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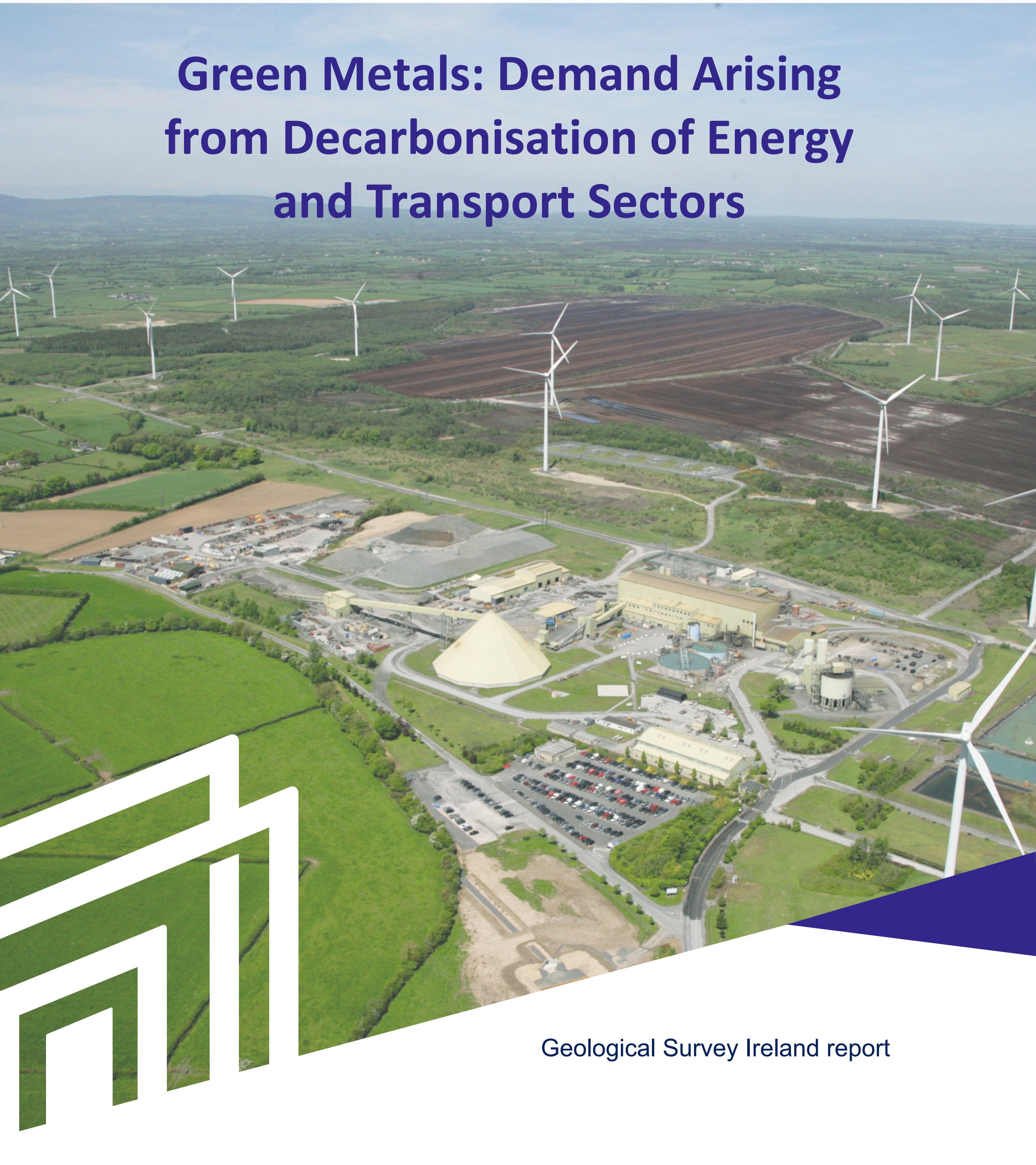
Green Metals: Demand Arising from Decarbonisation of Energy and Transport Sectors



Geological Survey Ireland report

Geological Survey Ireland/RS2023/01

Green Metals: Demand Arising from Decarbonisation of Energy and Transport Sectors

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Geological Survey Ireland

March 2023

This research was commissioned by the Department of the Environment, Climate and Communications and was compiled by Geological Survey Ireland in discussion with the Geoscience Policy Division.

The Research supports a key Implementation Action (C4.ii) from the Government's Minerals Policy Statement: "The Department will undertake research to better understand the life cycle of minerals developed in Ireland (cradle to recycling) and to better understand the demand for different minerals in Ireland (including Critical Raw Materials), the EU and globally as we transition towards net-zero greenhouse gas emissions by 2050."

Cover image: Lisheen mine and wind farm, Lisheen, Co Tipperary, Ireland.

Image courtesy of Geoscience Ireland.

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1 Executive summary

The Government of Ireland Climate Action Plan 2021 (CAP) provides the framework for delivering the government's commitments for reduction (relative to 2018) in greenhouse gas (GHG) emissions by 2030. The Plan follows the Climate Act 2021, committing Ireland to a legally binding emission reduction target of 51% by 2030, and net zero by 2050. Targets have been agreed for different sectors, and when combined will reach the overarching targets for 2030 and 2050. The most up-to-date sectoral targets for decarbonisation of the Energy and Transport sectors are analysed here in terms of the raw material demand that will arise from implementing the CAP. Targets to 2030 of note are those for electricity generation by wind (8 GW onshore and 7 GW offshore) and solar (5.5 GW) and the number of electric cars (845,000), vans (95,000), buses (1,500), and low emission HGVs (3,500) on the road. The raw materials in question have been dubbed 'green metals' as a result of their applicability in renewable energy generation and electric vehicle technology. Green metals include critical raw materials such as rare earth elements (REE), imperative for solar panels and motors used in wind turbines and electric vehicles, and battery critical materials including lithium, cobalt, and nickel. Other metals, including zinc, are also seeing an increase in demand because of their use in renewable energy and e-mobility, and the global drive to a greener economy.

In her 2022 State of the European Union address, European Commission President Ursula von der Leyen stressed the importance of raw materials for the future and announced a European Critical Raw Materials Act. Her address identified the current "global race for the supply and recycling of raw materials" and highlighted specific elements as growing exponentially in strategic importance "Lithium and rare earths will soon be more important than oil and gas. Our demand for rare earths alone will increase five-fold by 2030."

It is possible to reasonably estimate the metal and material demand stemming from energy and transport sectoral targets to 2030 using knowledge of raw material usage in green technologies (Table 1.1; Figure 1). Different technologies occupy varying market share of the sectors, and each have a slightly different associated metal and material intensity. Research, innovation, and recycling occurring in these sectors will also impact the metal and material intensities and efficiencies associated with each technology. As such predictions of technology market share and increases in efficiencies, capacities, and metal intensities are analysed and included into the reported figures below. Such impacts include the replacement of REE dysprosium in permanent magnet motors, or the impact of capacity increases in wind turbines on structural and technology specific materials.

Realisation of targets, particularly for the energy sector, includes generating capacity already in existence, which reduces the total outstanding capacity or shortfall. Some existing capacity will however reach the expected end of life prior to 2030, it is assumed that this will be replaced or repowered and is included in the calculations as such. In addition to energy generators there will also be a need for export of energy, energy storage and a grid network capable of integrating non-synchronous energy generation. Raw material demands arising from wind farm cabling, grid scale batteries, green hydrogen production, and grid upgrades have also been considered here to provide a more complete picture of raw material demand.

Uncertainty is inherent in the predictions of market share of different technologies, and associated material intensities. In order to reflect this in the calculations a range of values have been used reflecting potential outcomes and technology prevalence. The Low, Medium, and High demand scenarios are used for energy sector calculations, while in the transport sector analysis the scenarios reflect a range of conservative to innovative outlooks.

Cumulative Demand (t)	
Concrete	3,902,488.0
Steel	1,665,485.2
Polymers	62,252.0
Plastic	83,453.5
Glass/carbon comps	71,555.3
Aluminium (Al)	55,018.8
Boron (B)	48.2
Chromium (Cr)	6,318.0
Copper (Cu)	68,379.8
Cobalt (Co)	7,612.5
Dysprosium (Dy)	219.8
Iron (cast)(Fe)	241,665.0
Manganese (Mn)	19,057.1
Molybdenum (Mo)	1,314.0
Neodymium (Nd)	1,427.3
Nickel (Ni)	28,597.8
Praseodymium (Pr)	300.8
Terbium (Tb)	39.0
Zinc (Zn)	67,100.0
Silica (Si)	4,927.4
Silver (Ag)	24.6
Germanium (Ge)	0.2
Cadmium (Cd)	1.9
Tellurium (Te)	2.0
Indium (In)	0.5
Gallium (Ga)	0.1
Selenium (Se)	1.0
Graphite	41,967.7
Lithium (Li)	5,170.2
Platinum (Pt)	0.5
Iridium (Ir)	0.8

Table 1.1 Cumulative metal and material demand stemming from decarbonisation of the energy and transport sectors as set out in the Climate Action Plan.

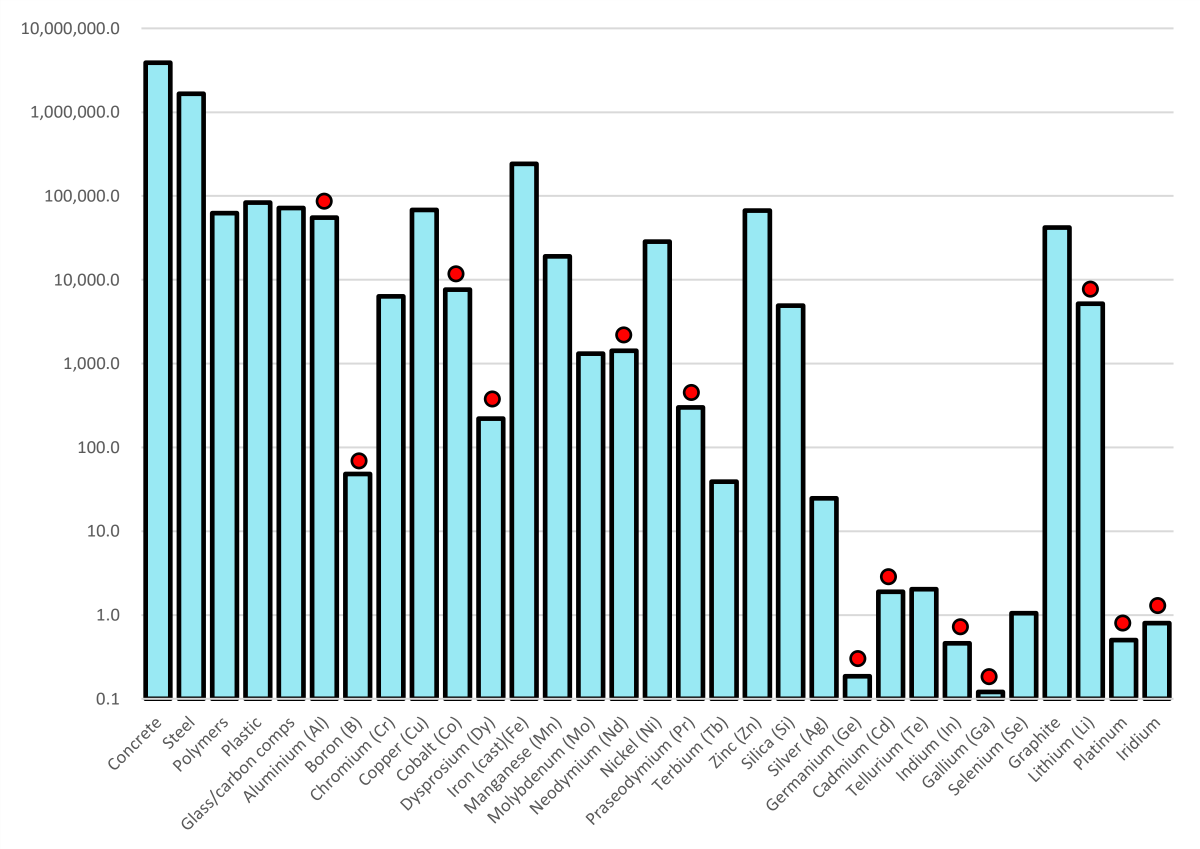


Figure 1.1 Total metal and material demand arising from decarbonisation of energy and transport sectors, inclusive of storage and grid upgrades. Note y-axis is logarithmic, red dots denote EU critical raw material.

