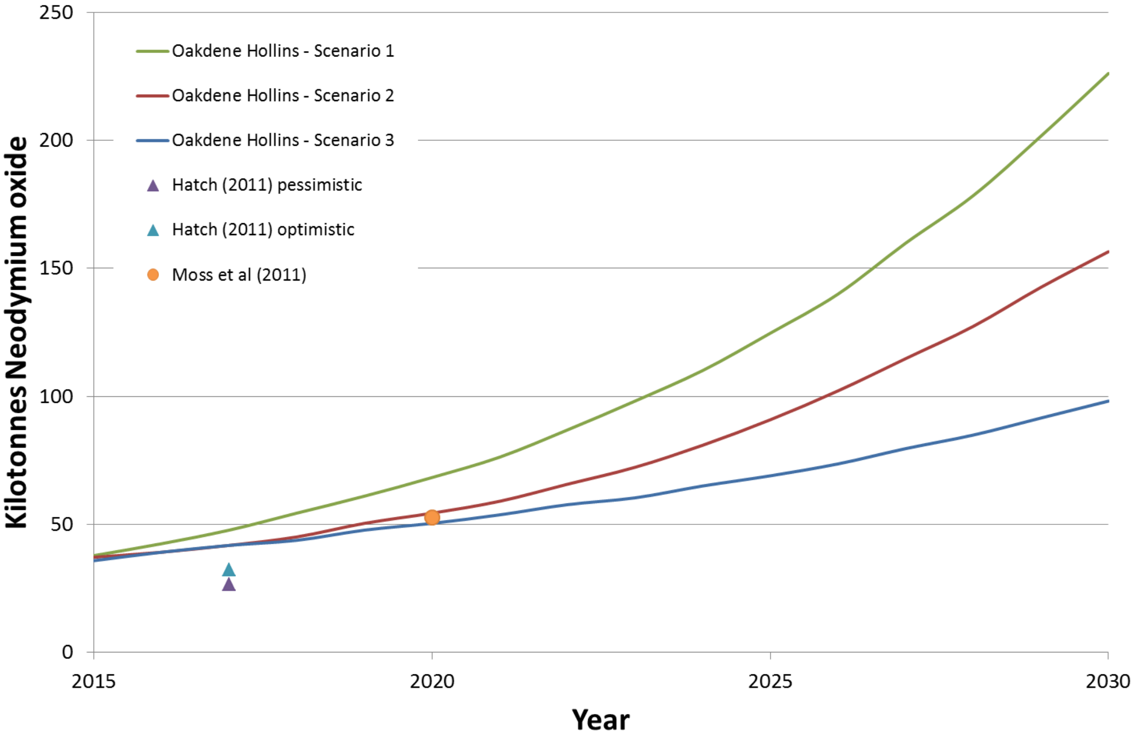
Figure 4.13. Estimates of future Nd supply (2009-2015) found in the literature.



Sources: Roskill (Chegwidden and Kingsnorth 2010); Zhanheng (2011b); Hudson Resources Inc. (2011) Hatch (2011); Lynas cited in Schuler et al (2011); DOE (2010; DOE 2011); IMCOA cited in Bubar (2011b); Moss et al (2011)

Notes: R.O.W. indicates rest of the world. Roskill, Hudson Resources and Zhanheng do not present disaggregated Nd supply forecasts; the former two, however, do present single figures for Nd supply shortages in 2014. This figure is used to estimate a percentage of neodymium oxide in total REO supply. According to this methodology Roskill assume that Nd represents 14.4 – 16.8% of total supply, and Hudson Resources assume a figure of 21.8%. For Zhanheng, this estimation was not possible and the figure was assumed from Roskill data, which is cited extensively in Zhanheng's (2011a; Chen 2011b) papers. For Roskill and Hudson Resources, data was extracted from graphs using Engauge Digitizer.

Figure 4.14. Estimates of neodymium oxide production beyond 2015 found in the literature.



Sources: Oakdene Hollins (Kara et al. 2010); Hatch (2011); Moss et al (2011)
Notes: Oakdene Hollins data is for rare earth oxide production. Kara et al assume Nd production is 16.2% of total REO production; this value was used to adjust the scenarios for neodymium content. Oakdene Hollins data was extracted from graphs using Engauge Digitizer.

5 Supply and demand in context

In Chapters 2 and 0 we discuss a wide range of factors which have a bearing on the demand for materials from electric vehicles, and the supply of those materials from their known sources. To investigate the implications of these factors for the future material availability for low carbon technology we now compare the findings of these chapters. We briefly revisit these chapters and their summary findings before discussing the implications.

In Chapter 2 we examined the potential future demand for lithium and neodymium in the manufacture of electric vehicles. Having investigated these issues and the available evidence surrounding them a range of potential future demand was derived. For lithium, demand in 2050 was estimated at between 184kt/y and 989kt/y. For neodymium, demand in 2050 was estimated at between 15kt/y and 111kt/y, including demand from direct drive wind turbines, as estimated in Chapter 0.

In Chapter 4 we examined the potential future supply of both lithium and neodymium. Ranges of potential future supply were estimated based on available literature which attempted to estimate future production. For lithium, supply in 2020 was estimated at between 74kt/y and 110kt/y. For neodymium, supply in 2030 was estimated at between 98kt/y and 226kt/y. The values discussed above are compiled in Table 5.1.

Table 5.1: Summary of ranges of supply and demand (kt) of lithium and neodymium for electric vehicles and wind turbines

	Supply (kt/y)		Demand (kt/y)			Demand in 2050 as a percentage of 2011 production
	2020	2030		2030	2050	
Lithium	74–110		Vehicles	57–268	184–989	540–2900
Neodymium		98–226	Vehicles & Wind Turbines		15–111	90–690

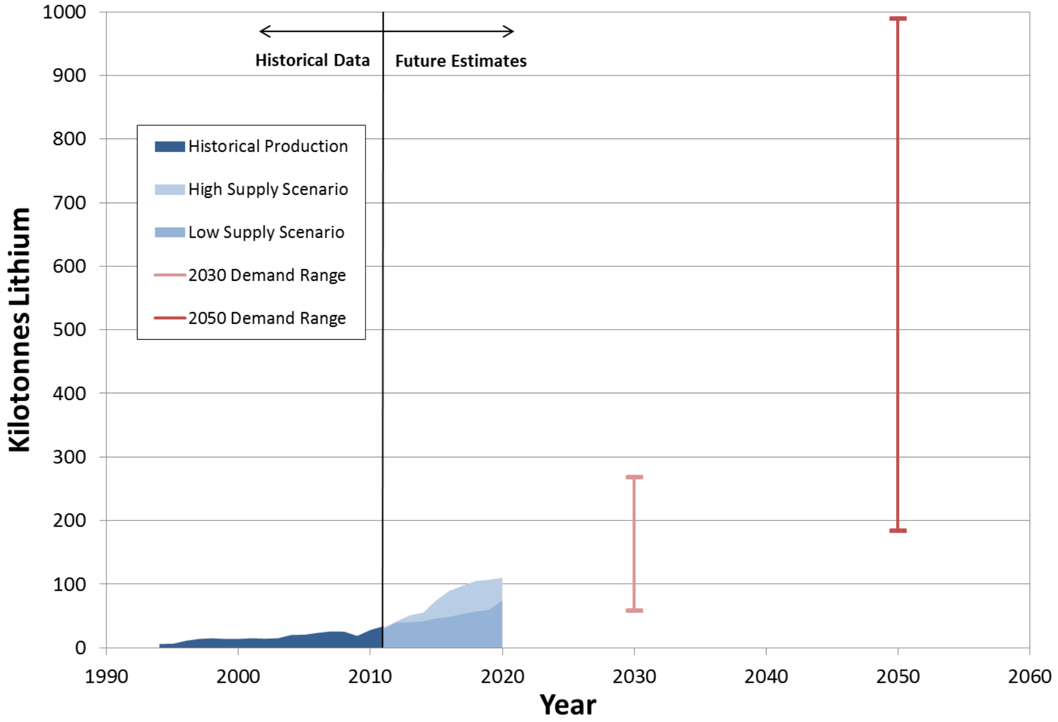
In Figure 5.1 and Figure 5.2 we present the results discussed above. Each figure includes USGS historical production, a range of future supply scenarios from the literature presented in Chapter 4, and a range of expected demand from low carbon technologies estimated in Chapters 2 and 0. In both cases, the demand ranges are based on the IEA Blue MAP scenario (IEA 2010) as it is consistent with the technologies investigated here, and consistent with 2050 global decarbonisation goals.