Intense research and testing in the sectors of energy and transport make prediction and calculations beyond 2030 to 2050 difficult and attempts at such are highly speculative. Complete decarbonisation of society is reliant on further technological breakthroughs currently in early development or testing phases. Technologies in each sector of interest with the greatest potential are discussed below, but their material intensities are largely unknown, making metal and material demand difficult, if not impossible, to predict. Using current technology and information available an attempt has been made to provide a maximum demand that could arise from wind generated electricity.

The analysis contextualises the total metal and material demand with global supply, using Ireland's population as a percentage of the global population to estimate an 'Irish allocation' of global metal and material supply (Fig. 2). This highlights the metals and materials that are of greatest concern as being critical in supply for an Irish context and includes REE and battery critical materials. Criticality analysis of green and critical raw materials from the EU and USA have also identified these and other metals and materials as being of strategic importance in the green transition and facing supply interruptions. The EU critical raw material analysis highlighted domestic production as key in realising climate action targets and avoiding supply disruption in green transition technologies. Currently Ireland supplies a significant amount of zinc, recently included on the critical raw material list in the USA Zinc is key in the production of galvanised steel, required particularly for wind turbines. Continuing and expanding production of zinc in Ireland has the potential to make the country's mineral sector of strategic importance in realisation of climate action targets in Europe. As well as zinc, potential exists for domestic Irish extraction of lithium, imperative in battery production, and germanium, gallium, and indium for use in solar panels as secondary yield from recycling existing mine waste. As such there is potential for Irish domestic production to supply and offset some of the demand that will be created by CAP 2021 targets for the energy and transport sectors.

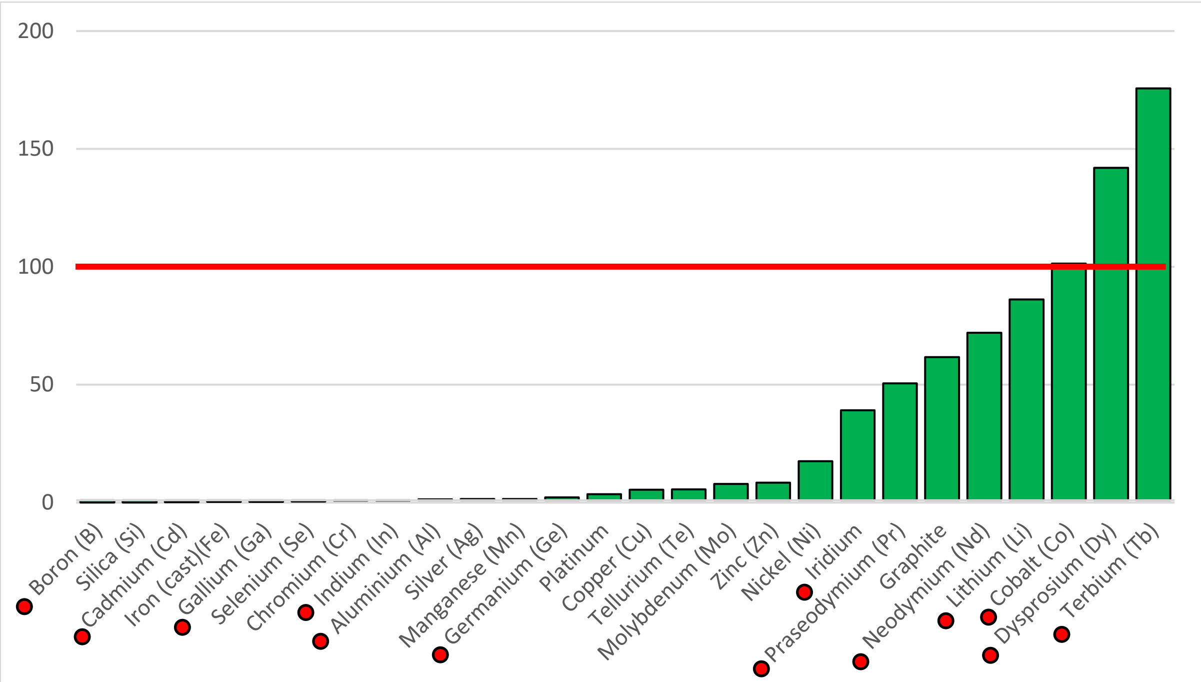


Figure 1.2 Demand arising from CAP targets in comparison to 'Irish allocation', see text for explanation. Red line indicates equal CAP demand and 'Irish allocation'. Red dots denote EU critical raw material.

2 Introduction / Scope

The Climate Action and Low Carbon Development (Amendment) Act 2021 commits the State to targets in 2030 and 2050 for reduction in greenhouse gas (GHG) emissions. These targets aim to prevent a global rise in temperature greater than 1.5°C. Ireland has targeted a reduction in GHG emissions of 51% by 2030 and to carbon neutrality by 2050 (CAP, 2021). Methods by which these targets will be achieved are outlined in the Climate Action Plan 2021 (CAP), National Development Plan 2030 (NDP); and Long-Term Strategy on Greenhouse Gas Emissions Reduction (2019).

Ireland's GHG emissions are estimated to be 57.7 million tonnes of carbon dioxide equivalent (Mt CO_2 eq). Energy production and transportation are two areas that have been targeted for de-carbonisation. In 2020 the transport sector represented 17.9% of all GHG emissions (approx. 10.3 Mt CO_2 eq) while the energy industries sector (primarily power generation) contributed 15% of emissions (approx. 8.7 Mt CO_2 eq; Figure 2.1). The transport sector has been the fastest growing source of GHG emissions with a 100% increase between 1990 and 2020 (CAP 2021; Figure 2.2). By 2030 Ireland aims to produce 80% of energy requirements through renewable means, predominantly wind and solar energy. Decarbonisation of the transport sector will also play a large role in meeting these targets with an increasing transition to battery electric vehicles, inclusive of passenger vehicles, commercial vehicles, and buses, taking the place of internal combustion engines (ICE).

This report explores the targets set out in the referenced reports with a focus on the metal and material demands that are required to meet targets for decarbonisation of energy production and transport. The report also explores the demands that arise from supporting infrastructure required for integration of renewable energy to the grid, and energy storage methods that are planned for Ireland. Criticality of the raw materials is highlighted throughout informed by the EU list of Critical Raw Materials (2020) and the USGS 2022 List of Critical Minerals. The demand that the CAP 2021 targets places on raw materials is then contextualised with current global demand and supply and how the demand could be offset with Irish domestic raw material production.

This analysis brings into sharp focus the level of raw material demand that will occur in response to Ireland's efforts to decarbonise energy and transport sectors. Highlighting the growing need for raw materials specific to established and emerging technologies. Current levels of raw material extraction in Ireland will meet some domestic and European demand growth but the field of research and innovation in mineral exploration is going through an exciting phase through which greater levels demand may be met. This topic is further explored below.

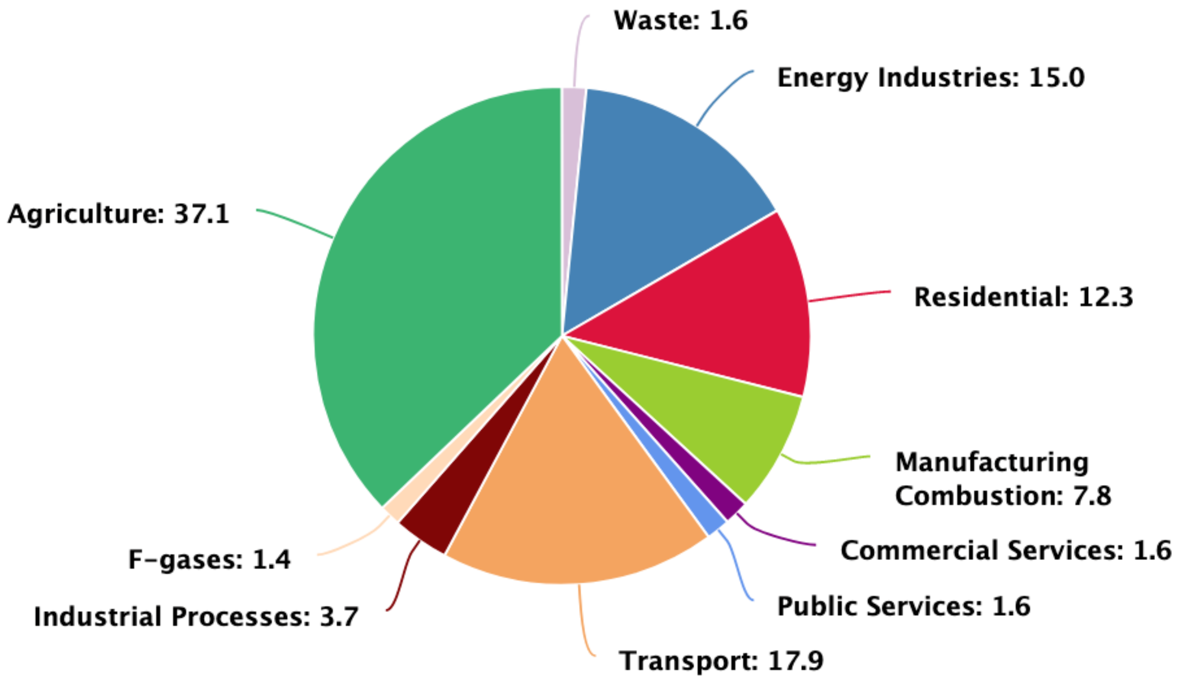


Figure 2.1 **Greenhouse gas emissions by sector in 2020 (epa.ie 2021)**

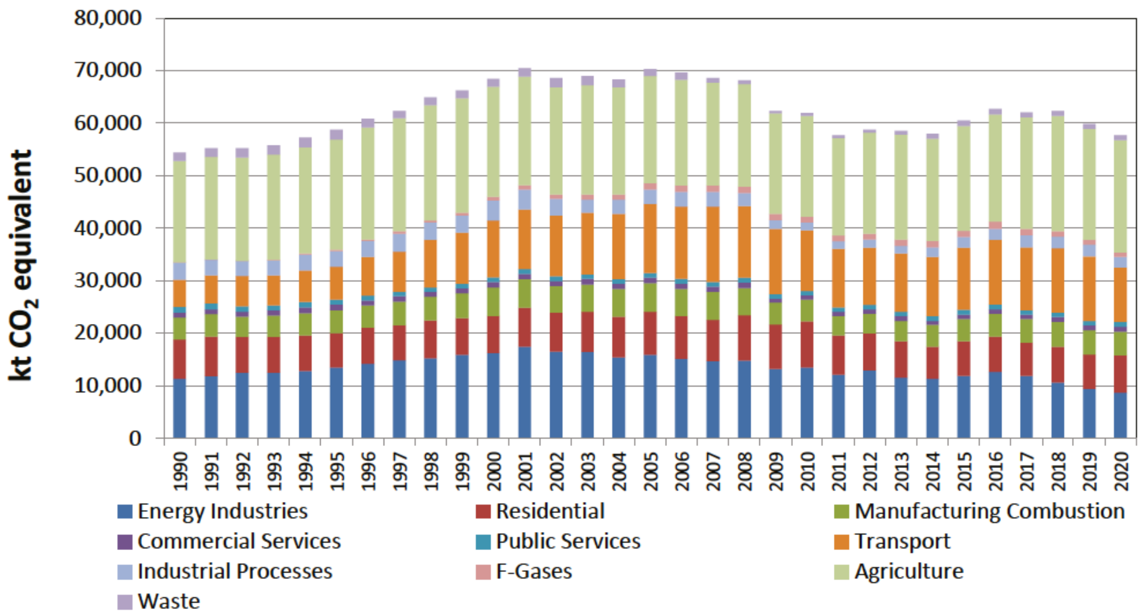


Figure 2.2 Ireland's CO_2 eq. Emissions Inventory 1990-2020 (CAP 2021 / epa.ie)

3 Explanatory notes

- Carbon dioxide equivalent (CO_2 eq.) measured in million tonnes is a metric measure used to compare the emissions from various greenhouse gases based on their global warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential (Knowledge for Policy, 2022).
- The Climate Action Plan 2021 emission reduction percentages for 2030 are as compared to emissions in 2018 – for this reason the 2018 emission levels are provided for reference as well as the most recent available emission levels (2020).
- Capacity is the maximum output of electricity a generator can output and for renewable energy sources is measured in Megawatts (MW), or Gigawatts (GW; MW x 1000). The output from a generator (wind turbine/solar panel) is the potential electricity generation at the perfect conditions for that generator.
- Electricity generation refers to the amount of electricity that is produced over a specific period. This is measured in kilowatt hours (KWh), megawatt hours (MWh), or gigawatt hours (GWh). This unit considers that not all generation of sources are always operating at their maximum capacity, such as periods with low wind or little sunshine.
- Solar power is defined as either photovoltaic (PV) or thermal. Photovoltaic refers to electricity production and is the facet of solar energy that this report elaborates on. Solar thermal produces hot water.
- Critical Raw Materials (CRMs) are those raw materials which are economically and strategically important for the European economy, but which have a high risk associated with their supply. Used in environmental technologies, consumer electronics, health, steelmaking, defence, space exploration, and aviation, these materials are not only 'critical' for key industry sectors and future applications, but also for the sustainable functioning of the European economy.

  It is important to note that these materials are not classified as 'critical' because these materials are considered scarce, rather they are classified as 'critical' because:
    - They have a significant economic importance for key sectors in the European economy, such as consumer electronics, environmental technologies, automotive, aerospace, defence, health, and steel.
    - They have a high supply risk due to the very high import dependence and high level of concentration of set critical raw materials in particular countries

    - There is a lack of (viable) substitutes, due to the unique and reliable properties of these materials for existing, as well as future applications
- Evaluation of metal and material demands for the decarbonisation of transport by electrification of vehicles encompasses the demand that will arise from electric car components (battery and electric motor) and does not include the use of metals that would otherwise be common to both internal combustion and electric vehicles, i.e., car frame or shell.

4 Climate Action Plan (2021) Targets

4.1 Targets for the Energy Industry

Electricity derived emissions in Ireland in 2018 equated to 10.5 Mt CO_2 eq. which was 17% of total GHG emissions. There is an established decrease in GHG emissions from the energy industries sector, with a decrease of 7.9% from 2019 to 2020, and a decrease in emissions overall from 1990 to 2020 of 21.2%, despite an increase in electricity consumption of 139.5% (EPA). The decrease reflects the improvement in efficiency of modern gas-fired power plants replacing older peat and oil-fired plants and the increased share of renewable, primarily wind power along with increased interconnectivity (EPA, 2021). Existing measures are believed able to reduce electricity emissions to 4-5 Mt CO_2 eq. by 2030. More ambitious targets have been set, however, to reach emissions of ~3 Mt CO_2 eq. (CAP, 2021; Gov.ie, 2022). Decarbonising the electricity sector will also enable further emissions reductions that equate to 6 Mt CO_2 eq. in the business, residential, and transport sectors. This can be achieved by significantly expanding electricity output to meet additional demand from the electrification of heat in business and buildings, and of transport vehicles.

An expansion of renewable energy generation, by wind (onshore and offshore) and solar PV energy, is planned to meet the emission targets for 2030. Table 4.1 details the targets for renewable energy share and capacity from respective technologies. The targets for offshore wind and solar PV reflect the most recent increase in targets announced in July 2022. This announcement targets a reduction of emissions by 75% and realising a sectoral emissions ceiling of 3 $MtCO_2eq$ for the electricity sector (Table 4.1).

Key Metrics	KPI 2030	Additional abatement Impact, $MtCO_2$ eq.
Share of Renewable Electricity (%)	Up to 80	6-8
Indicative Onshore Wind Capacity, GW	Up to 8	
Indicative Offshore Wind Capacity, GW	At least 7	
Indicative Solar PV Capacity, GW	5.5	

Table 4.1 Metrics from CAP 2021 to deliver further abatement in electricity and amended to reflect sectoral emission target announcements (July 2022).

Considerable onshore wind generation capacity exists in Ireland reducing the amount of new capacity required to meet 2030 targets. Some of the existing capacity will however require replacing or repowering prior to 2030. How this impacts the additional capacity required for onshore wind is explored in further detail in Section 5.1. Offshore wind generation capacity existing in Ireland is on a much smaller scale than that onshore, and will also require repowering prior to 2030, this is further explained in Section 5.1. Similarly solar electricity generation capacity also already exists in Ireland which will impact the level of further capacity required (Section 6.1).

Included in CAP 2021 targets for generation of electricity by renewable means is the discussion of supporting infrastructure as well as grid upgrades that are required to accommodate the integration of new and non-synchronous power generation technologies. The analysis of necessary grid upgrades is to be undertaken by ESB Networks and EirGrid. Analysis of the material intensities that may arise because of these upgrades associated with wind and solar farms is included in this report in Section 9.

4.2 Targets for Transportation

Historic transport emissions peaked in 2007 (14.4 Mt CO_2 eq.) and fell to 10.9 Mt CO_2 eq. in 2012 before rising again to 2018. Transport in Ireland accounted for 19.6% of all GHG emissions in 2018, equating to 12.2 Mt CO_2 eq. This reduced to 17.9% in 2020, of this road transport is responsible for 96% of transport related GHG emissions. The fluctuations in emissions through time were impacted by the economic downturn, vehicle fuel efficiency because of changes to the vehicle registration tax, the increase in biofuel use, significant decrease in fuel tourism, and the COVID-19 pandemic in recent years. The impact of electric vehicles is still low given the low number in the vehicle fleet (EPA, 2020). The Climate Action Plan (2021) has targeted electrification of the national fleet to achieve emission targets of 6-7 Mt CO_2 eq. by 2030 (CAP, 2021).

Measures to meet this reduction in GHG emissions associated with transport include an increase in battery electric vehicles, electric vans and electric buses. How each of these measures are projected to contribute emission reductions is detailed in Table 4.2. (CAP, 2021).

Key Metrics	2030 (Based on CAP 2021)	Additional Abatement Impact, $MtCO_2$ eq.
Electrification of Passenger Cars	845,000 with a focus on BEVs	c. 2.7
Transition to Low Emission Vans	95,000 with a stronger focus on BEVs	c. 0.2
Electrify Mass Transportation	1,500 EV buses	c. 0.3
Improved HGV Technology	3,500 low emission HGVs	c. 0.3

Table 4.2 Potential Metrics to Deliver Further Abatement in Transport

Other measures include: Greater use of public transport and a reduction in ICE car kilometres; and an increased biofuel blend rate. As these are targets that will not impact raw material demand, they are not included in any further detail within this report.

The CAP focuses on Battery electric vehicles (BEVs) to achieve targets, as opposed to hybrid electric vehicles (HEV) and plugin hybrid vehicles (PHEV). This is an important classification as material demands differ based on type of electric car. Material and metal demand arising from decarbonisation of the transport sector is analysed and detailed in Section 6.

5 Wind Generated Energy

This section details the shortfall in wind farm capacity that must be made up by 2030 to reach targets and will introduce the main trends in technologies used onshore and offshore as well as the metal and material demand scenarios that will arise by 2030 as a result.

5.1 Calculating the wind power generation shortfall

The targeted total capacity for wind generated energy in Ireland by 2030 is 15 GW. This will be made up of 8 GW of onshore wind and 7 GW of offshore wind. The current level of installed capacity onshore and offshore, and the shortfall that must be made up between now and 2030 is detailed in Table 5.1. Included in the shortfall is a sizeable proportion of current wind turbines that will reach the end of their design lifetime by 2030. Wind turbines are designed to withstand operational and environmental loading for a specified design lifetime with an appropriate safety level (Ziegler *et al.*, 2018). This lifetime is in the region of 20 -25 years (Ziegler *et al.*, 2018; WEI, 2019). By 2030 almost 35% of the existing installed capacity will exceed 20 years of service (EirGrid, 2019), this includes all the current offshore capacity in the Arklow Bank Wind Farm, which was constructed in 2003/2004 (SSE Renewables, 2022). The repowering or new replacement of these wind farms is presumed for the purposes of the report and the reaching of targets. The Renewable Energy Support Scheme (RESS) auctions have thus far offered 0.48 GW (RESS auction 1) and 0.414 GW (RESS auction 2) in onshore capacity.

	Onshore	Offshore
CAP Target	8 GW	7 GW
Existing Capacity	-4.2838 GW (WEI, 2021)	-0.0252 GW (SSE renewables)
Difference	3.716 GW	6.9748 GW
Replacement / Repowering	+1.4828 GW	+0.0252 GW
Shortfall	**5.2 GW**	**7 GW**

Table 5.1 Capacity shortfall required to meet 2030 targets*.

***Calculations explained:**

Existing capacity = Onshore + Offshore

4.309 (WEI, 2021) = 4.2838 + 0.0252 (SSE renewables, 2022)

All replacement required by 2030 = 35% of Existing Capacity (EirGrid, 2019)

Replacement required = (4.309 GW x 0.35)

Replacement required = 1.508 GW

Onshore replacement = 1.508 – Offshore*

Onshore replacement = 1.508 – 0.0252 = 1.4828

Additional capacity required to meet 2030 targets:

Onshore = CAP Target – Existing capacity + Onshore replacement

Onshore = 5.2 GW

Offshore = CAP Target – Existing Capacity + Offshore replacement

Offshore = 7 GW

*All current offshore capacity will reach end of life by 2030

5.2 Wind Turbine technology

Wind turbine technology is advancing at a rapid pace, with increases in capacity occurring all the time. Since 2015, in Europe, turbine capacities have grown at a constant 16% rate (Wind Europe, 2021). Average European onshore installed capacity was 4 MW in 2021, whereas offshore turbine installations had an average capacity of 8.5 MW with the largest being 9.3 MW (Wind Europe, 2022).