Before discussing these in detail we highlight the following caveats. No account of other uses of lithium or neodymium is included in the demand estimates, and these are purely based on demand for EVs (and wind turbines in the case of neodymium) as analysed in Chapter 2 and 0. There is also no additional analysis of the quantitative impacts of recycling on supply. The impact of these omissions depends on the development of these factors over time. It seems reasonable to assume, however, that other uses of these metals will continue into the future decreasing lithium and neodymium availability, and that recycling will contribute to supply within the timeframes considered here, increasing availability.

On the left of Figure 5.1 we present historical lithium metal production, using data from Figure 4.3 showing the approximately geometric growth in supply to date. The future lithium supply estimates, presented in the middle of Figure 5.1 are limited, both in number and in timescale. These estimates, however, represent a two to three fold increase in production by 2020, maintaining the historical compound rate of growth, if not exceeding it. Due to the short timescale in available estimates we present estimates of future demand from EVs in both 2030 and 2050.

The range of demand presented is large, driven by several factors. First, there is significant uncertainty regarding the future average battery size and weight of metal in batteries. There is a paucity of literature discussing the likely development of these factors over time, and the current vehicle fleet data provides a very wide range of battery sizes and material intensities (Table 2.5 and Table 2.9). However, the low estimate of future demand is unlikely to be reduced without reducing assumptions on car sales in 2030 or 2050. This is a result of the fact that the main priority currently pursued by EV manufactures is increasing vehicle range rather than decreasing material intensity. It is reasonable therefore to assume that battery size and material intensity are more likely to increase in the coming years. The difference between estimates in 2030 and 2050 is entirely driven by the growth in vehicle sales assumed. While it is possible for the future trajectory to be less dramatic than forecast in the IEA BLUE Map scenario, it is also possible that this scenario be exceeded, if EVs become attractive as range improvements are realised and vehicle costs are reduced. As highlighted in Table 5.1 the estimated range of future demand is many times greater than current supply. While this highlights the challenge for future supply, it does not follow that future production cannot increase at a sufficient pace. Though long term compound growth in production would be unsustainable, if levels of growth to date could be sustained over the next two decades, future demand may appear more achievable. Supporting this optimism are the significant resource estimates for lithium seen in Figure 5.1, though these estimates make no assessment of how easy these resources are to access, and over what timescales they can be produced.

Figure 5.1: Lithium: comparison of historical production, forecast supply, and forecast demand