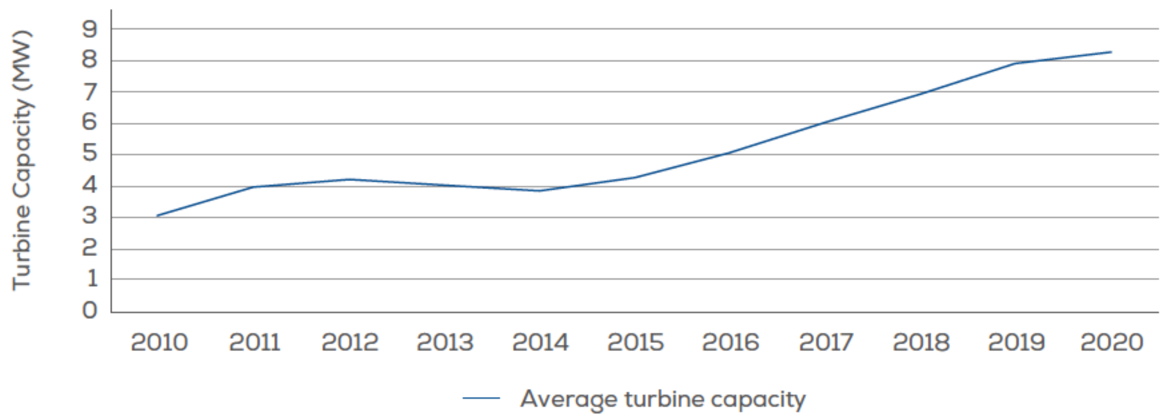


Figure 5.1 Average offshore turbine capacity growth in Europe from 2010, which grew again to 8.5 MW in 2021 (Wind Europe, 2021; 2022)

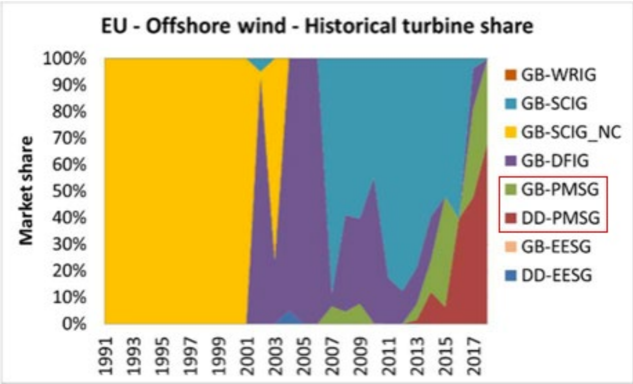
A wind turbine is composed of the tower, rotor blades and nacelle (Vestas, 2017). The nacelle contains many of the electrical and mechanical components, including the main shaft, gearbox, generator, and control system (Carrara *et al.*, 2020). There are two main technical designs of wind turbines: direct drive (electrically excited or high content permanent magnet (PM) using a synchronous generator); and gearbox which has electromagnetic or low share permanent magnet generator. Blades and generator rotate at the same speed in a direct drive configuration whereas a gearbox makes the generator rotate faster than the blades and enables lighter magnets to be used (Manberger and Stanqvist, 2018).

There are advantages and disadvantages to different technologies which make them better suited to different settings, whether onshore or offshore. For example, although reducing the required rare earths in a permanent magnet, a gearbox is heavy, requires maintenance, and efficiency is reduced by up to 15% (Habib and Wenzel, 2016) and is therefore less competitive in larger plants and offshore. Direct drive configurations can generate electricity at much lower speeds and do not require a gearbox and can be coupled with permanent magnet or electrically excited generators (Carrara *et al.*, 2020).

It is important to understand the different technologies in use, and the proportion of the market share that each occupies both currently and into the future, as different technologies differ in their material intensities (Carrara *et al.*, 2020). The market share of different turbine technologies has evolved over time to be dominated by the combinations listed below. Today a mix of wind turbines is used to meet the various specific onshore and offshore conditions:

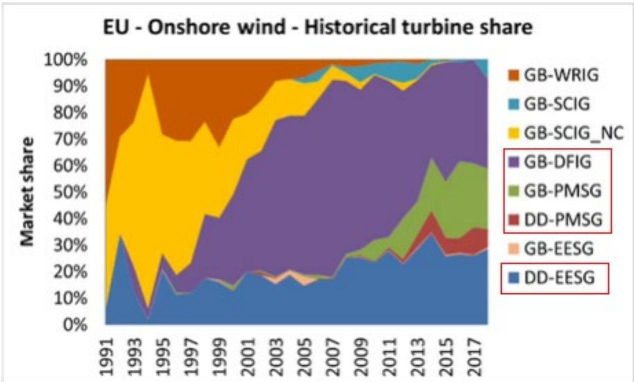
- DD-EESG – Direct drive electrically excited synchronous generator
- DD-PMSG – Direct drive permanent magnet synchronous generator
- GB-PMSG – Gearbox permanent magnet synchronous generator
- GB-DFIG – Gearbox double fed induction generator
- GB-SCIG – Gearbox squirrel cage induction generator

The evolution of turbine technology market share through time differs for onshore (Fig. 4.2) and offshore (Fig. 4.3) settings. The dominance of technologies with greatest longevity and reliability are preferred for offshore wind farms given the greater difficulty required for maintenance (World Bank, 2017). Turbines that involve a permanent magnet have become the preferred option for offshore installations whereas a mix of permanent magnet and electromagnetic generators exists in onshore installations.



Turbine technology	Market Share (2018)
GB-DFIG	35%
GB-PMSG	20%
DD-PMSG	10%
DD-EESG	30%
GB-SCIG	~5%

Figure 5.2 Wind turbine market share for European onshore wind turbines (Carrara et al., 2020)



Turbine technology	Market Share (2018)
GB-PMSG	40%
DD-PMSG	60%

Figure 5.3 Wind turbine market share for European offshore wind turbines (Carrara *et al.,* 2020)

This information provides a good understanding of the current turbine technology market share mix but considering rapid technological advances it is important to understand future trends and how these may impact material intensities and demand to 2030.

Predicting the future of wind turbine technology trends has been considered by Manberger and Stanqvist (2018); and Carrara *et al.* (2020). While future predictions of turbine technology are difficult and variable there are several points that most agree on, including:

- The use of permanent magnets is well suited to the offshore environment, despite their high expense and metal intensity (World Bank, 2017).
- Some scenarios aim to reduce use of permanent magnets, particularly in the onshore environment, as a method to circumvent supply risk driven by Chinese export restrictions (World Bank, 2017).
- The increasing size and capacity of offshore wind turbines will result in reduced use of most conventional generators that do not need permanent magnets (DD-EESG / GB-DFIG) which although successful onshore, are unsuitable for offshore installations in future scenarios

because of their considerable weight (Rabe *et al.*, 2017; Centre for Sustainable Energy, 2017).

The estimates made by Carrara *et al.* (2020) for the Joint Research Centre (JRC) of the European Commission have been adopted here for future EU market share of wind turbines. Their estimates also reflect a range of scenarios termed the Low, Medium, and High demand scenarios. These scenarios have been adopted in this report to explore a range of potential metal demand scenarios in future. The methodology behind these scenarios is as follows (Carrara *et al.*, 2020)

Low Demand Scenario (LDS): Extrapolation based on historical time series (focusing on the period post 2000) with an uptake of offshore High Temperature Superconductor (HTS) generator (after 2030).

Medium Demand Scenario (MDS): Extrapolation based on historical time series (same period as above) modified to accommodate a higher penetration of generators with permanent magnets (notably direct drive) in the offshore sector and, to a lesser extent, in the onshore sector.

High Demand Scenario (HDS): For the offshore, mixes of sub-technologies in future energy scenarios are assumed to substantially mimics today's average values at global level. For the onshore, technology replacement rates are based on historical time series (same as above) modified to accommodate a higher deployment of turbines with permanent magnets (again, notably direct drive).

Onshore Market Share Prediction (Carrara *et al.*, 2020)				
	DD-EESG	**DD-PMSG**	**GB-PMSG**	**GB-DFIG/SCIG**
LDS				
2018	0.3	0.1	0.2	0.4
2024	0.3	0.1	0.25	0.35
2030	0.3	0.1	0.3	0.3
MDS				
2018	0.3	0.1	0.2	0.4
2024	0.3	0.1	0.25	0.35
2030	0.3	0.15	0.3	0.25
HDS				
2018	0.3	0.1	0.2	0.4
2024	0.28	0.13	0.27	0.32
2030	0.25	0.20	0.3	0.25

Table 5.2 Market share of European onshore wind turbine technology between 2018 and 2030 as predicted by Carrara *et al.* (2020) and used in calculations in this report.

Offshore Market Share Prediction (Carrara *et al.*, 2020)			
	GB-PMSG	**DD-PMSG**	**GB-SCIG**
LDS			
2018	0.3	0.1	0.2
2024	0.2	0.55	0.25
2030	0.15	0.35	0.5
MDS			
2018	0.4	0.6	
2024	0.2	0.65	0.15
2030	0.1	0.6	0.3
HDS			
2018	0.4	0.6	
2024	0.15	0.8	0.05
2030	0.1	0.85	0.05

Table 5.3 Market share of European offshore wind turbine technology between 2018 and 2030 as predicted by Carrara *et al.* (2020) and used in calculations in this report.

The major wind turbine suppliers to the European market (Vesta; Siemens Gamesa; and GE) have released plans for future turbines as well as the expected technology that will be employed. The planned technology split employed by these turbine manufactures informed the predictions of Carrara *et al.* (2020) and thus lends confidence it the use of these predictions as accurate for future demand determining.

5.3 Wind Turbine Capacity

Most recent average European wind turbine capacity onshore is 4 MW and 8.5 MW offshore. Blagoeva *et al.* (2016) predicted onshore capacity of 4 MW in 2020 with an increase to 6 MW in 2025. This would agree with the wind farm planning that is currently submitted for Irish onshore wind farms, with most proposing wind turbines with 6 MW of power generation. Marginally greater capacity turbines are planned onshore by some manufacturers (6.6 MW Siemens Gamesa, 2022; 7.2 M Vesta, 2022). There are demonstrated trends in material usage variation as turbine capacity increases (Vestas 2014; 2018; Vestas LCA reports), the increase in size results in greater demand for structural components (steel & polymers) while higher energy production, owing to more resource-efficient turbine designs, results in a decreased demand for some materials. In the cases of glass/carbon composites and electronics, increasing turbine capacity has had the effect of reducing consumption (Table 5.4; Carrara *et al.*, 2020).

Turbine Capacity increase (MW)	Steel	Aluminium	Copper	Polymers	Glass/carbon composites
Onshore: 2	13%	-6%	-6%	13%	-30%
Offshore: 2.5	16%	-8%	-8%	16%	-38%

Table 5.4 Percentage of increase or decrease in material usage based on increases in turbine capacity.