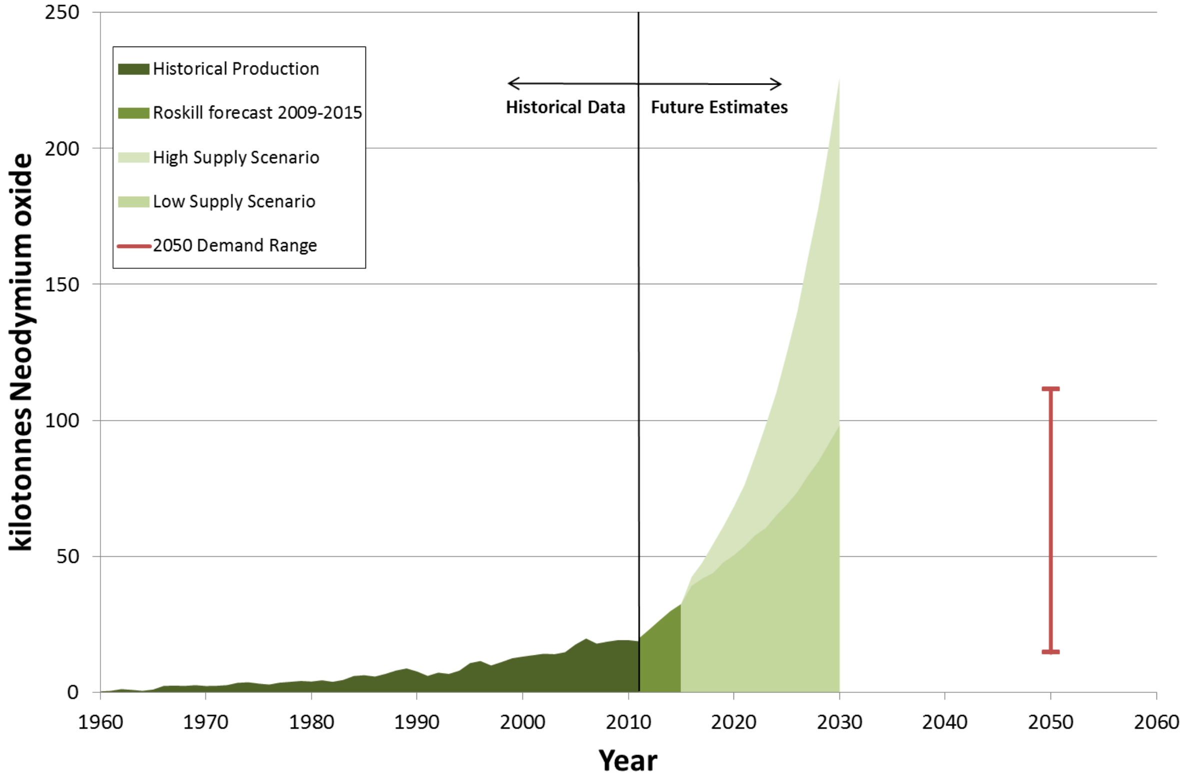


In the case of neodymium (Figure 5.2), historical and forecast supply also seems to display an exponential trend. The supply data is less limited than for lithium, reaching out to 2030, but no estimates exist for the estimated demand in 2050 that is consistent with global decarbonisation goals. This demand range is driven by assumptions made on:

- the weight of magnets per vehicle,
- the composition of those magnets and their corresponding neodymium content,
- the market share of permanent magnet motors respective to other motor types discussed in Section 2.3.4,
- the possibility of material intensity reduction via manufacturing improvement, and the demand for wind turbines which is an order of magnitude less than EV demand.

The principal limitation in the estimate of demand is that the neodymium content of magnets is reported on a *per-vehicle* basis, as opposed to a more transparent case for lithium where intensity is reported per kWh battery capacity. The assumption of a figure for neodymium intensity per vehicle is not a fair assumption, since it is evident that due to the variation in motor size, vehicle type and choice of magnet, not all future electric vehicles will use the same amount of neodymium. Nevertheless, no available evidence can account for these variations, and, while from an engineering perspective it does not seem obvious that neodymium content will vary strongly depending on motor size (kW), from a resource perspective the impact on a demand assessment may be significant. Overall, however, the maximum demand in 2050 is estimated to be slightly larger than the minimum supply scenario in 2030, suggesting that the issue of availability to low-carbon technologies may be less challenging for neodymium than for lithium. Where there is still concern over the availability of neodymium for low carbon technology manufacturing, research may focus on EV motors given the relatively small contribution made by wind turbines to the demand estimates. Dysprosium, briefly discussed in Section 2, may have a more constraining impact on EV motors given the need to improve coercivity. A number of studies have recently designated dysprosium as a ‘critical’ material for clean energy technologies and examined its situation in detail (DOE 2011; Hoenderdaal 2011; Moss et al. 2011). High dysprosium prices have recently led to a substantial amount of magnetics research focused on reducing or eliminating dysprosium content (Brown et al. 2002; Sepehri-Amin et al. 2010; Gutfleisch et al. 2011). However, the issue of dysprosium availability is not covered in sufficient detail here to draw robust conclusions.

Figure 5.2: Neodymium: comparison of historical production, forecast supply, and forecast demand



The findings for both lithium and neodymium present a significant uncertainty regarding future demand. This is a function of the uncertainty on battery and motor size, and the intensity of material contained within. This uncertainty found in the literature is a key area to explore in future research.

6 Conclusions

This working paper has examined the demand and supply of materials for electric vehicles and wind turbines, focusing on lithium in Li-ion EV batteries and neodymium electric vehicles using permanent magnet motors. We have also considered the demand for neodymium in the wind energy sector, where it is used in the generators of direct drive wind turbines.

The paucity and poor quality of literature assessing availability of materials for electric vehicles is a key concern. Lithium availability for EV batteries has been assessed in only a few studies (Yaksic and Tilton 2009; Angerer et al. 2009b; Gruber et al. 2011), while neodymium availability for electric vehicle motors and wind turbine generators has been subjected to more detailed analysis, though in fewer studies (Kara et al. 2010; Schüler et al. 2011). Both materials have been examined at a broader level in conjunction with other so-called ‘critical metals’ in a number of studies (Angerer 2009a; DOE 2010; APS and MRS 2011; DOE 2011; Moss et al. 2011), and often the evidence base for issues of availability of both metals consists primarily of this less detailed literature.

The review has examined the key variables needed to make an assessment of future availability. On the demand side, these variables include future market size of the relevant technology, its future market share, and the material intensity —the amount of material per unit of installed capacity. We have gathered and presented the literature base for these three factors and used them to present a range of demand for lithium and neodymium for electric vehicles and wind turbines in 2050. In several cases, however, illustrative assumptions have been made owing to lack of evidence or published estimates. Estimation of the lithium intensity in batteries was found to be particularly complex and is assessed in the literature in various ways. The evidence base for neodymium intensity was only present in the literature on a *per-vehicle* basis, allowing for no variation in motor size or vehicle type, both of which could affect neodymium intensity.

On the supply side, the key variables involve historical supply and estimates of future supply. The latter depend in turn on assumptions regarding global reserves and resources, anticipated demand, recyclability and cost. Estimates of future supply of both materials are shorter than the range of estimated demand to 2050, reaching up to 2020 for lithium and 2030 for neodymium. As a result, an extra demand estimate has been made for lithium for the year 2030.

In addition, the review has explored the options and possibilities for reductions in material intensity via manufacturing improvements, partial substitution or complete substitution. While it is likely that manufacturing improvements will contribute noticeable reductions to material intensity, and that some options for partial substitution will succeed, the technologies involving total substitution of lithium have not yet been demonstrated at a commercial scale and it is difficult to draw conclusions on their full potential. Neodymium motors may be totally substituted by induction motors but limitations in their performance and attributes currently insures continuing interest in PM motors with neodymium magnets.

The demand for lithium and neodymium

The analysis conducted here highlights a wide range in demand for lithium and neodymium, especially due to the large uncertainty in material intensity figures, which range from 50-563 g Li/kWh for lithium in vehicles, and for neodymium from 218-1152g Nd per vehicle and 43.6–320 kg Nd per MW installed wind capacity. This uncertainty leads to largely varying results in estimated demand for 2050. A key objective for future assessment of material availability is reducing this uncertainty range through improved information availability and a better understanding of the key variables of technological demand.

In addition to the uncertainty surrounding material intensity, there is also no consensus on the future market share of BEVs and PHEVs versus that of HEVs and FCVs, which have smaller batteries and thus contain less lithium. This is also the case for the future market share of direct drive versus geared wind turbines. In this review, we have used the uptake scenarios and market size and share values forecasted by the International Energy Agency (IEA), because their projections are commensurate with a 50% reduction in carbon emissions by 2050, and also because no other global scenarios to 2050 were identified in the literature. However, while the IEA scenarios are consistent with 2050 decarbonisation goals, it is worth noting that by virtue of the IEA's aggressive growth assigned to BEVs and PHEVs in the 2030–2050 period, demand in 2050 is set to be large. Also, because the IEA assigns a relatively low annual growth in installed wind energy capacity relative to that of today, wind turbines do not contribute significantly to neodymium demand in 2050, representing 4–6% of the total demand range presented in Figure 5.2. Assuming different uptake scenarios would have altered future demand estimates and increased the uncertainty associated with these.

Supply of lithium and neodymium

The evidence base for reserves and resources of lithium and neodymium does not point to a consensus; this is less the case for rare earths and neodymium, for which only two estimates (based on similar datasets) were identified. As shown in Chapters 2–4, it is common in the published literature to find that the scarcity or criticality of these materials is judged by a comparison of reserves and resources with anticipated demand. This method gives little information about the rate at which production can be increased to meet demand. As a result, we have focused on estimates of future production. However, it appears that there are few estimates of future production and little consensus, particularly for lithium. The latter metal's production forecasts vary from 75 to 110 kilotons Li in 2020, and neodymium production forecasts range from 98 to 226 kilotons in 2030.