Onshore wind turbine capacity of 4 MW is expected to increase to approx. 6 MW from ~2025. As a result, the impacts of increased capacity (~2 MW) will likely be reflected in the material intensity in meeting CAP targets. As the deployment of onshore wind farms is likely to accelerate in the later stages of the decade (2025 – 2030), it is assumed that 30% of the target capacity will be deployed before 2025 and the remaining 70% will be deployed between 2025 and 2030 (Table 5.5). Therefore 30% of the CAP target for onshore wind will be calculated as if the standard wind turbine capacity will be 4 MW (2022 – 2025) and the remaining 70% will be calculated inclusive of the impacts of increased wind turbine capacity (2025 – 2030).

For offshore wind turbines the expected increase in capacity is much greater than that seen onshore. Predictions of average increase in capacity from 8.5 to 11 MW (Blagoeva *et al.*, 2016) may now be conservative, reflecting the speed at which technological advances are occurring in this sector. Turbine manufacturers have released plans for offshore turbines with capacities 14-17 MW being operational by 2024 (Vesta, 2022; GE, 2022; Siemens Gamesa, 2022). These larger turbines with greater capacity may have been designed with mature offshore wind markets in mind, such as the UK where wind farms are being built further from shore and in deeper water. Uncertainty exists whether the largest turbines available in 2024 will be suitable for deployment in Irish waters as wind farms will be in shallower water closer to shore and accessibility to installation vessels potentially problematic. To reflect this uncertainty the calculations for wind turbine material intensity assumes an average turbine capacity of 11 MW deployed in Ireland, reflecting the presence of a mix of turbines ranging from 8 to 14 MW.

Given the current expected timeline from initiation of a project to operational offshore windfarm, it has been assumed here that all the offshore wind farms that will make up the offshore generation target will be deployed in the latter half of the decade, between 2025 and 2030 (Table 5.5). As a result, the material intensity for the entire offshore target will include changes in material demand reflecting increased turbine capacity.

	Offshore	Onshore	Offshore	Onshore
GW breakdown	%		GW	
2022-2025		30		1.55
2025-2030	100	70	7	3.65

Table 5.5 Split of wind generated electricity targets through time for onshore and offshore wind reflecting timing of wind farm deployment.

5.4 Wind turbine metal and material intensity

Availability of information on the material intensity of wind turbines has gradually increased in the last decade (Zimmermann *et al.*, 2013; Viebahn *et al.*, 2014; 2015; Manberger and Stanqvist, 2018; Shammugam *et al.*, 2019; Carrara *et al.*, 2020). As mentioned above the material intensity differs across the spectrum of wind turbine technologies with a notable increase in Rare Earth Elements (REE) required for those containing permanent magnets and a large increase in copper use required for Direct Drive generators, 2-3 times as much as gearbox configurations (Manberger and Stanqvist, 2018). Permanent magnet generators have gained popularity, especially in offshore turbines, as they allow for high power density and small size with the highest efficiency at all speeds, offering a high annual production with a low lifetime cost (Alves *et al.*, 2020). This is reflected in their greater market share across the three considered scenarios, particularly for the HDS scenario where 95% of offshore deployment by 2030 is expected to have permanent magnet generators.

Understanding metal and material intensity that will be generated by wind turbine deployment to meet CAP targets to 2030 requires consideration of several factors:

- Power capacity generation – The power capacity that is required to be supplied by onshore and offshore wind farms in Ireland is a defined figure as per the CAP (2021) and subsequent announces increases. This is discussed above and is cumulatively 15GW, inclusive of existing wind farms in Ireland.

- Plant lifetime – There is an expected lifetime of turbines. To meet the targets for wind power generation, wind farms meeting their expected end of life must be repowered to maintain the existing level of wind power generation. This has been factored into the calculations in this report (Sect. 4.1). The addition of the repowering capacity allows the provision of technological advances and material efficiencies (see below).

- Material intensity – A common trend is the increase in size and capacity of wind turbines, while the absolute consumption of raw materials will increase with the size of the equipment, this effect could be offset by higher energy production thanks to resource-efficient designs (Carrara *et al.*, 2020).

- Sub-technology designs – As mentioned above (Sect. 4.2) the material demands stemming from different sub-technologies differ, therefore the prediction of future market share of technologies is an important consideration in calculating future material intensities.

Material intensities are assessed in tonnes per Gigawatt (t/GW) – the amount of material "x" embedded per GW of installed capacity of technology" y". Table 5.6 indicates the material intensities that are used for this report, in t/GW, and are from several sources (Blagoeva *et al.*, 2016; Centre for Sustainable Energy, 2017; Pavel *et al.*, 2017; Manberger and Stanqvist, 2018; Carrara *et al.*, 2020)

	Material Intensity (t/GW)			
Material	**DD-EESG**	**DD-PMSG**	**GB-PMSG**	**GB-DFIG**
Concrete	369,000	243,000-413,000	243,000-413,000	355,000
Steel	132,000	119,500	107,000	113,000
Polymers	4,600	4,600	4,600	4,600
Glass/carbon comps	8,100	8,100	8,400	7,700
Aluminium (Al) C	700	500	1,600	1,400
Boron (B) C	0	6	1	0
Chromium (Cr)	525	525	580	470
Copper (Cu)	5,000	3,000	950	1,400
Dysprosium (Dy) C	6	17	6	2
Iron (cast)(Fe)	20,100	20,100	20,800	18,000
Manganese (Mn)	790	790	800	780
Molybdenum (Mo)	109	109	119	99
Neodymium (Nd) C	28	180	51	12
Nickel (Ni)	340	240	440	430
Praseodymium (Pr) C	9	35	4	0
Terbium (Tb) C	1	7	1	0
Zinc (Zn)	5,500	5,500	5,500	5,500

Table 5.6 Material intensity (t/GW) for wind turbine sub-technologies with critical raw materials highlighted (C).

The calculations of material intensity arising from CAP targets for wind generated electricity therefore encompass:

1. The market share of turbine technologies used onshore and offshore and how this is expected to change into the future – reflecting the Low, Mid, and High demand scenarios. (Table 5.2; Table 5.3).
2. The impact of changing material intensity reflecting expected increasing wind turbine rated capacity, onshore and offshore (Table 5.4)
3. The breakdown of when wind farms will likely be operational and producing energy towards CAP targets (Table 5.5).
4. The published material intensities for different wind turbine technologies (Table 5.6).

Using these factors, the following numbers in tonnes emerge for the metal and material intensities required to meet Ireland's CAP plans for wind generated electricity by 2030 (Table 5.7).

Material	LDS	MDS	HDS
Concrete	3,923,528	3,824,492	3,843,056
Steel	1,561,788	1,563,499	1,570,014
Polymers	62,143	62,252	62,360
Glass/carbon comps	72,409	72,403	71,968
Aluminium (Al) C	12,465	11,934	11,376
Boron (B) C	27	33	37
Chromium (Cr)	6,221	6,318	6,309
Copper (Cu)	24,507	24,958	25,534
Dysprosium (Dy) C	98	113	122
Iron (cast)(Fe)	235,514	238,473	238,611
Manganese (Mn)	9,605	9,622	9,620
Molybdenum (Mo)	1,296	1,314	1,312
Neodymium (Nd) C	940	1,106	1,209
Nickel (Ni)	4,392	4,246	4,123
Praseodymium (Pr) C	162	194	216
Terbium (Tb) C	32	39	43
Zinc (Zn)	67,100	67,100	67,100

Table 5.7 Material Intensity required to produce the required additional electricity generation from wind, reflecting scenarios described above with critical raw materials highlighted (C).

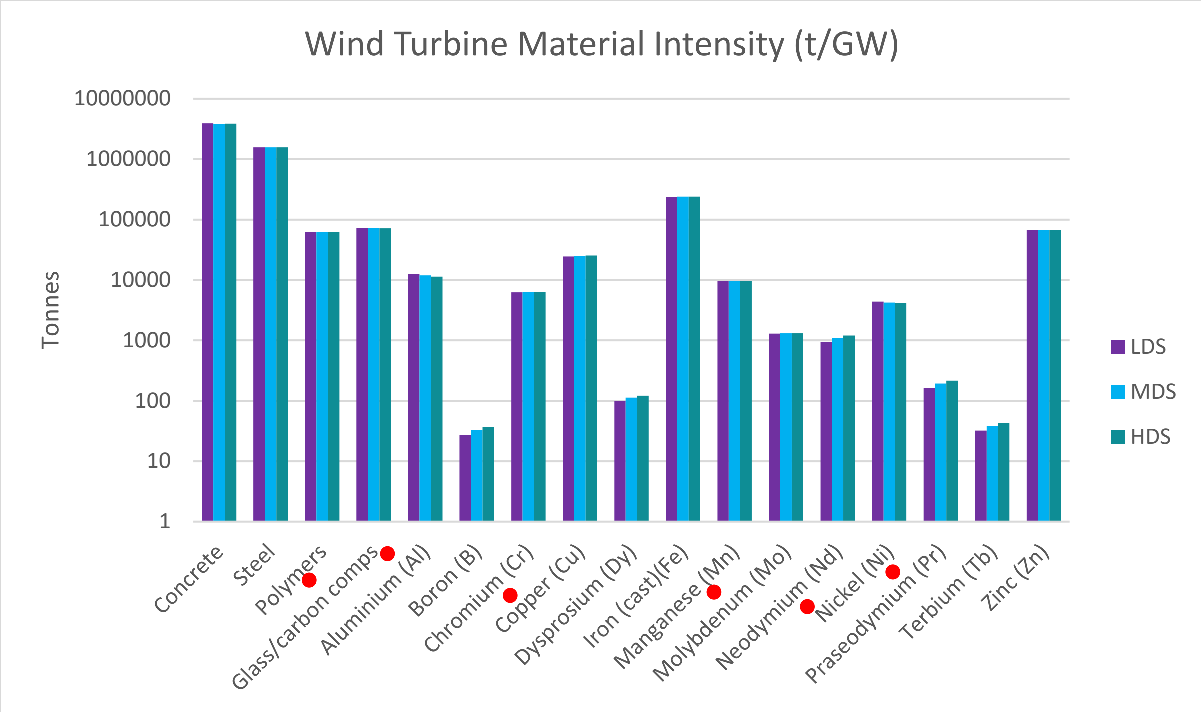


Figure 5.4 Material intensity resulting from additional electricity generation required by wind generation to meet CAP targets by 2030. Note Y-axis is a logarithmic scale. Critical raw materials highlighted by red dots.

The above calculations are related to just the turbines and do not consider other infrastructure related to wind farms such as cabling and substations. Considering that cabling can account for 20-30% of an offshore wind farm cost it represents a considerable component for inclusion. Major metal intensities arise from cabling as a result of the conductor used, copper or aluminium. The metal requirements that arise from cabling is further discussed in Section 7.

5.5 Offshore Wind Cabling

There are several different types of cables that are associated with wind farms:

- Array or feeder cables – cables that transmit low voltage from the turbines to the offshore substations. These cables commonly carry 33 kV but also 66 kV. It is expected as turbine capacity increases and the average total capacity of wind farms also increases, a higher voltage level of 66 kV is expected to be used in inter-array connections of new offshore wind projects (DNV, 2015). The length of this cable required depends on the number and capacity of turbines, the spacing between turbines, the layout of the wind farm, and the voltage of the cable. 66 kV inter-array cable may decrease the length required by up to 33% because of the increased power transportable by higher volt cable, potentially reducing the number of circuits required (DNV, 2015). This is strongly dependant on the wind farm layout however.