Implications, overarching conclusions and future research needs

This review has compared the evidence base for the historical and future supply of lithium and neodymium as well as their anticipated demand for uses in two low carbon energy technologies, electric vehicles and wind turbines. If the market for these technologies grows as substantially as suggested by the IEA Blue Map scenarios then the implications of anticipated 2050 demand for lithium will be significant, exceeding 2011 production by up to 2,900%. In the case of neodymium, the implications are comparatively less challenging, with anticipated demand exceeding 2011 production by a maximum of 600%. Dysprosium, used along with neodymium in magnets for electric vehicle motors and direct drive turbine generators, has been highlighted here and in recent studies for future research.

Although these are challenging outlooks, there is no evidence suggesting an actual barrier to increasing production to at least the midpoint of the 2050 demand range for both metals. In the case of lithium, identified resources excluding seawater appear substantial, and end-of-use recycling could contribute to future supply if the vehicle market grows as strongly as forecast by the IEA, although it is unclear which lithium price levels will make this recycling viable. For neodymium, rare earths projects outside China as well as recycling of magnet scrap are options for expanding production.

Moreover, the market for electric vehicles includes a number of technologies for batteries and motors. The former component is likely to continue using lithium even in foreseeable technological developments, while for the latter, improvements in induction motor performance may well lead to an elimination of neodymium demand for vehicle motors. This is also true for wind turbines, where direct drive generators compete with a number of other drive train concepts and technologies that do not use neodymium. Thus, there is no reason to believe that the future deployment of electric vehicles and wind turbines *per se* will be undermined by lithium and neodymium availability.

Future analysis of material demand for electric vehicles and magnets for vehicle motors and wind turbine generators is needed to assess the issue of present and future material intensity, in order to reduce uncertainty concerning the quantity of both lithium and neodymium demanded per battery or motor in the future. Analyses of the production potential of both metals is also needed to better assess which parts of identified lithium resources are economic and, in the case of neodymium, disaggregate the information relating to the supply of rare earths and improve the availability of data specific to neodymium. While there is evidence in the literature that these steps are being taken, a thorough assessment of the long term effects of material availability on the deployment of electric vehicles and wind turbines still requires a much improved understanding of the potential for, and the economic implications of, expansion in both the production and recycling of lithium and neodymium.

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8 Annexes

Annex 1. Units and conversion factors

1 kg lithium (Li) = 5.33 kg lithium carbonate (Li_2CO_3)
1 kg neodymium (Nd) = 1.166 kg neodymium oxide (Nd_2O_3)
1 part per million (ppm) = 0.0001%

Annex 2. Speed, power and torque in a permanent magnet DC motor

In electric motors used for automotive applications, speed, torque and power are terms used to give motor specifications as well as to describe driving conditions. Motor speed is in fact the name used to describe angular velocity, the rotational speed of a shaft turned by the motor upon being supplied with a specific voltage, and is often measured in rotations per minute (rpm). Torque or moment is the term used for a force that produces rotation or torsion; thus, the motor delivers torque to the drive shaft. The SI unit for torque is the Newton-metre (Nm), and the imperial unit is the pound-foot (lb-ft). Motor power is simply the product of torque and speed, often divided by a constant to adjust the units. Motor power is traditionally measured in units of horsepower (hp) for automotive engines, although in the case of electric vehicles it is more often quoted in kilowatts (kW).

For a permanent magnet (PM) brushless DC motor, torque and speed are inversely proportional: torque decreases with increasing speed, and there is a tradeoff between how much torque the motor can deliver and how fast the shaft spins. Two points are usually used to describe this relationship: the stall torque, or the maximum torque at which the shaft does not rotate (motor speed is zero), and the no load speed, which is the maximum motor speed when no torque is delivered to the shaft (torque is zero). Because of this inverse proportionality, maximum power occurs at the point along the torque-speed curve where torque equals half of the stall torque value, and speed equals half of the no load speed value.