As the 33 and 66 kV cables commonly have the same diameter of conductor their use represents a considerable reduction potential in metal intensity.

- Export cables – higher voltage cables from the offshore substation, typically high voltage direct current (HVDC) or copper based high voltage alternating current (HVAC) transmission lines are used (Mokhi *et al.*, 2020).

A detailed assessment of wind farm layout optimisation combined with turbine output and cable voltage would be required to work out exact cable lengths and how they varied based on cable voltage, but this is outside the scope of the current report. A rough calculation has been completed in lieu of this, providing an estimate of offshore cable length that may be required for planned offshore wind farms and meet CAP targets. To ascertain this estimate, several factors were used that drew on information from planned offshore wind farms in Ireland (Oriel; Dublin Bay; Codling; Skerd; and North Irish Sea Array):

1. Turbine capacity of 11 MW used.
2. Average wind farm capacity – 570 MW
3. Average distance offshore – 11 km
4. Number of wind farms – 12.28
5. Number of turbines per wind farm - 52
6. Rotor diameter (Dr) – 200 m (Siemens Gamesa)
7. Turbine spacing (5*Dr) – 1,000 m

Using these factors, an estimate of inter-array cabling required is in the region of ~640 km, and export cable length of 135 km.

Typical 33 / 66kV wet-type cable for inter-array cabling should be three phase copper cable, with three strands of conductor (DNV, 2015). Each conductor strand typically has a diameter of 23 – 32 mm (Ergon factsheet, Prysmian factsheet). A median value of 28 mm is used in calculations. Three of these conductor strands results in a total diameter of conductor of 84 mm. Using this diameter, it is possible to determine the mass of copper or aluminium in 1 m of cable:

$$V = \pi r^2 h$$

- V = Volume (m^3)
- R = Radius
- H = height (1m)

The volume is then multiplied by the density of Copper (8940 kg/m^3) or aluminium (2710 kg/m^3) to yield the mass of conductor in each m of inter-array cable.

The metal requirement in 1 m of 33/66v cable with a total conductor diameter of 84 mm is 49.5 kg of copper or 15 kg of aluminium. It is assumed that using the 66kV cable with greater voltage can reduce the total length of cable required by 33% (see above).

The inter-array cables collect the output from the wind turbines and route it to a central substation location where the voltage can be stepped up for the efficient onward transmission of power to the land-based transmission system. The transmission to land is via high voltage cables, in this instance 220 kV as specified by EirGrid for submarine cables attaching wind farms greater than 5 km offshore (EirGrid Functional Specifications, 2020). Export cable core sizes are typically 1200 mm^2 (Corewind, 2020) which gives a total diameter of 117 mm and a volume in 1 m of cable of 0.0107 m^3. This results in conductor requirement of 96 kg of copper or 29 kg of aluminium in 1 m of export cable.

Inter-array Cabling			Export Cable	
Conductor	**Copper**	**Aluminium**	**Copper**	**Aluminium**
Kg/m	49.5	15	96	29
Cable distance estimate (m)	638,560	638,560	135,080	135,080
Conductor Demands (t)				
33kV Cable (t)	31,609	9,578		
66kV Cable (t)	20,861	6,322		
220 kV Cable (t)			12,967	3,917

Table 5.8 Estimate of metal demand arising from offshore cabling using input factors defined above.

The use of 11 MW turbines were used in these calculations. The use of lower or higher capacity turbines will impact the cabling demands as rotor diameter, spacing between turbines, and the number of turbines required changes. At lower capacities lower spacing but greater numbers of turbines are required and with higher capacity turbines spacing increases but the number of turbines required decreases. Fig. 4.5 presents a rough estimate on cable metal requirements factoring in turbine capacity, spacing, and number of turbines. A reduction in cabling metal requirements is seen as the turbine capacity changes. This indicates that the increased capacity of turbines reduces the intensity of each turbine as well as also reduces material intensity of supporting infrastructure.

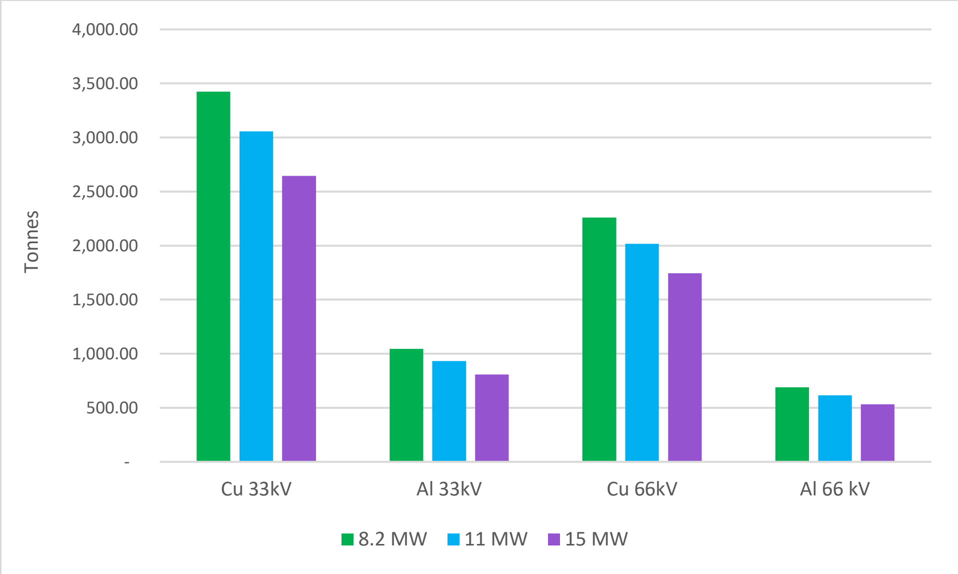


Figure 5.5 Impact of wind turbine capacity on inter-array cabling metal requirements. These figures are based on one offshore wind farm with total capacity of 0.57 MW.

The figures above (Table 5.8) represent scenarios where the entire demand is met by one cable and conductor type i.e., 33kV copper cable or 66 kV aluminium cable. It is more likely that a mix of cable types and conductors will be used. To reflect this in final calculations a mix has been used with an even split of the four different inter-array options and the two export cable options (Fig. 4.6).

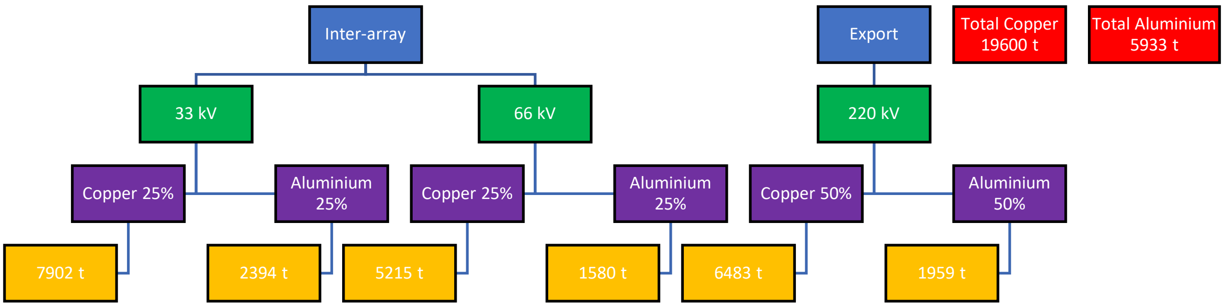


Figure 5.6 Breakdown of cable conductor type for material demand calculations.

Conductor Material	Turbine Demand (t)	Cable Demand (t)	Total (t)	Cable Demand as % of Total
Aluminium (Al)	11,934	5,933	17,867	50 %
Copper (Cu)	24,958	19,507	44,465	78 %

Table 5.9 Demand for aluminium and copper for turbines and cabling.

5.6 Considerations and potential demand alterations.

There are several factors that may come to fruition prior to major wind farm deployment in Ireland that will make up the power generation shortfall, these factors may alter the landscape of turbine technology market share in the coming years or impact the level of material and metal demand that will arise. These factors include: (1) Supply and demand issues; (2) Emergence of new technologies; and (3) The impact of recycling of material. Supply and demand are discussed in later sections (Section 9) as it is a common theme across the spectrum of renewable energy generation methods and electrification of vehicles. The advancement of technology specific to wind generated power, and potential impact of turbine recycling is discussed here.

5.6.1 Technological advances and material substitutions

There are numerous trends in wind turbine materials that at present are hampered by cost and are not expected to penetrate the market until cost reductions occur, this includes greater use of lightweight materials including high strength steel and carbon fibre. With increased usage of carbon fibre of 0.5% could result in a proportional reduction in the use of glass fibre of 3.5% in 2030 (McKinsey, 2012).

Wind turbine manufacturers have significantly reduced or removed the use of dysprosium in their permanent magnets due to the price volatility and supply chain risk associated with the rare earth element (REE) (Wind Power Monthly, 2021). The reduction or removal is balanced by a proportionate increase in neodymium, which is significantly less costly (Carrara *et al.*, 2020). The removal of permanent magnets in the offshore wind turbines would result in dramatically reduced demand on REE, but is currently not feasible, although attempts have been made, replacements result in less efficient turbines. The use of aluminium in place of copper is also a possibility. Selective incorporation of aluminium into certain turbine components can reduce copper usage significantly (BBF Associates Kundig, 2011). The replacement of copper with aluminium to presents some challenges, however, due to lower strength, relaxation behaviour and corrosion resistance (BBF Associates and Kundig, 2011). Replacements and substitutions as well as their predicted occurrences generally target cost saving and as such are highly reliant on raw material prices, which is volatile and difficult to predict.

5.6.2 Material available for recycling

The current capacity of wind turbines that will reach their end of life by 2030 is ~1.5 GW. Repowering of a wind farm involves the complete dismantling and replacement of turbine equipment at the wind farm, with existing infrastructure on site being reused where possible. The number and layout of turbines will usually change, and the foundations will most likely need to be replaced (WEI, 2019). Repowering has the benefit of using existing locations and infrastructure as well as the use of modern turbines, potentially reducing the number required in the same location.

Using the material intensities from above (Table 5.6) and the likely turbine types deployed onshore between 2005 and 2010, it is possible to estimate the material that makes up the turbines that are nearing their end of life.

Material	Material intensity (t)
Concrete	535,650
Steel	173,775
Polymers	6,900
Glass/carbon comps	11,640
Aluminium (Al) C	1,942.5
Boron (B) C	0
Chromium (Cr)	717.375
Copper (Cu)	2910
Dysprosium (Dy) C	3.9
Iron (cast)(Fe)	27,472.5
Manganese (Mn)	1,172.25
Molybdenum (Mo)	150.75
Neodymium (Nd) C	21.6
Nickel (Ni)	624.75
Praseodymium (Pr) C	2.025
Terbium (Tb) C	0.225
Zinc (Zn)	8,250

Table 5.10 Material composing turbines in Ireland that will reach their end of life by 2030.