For a PM motor in an electric vehicle, the typical desired characteristics described in Section 2.3.2 are those that meet specific driving criteria. For example, a motor needs to have high torque at low speeds, in order to quickly deliver the force to rotate the shaft and thus accelerate the vehicle at start-up (e.g. when the vehicle is stationary) and during hill climbing. It also needs to have high power at high speed for cruising conditions. Electric motors in EVs are characterised by a ‘base’ or ‘rated’ speed, below which torque is constant, and above which torque decreases while power is constant. This leads to the concepts of a ‘constant torque region’ and a ‘constant power (or field-weakening) region’. A key objective in motors is to operate at constant power throughout as much of the speed range as possible (Xue et al. 2008). PM motors inherently have a short constant-power region due to the presence of the permanent magnet field which limits their field-weakening ability; this issue can be improved using systems for automatic adjustment of the conduction angle of the power convertor (Zeraoulia et al. 2006). The typical expected characteristics and the constant torque and constant power regions of a PM motor for EV applications are shown in Figure 2.2.

Annex 3. Definitions of resource classifications found in the literature

Resource Classification	Definition
Reserve	That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system (USGS 2012)
Recoverable resource	Not defined in the literature
Broad based reserves	A concept used by Clarke and Harben (2009) to describe the need for a wider view of reserves as they become available due to the fast growth of demand for lithium, particularly for electric vehicles. The definition given by Clarke (2009) used is that found in Meadows et al (2004): "a concept related to the amount of the material that has been discovered or inferred to exist and that can be used, given reasonable assumptions about technology and price".
Reserve base	That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the inplace demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). The term "geologic reserve" has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve-base category; it is not a part of this classification system (USGS 2012)
In Situ resources	Not defined in the literature
Ultimate global reserve base	Not defined in the literature

Annex 4. The effect of elemental additives on magnetic properties of neodymium (NdFeB) magnets

Neodymium: High Nd content can optimise coercivity, but maximum energy product and remanent magnetisation increase with decreasing Nd content (Fidler et al. 2000). Increased

Nd content can increase magnet strength and toughness, protecting it from fracture (Zhang et al. 2006).

– Dysprosium: similar to Nd, as Dy content increases, intrinsic coercitivity increases while maximum energy product and remanent magnetisation decrease (Bai et al. 2007). This effect can be seen with praseodymium (Pr) and terbium (Tb) (Honshima and Ohashi 1994; Yan et al. 2011). To optimise coercitivity and energy product, a 3–4% wt addition is suggested (Bai et al. 2007). Dy additives also improve corrosion resistance and microstructure and reduce iron precipitation (Brown et al. 2002; Bai et al. 2007).

– Cobalt: partly substitutes for iron, improves high-temperature stability and corrosion resistance (Brown et al. 2002; Yan et al. 2011). Excess cobalt may decrease coercivity.

– Gallium: can strongly increase intrinsic coercitivity and improve high-temperature stability, but maximum energy product and remanent magnetisation slightly decrease with increasing Ga content (Bai et al. 2007).

– Aluminum and copper: improve intrinsic coercitivy (Yan et al. 2011)

– Gadolinium and niobium: improve corrosion resistance; niobium can also offset the adverse Dy effect on maximum energy product and remanent magnetisation (Yu et al. 2004)

– Zirconium: reduces iron precipitation and improves microstructure (Shaaban 2007)

Thus, a number of elemental additives have a number of complex effects on different magnetic properties. Attempts to improve magnet performance without resulting in adverse properties have resulted in the inclusion of a larger number of additives, for example in the sintered compound $\mathrm{Nd_{11.13}FebalTb_{2.67}Dy_{0.61}Co_{1.12}Zr_{0.14}Al_{0.49}Cu_{0.24}B_{6.07}}$ (Yan et al. 2011). Thus it is difficult to predict future composition or provide an ‘averaged’ composition for today’s magnets. The concern in this report is the neodymium content. It is possible that reductions in the oxygen concentrations of final sintered magnets may reduce Nd requirements (Harris 2011) but due to effects on coercivity and the role of Nd as a sintering aid, there may be a limit to this reduction.

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