Theoretically this material is available for recycling and potential reuse, but the technology and economic benefit is currently not in place to facilitate large scale recycling of most of the turbine materials. Recycling research thus far for REE in permanent magnets has produced few breakthroughs, as reclamation of dysprosium and neodymium is extremely complex (Rabe *et al.*, 2016). Considering the largescale deployment of wind turbines that employed permanent magnets did not occur until after 2010 and the expected life of wind turbines being 20 – 25 years, the availability of REE for recycling will occur after 2030 and will increase significantly from then.

Currently there are no industrial recycling plants for permanent magnets, but there are pilot plants assessing a range of recycling processes (Khakmardan and Schmitt, 2020). Other components are currently recycled to a large extent, particularly copper and nickel. Copper is used in its metallic form in copper alloys, thus nearly all copper products can be recycled repeatedly without loss in product properties. European average of copper demand supplied by copper recycling was 17% between 2008-2017 (European Commission, 2020) implying that the full amount of copper recovered from end-of-life turbines could be used to offset the demands of turbine deployment to 2030. There are several enterprises in the EU for recycling nickel which can be recycled without loss of quality and sourced as secondary raw material to be used in many of its applications (Nickel Institute, 2018; EU Commission, 2020). Recycling efficiency of nickel is estimated to be around 68% (EU Commission, 2020). For the majority of components however with the current recycling status of wind turbine materials, the level of demand arising is not expected to be offset to any large extent by recycling of most components from wind farms reaching end of life prior to 2030.

6 Solar PV

This section will introduce the current landscape of solar PV technology, how this may change between now and 2030, and the raw material demand that will arise to meet the Climate Action Plan targets for Solar PV. The target for solar generated electricity in the CAP is between 1.5 and 2.5 GW. In late July 2022, however, an increased target of 5.5 GW was announced for electricity generation by Solar PV.

6.1 Current Shortfall in Solar PV

At the end of 2019 there was an installed capacity of solar PV of 0.706 GW (SEAI, 2020). It is estimated that by end 2022 the installed capacity will reach 1.5 GW (Energy Ireland, 2019). In the Renewable Energy Support Scheme (RESS) auction, solar secured 0.796 GW of generation capacity (EirGrid, 2020) which is due for installation by end 2022. The second auction held under the Renewable Energy Support Scheme (RESS2) announced results in May 2022. In these auction results 66 solar PV energy projects were successful adding an additional 1.534 GW of energy. With delivery of these projects Ireland will have installed solar PV capacity of approx. 3 GW.

For the purpose of this report the shortfall is based on the installed capacity reported for the end of 2019 (0.706 GW) prior to publication of 2021 CAP targets and subsequent updates. Calculations below indicate the metal and material demand required to achieve the most recently published target of 5.5 GW of solar PV capacity. The capacity shortfall is thus 4.4794 GW.

6.2 Solar PV Technology

There are 4 main technologies commercially available for solar PV, each of which has a different material intensity and market share:

- Crystalline silica (c-Si) is the most popular choice for solar panels and currently occupies the dominant share of the market which has remained constant at 95.4% (Manberger and Stanqvist, 2017; Carrara *et al.*, 2020; Fraunhofer, 2021).
- Amorphous Silica (a-Si) - 0.3% of the market share.
- Cadmium Telluride (CdTe) - 2.4% of market share.
- Copper Indium Gallium Diselenide (CIGS) – 1.9% market share.

A-Si, c-Si, and CdTe are grouped into a category termed Thin Film technology. Material intensities for the different solar panel technologies are detailed below. There are common materials across all technologies (Table 6.1) and technology specific materials (Table 6.2). Copper demand appears in the general electric system as well as appearing in the material intensities for CIGS panels. The demand arising for copper from general electrical use is far greater than that in the technology specific intensity list. It is important to note that technology is still recent, so it is difficult to determine the precise composition of panels (Carrara *et al.*, 2020). The figures for material intensities have been obtained from several published sources (Moss *et al.*, 2013; Fizaine *et al.*, 2015; Viebahn *et al.*, 2015; Manberger and Stanqvist, 2017; Carrara *et al.*, 2020). There are a range of estimates for cadmium, tellurium, copper, indium, selenium, and gallium (Table 6.2). These values reflect the potential scenarios of future technology market share reflecting the Low, Mid and High demand scenarios used previously for material intensity predictions. The predictions vary based on differing levels of market penetration by Thin Film technology, which contain greater proportions of critical raw materials. Higher demand for critical raw materials occurs with greater market share occupancy by Thin Film technologies, specifically CdTe and CIGS (Carrara *et al.*, 2020).

Technological advances are expected to alter the material intensities in the near future, most notably in the crystalline silicon solar PV panels, where the thickness is expected to decrease corresponding to silicon demand reducing progressively from 4,000 t/GW to 2,000 t/GW by 2030 (Carrara *et al.*, 2020). This progressive decrease in silicon demand is factored into the calculations by estimating the decrease to 3,000 t/GW by 2025 and again to 2,000 t/GW from 2028 onward. The addition of capacity to meet demand is presumed spread evenly across the remaining years to 2030.

General structural and electric materials common to all PV technology	
Material	**t/MW**
Concrete	60.7
Steel	67.9
Plastic	8.6
Glass	46.4
Aluminium (Al) C	7.5
Copper (Cu)	4.6

Table 6.1 Common material intensities to all solar panel technologies.

Material intensity (t/GW)								
	c-Si	a-Si	CdTe			CIGS		
			LDS	MDS	HDS	LDS	MDS	HDS
Silica (Si)	2,000-4,000	150						
Silver (Ag)	20							
Germanium (Ge) C		48						
Cadmium (Cd)			35	50	85			
Tellurium (Te)			35	52	95			
Copper (Cu)						20	22	24
Indium (In) C						10	15	27
Gallium (Ga) C						3	4	7
Selenium (Se)						22	35	60

Table 6.2 Technology specific material intensities.

6.3 Solar PV - Metal and Material Demand

The metal and material demand that arises from increasing the generation capacity in Ireland by 4.794 GW to 5.5 GW is detailed below. The structural and electrical elements that are required are shown below (Table 6.3; Figure 5.1). The technology specific material and metals differ in their projected demand as discussed above and a range of potential levels of demand are presented as a result. Table 6.4 and Figure 5.2 display the material demands that will arise to meet the target of 5.5 GW.

Material	Additional 4.794 GW (t)
Concrete	290,995.8
Steel	325,512.6
Plastic	41,228.4
Glass	222,441.6
Aluminium (Al) C	35,955
Copper (Cu)	22,052.4

Table 6.3 Material intensity (t/MW) and absolute values of material required to meet Climate Action Plan targets - Target of 1.5 GW requiring additional 0.794 GW; and target of 2.5 GW requiring additional capacity of 1.794 GW.

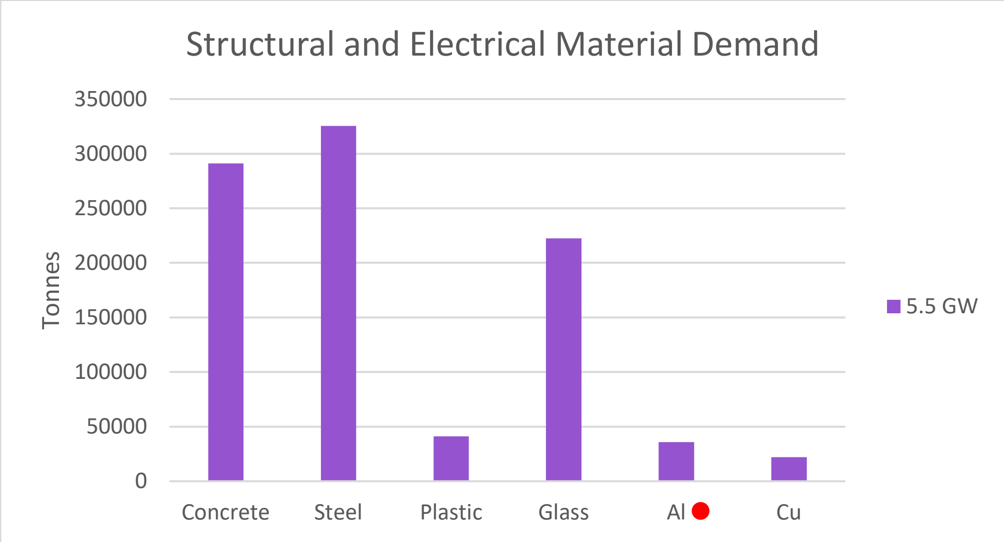


Figure 6.1 Material requirements to meet CAP targets for solar PV. Note red dot denotes critical raw materials.

Metal	c-Si	a-Si	CdTe			CIGS		
			LDS	MDS	HDS	LDS	MDS	HDS
Silica (Si)	14,405.0	2.2						
Silver (Ag)	91.5							
Germanium (Ge) C		0.7						
Cadmium (Cd)			4.0	5.8	9.8			
Tellurium (Te)			4.0	6.0	10.9			
Copper (Cu)						1.8	2.0	2.2
Indium (In) C						0.9	1.4	2.5
Gallium (Ga) C						0.3	0.4	0.6
Selenium (Se)						2.0	3.2	5.5

Table 6.4 Material demand to meet target capacity of 5.5 GW.

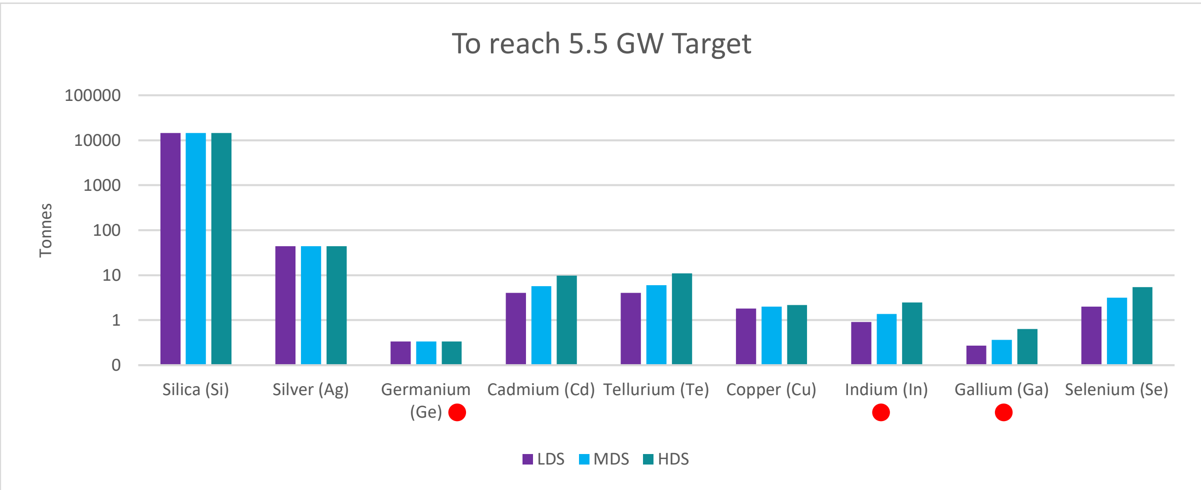


Figure 6.2 Material demand range arising from technology specific metals and 5.5 GW target. Note Y-axis is logarithmic. Note red dots denote critical raw materials.

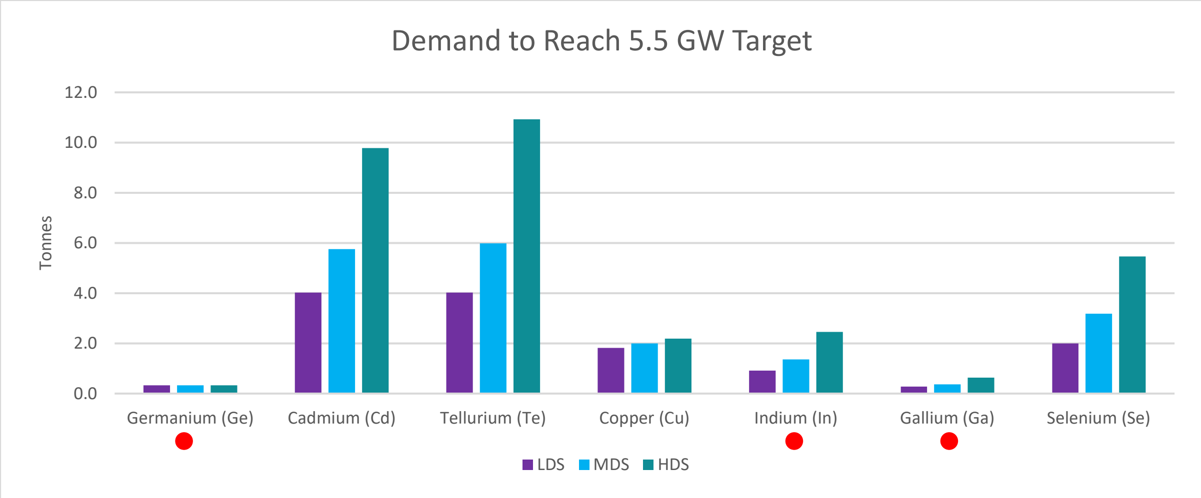


Figure 6.3 Technology specific metal demand to reach 5.5 GW target (Silica removed). Red dotes denote critical raw material.

6.4 Considerations and Points to Note

Predictions on the level of demand for certain materials are highly speculative, but the range employed across the LDS to HDS should cover the most likely scenarios. The variation in material demand is largely dependent on the market share of each technology and the trajectory this takes over the coming years. The evolution of technology market share will likely be impacted by the supply, consumption, and criticality of materials, largely REE in the case of solar panels. The topic of supply and demand and future shortages is discussed in Section 9.

The market for solar panel manufacturing, like all renewable energy generating technology, is advancing rapidly with measures being taken constantly to increase efficiency and reduce the material intensity. The raw material demands assessed here are based on existing technology but attempts to increase efficiency and reduce raw material demand in future may involve technologies currently in their infancy that make use of alternate technology and materials. One such material that is used in 'next generation' solar cells is perovskite. Current solar panels capture 15-18% of solar energy on average, while a solar cell made using perovskite have been found to be as much as 28% efficient (Renewable Energy Hub, 2022). Multijunction Cells have also shown a dramatic increase in efficiency, as high as 46% (Energy Institute, 2015). Conventional solar PV cells have a single junction, or single layer of semi-conductor cells, whereas introducing multiple layers increases efficiency by increasing the ability to absorb light efficiently across the solar spectrum (Energy Institute, 2015). These solar cells use a variety of semiconductor materials including gallium, germanium, indium, and aluminium but may have the potential to reduce material demand by their vastly greater efficiency, cost however could potentially hamper their large-scale role out.

7 Transport Sector

As part of plans to decarbonise the transport sector in Ireland, the Climate Action Plan has targeted an increase in the use of electric vehicles across the spectrum of passenger vehicles, vans, and buses as well as increased use of low emission trucks. The targets, detailed in Section 3.2. are to have 845,000 electric cars, and 95,000 electric vans, with a focus on battery electric vehicles for these two categories. The targets also include 1,500 electric buses by 2030. In this section the metal and material demands that arise from these targets are discussed and consider: (1) demand variation across battery and motor types and technologies; (2) technology advancement in the near future; (3) the rate of electric car production and how it aligns with market share of different technologies.

For this report the production and roll out of vans to meet targets is included with the passenger car calculations, as the battery and motor technology used in both vehicle categories is similar. The grouping of vans and passenger vehicles are together termed 'small vehicles' for simplicity in this report. Buses, however, are treated separately as their technology varies to that typically used for smaller vehicles, most notably the battery.

7.1 Electric Vehicle Technology

Electric vehicles (EVs) are categorised into Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Hybrid Electric vehicles (HEVs). Both PHEVs and HEVs combine electric drive as well as an internal combustion engine. The battery capacities and electric motors in the PHEVs and HEVs are much smaller and thus require less raw materials. The spread of EV types in 2020 had HEVs representing 55% of the stock, PHEVs at 25%, and BEVs making up 20%. Predictions range on how this mix will change to 2030 with some predicting the proportion of BEVs to PHEVs reaching 80:20 (Deloitte, 2020) while others believe that BEVs will represent 99% of all EV stock, and that dominance is expected to remain to 2050 (Sterchele *et al.*, 2020). While other predictions have the predominance of BEV at 89% by 2030 with PHEV and HEV making up the remaining 11% (Bongartz *et al.*, 2021). The CAP targets assert a focus on BEV for 2030 which aligns with these predictions.

7.1.1 Electric Vehicle Battery Chemistries

Batteries in electric vehicles are predominantly lithium ion (Li-ion) (95-99% of market), and this is unlikely to change prior to 2030. Their appealing characteristics such as high energy density, low self-discharge, low maintenance and strong decrease in costs have made Li-ion batteries superior to other existing commercial batteries in the market (Bongartz *et al.*, 2021). As such the material and metal demand calculations for all vehicles in this report are based on Li-ion technology.

Li-ion batteries encompass an anode, usually composed entirely of graphite, an electrolyte (lithium salt), and a cathode. The cathode chemistry differs across the spectrum on Li-ion batteries which results in differences in metal demands. The different Li-ion battery types that are used in EVs and their metal constituents are detailed in Table 7.1. While Li-ion batteries are similar in design, their performance differs across the various cathode compositions. The naming convention of battery chemistries is based on the first letter of the key materials included in the cathode.

Lithium-Ion Battery Types	
Cathode Chemistry	**Acronym**
Nickel Manganese Cobalt	NMC 111
	NMC 523
	NMC 622
	NMC 811
	NMC 9.5.5
Lithium Iron Phosphate	LFP
Nickel Cobalt Aluminium	NCA
Lithium Manganese Oxide	LMO

Table 7.1 Lithium-ion battery types based on cathode chemistry.

The nickel manganese cobalt cathode chemistries are further broken down into subcategories based on the ratios of nickel : manganese : cobalt. i.e., NMC111 has an equal proportion of all three metals. Nickel rich cathode materials are of interest as they have a higher energy density and reduce reliance and use of cobalt (Battery Design, 2022).

The material intensity for each of these Li-ion battery chemistries have been drawn from various sources (Bongartz *et al.*, 2021; Matieu and Mattea, 2021). The evaluation of material intensities encompasses the battery cell cover, cathode, anode, electrolyte, and current collector (Fig. 6.1).

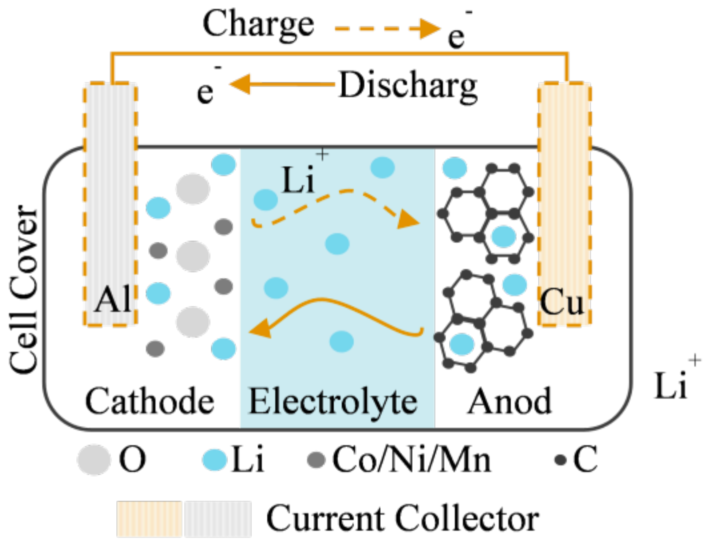


Figure 7.1 Components of a typical Li-ion battery. Taken from Bongartz *et al.,* (2021).

Market shares to 2030 of different cathode chemistries within the Li-ion battery group are broadly similar across different predictions. Some scenarios, indicate the commercial production of advanced non Li-ion chemistry batteries in the automotive battery market prior to 2030 (Fig 6.2). An *innovative* scenario is represented in the calculations below to include the potential future success of next generation battery chemistries in electric vehicles prior to 2030. These advanced chemistries include Lithium-Sulphur (LiS) batteries which have the potential to increase capacity from the Li-ion range 150-260 Wh/kg to 550 Wh/kg (U.S. Dept. of Energy, 2019). Other advances in battery chemistry aimed at increasing capacity include incorporating silicon into the anode and solid-state batteries, although this technology is not projected to alter the EV market prior to 2030 (Mathieu and Mattea, 2021).

The average annual battery sales composition projections show similar trends of increasing market share of NMC battery chemistries which are expected to evolve to greater energy density versions. The projections below (Fig. 6.2; 6.3) have been used to determine market share of EV battery types currently and how this is expected to change into the future.

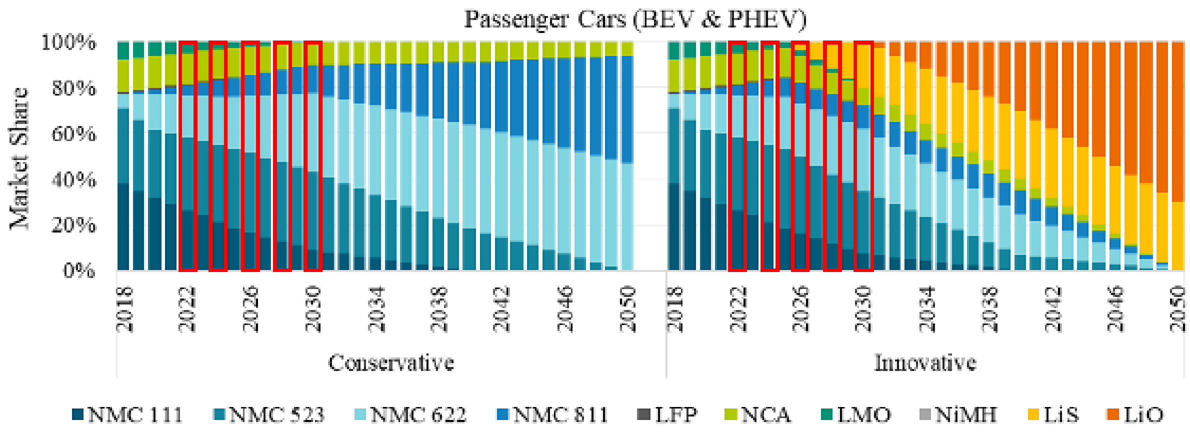


Figure 7.2 Average battery sales composition, modified from Bongartz *et al.* (2021). Red bars indicate the market share splits used in calculation of material demands in this report (every 2 years).

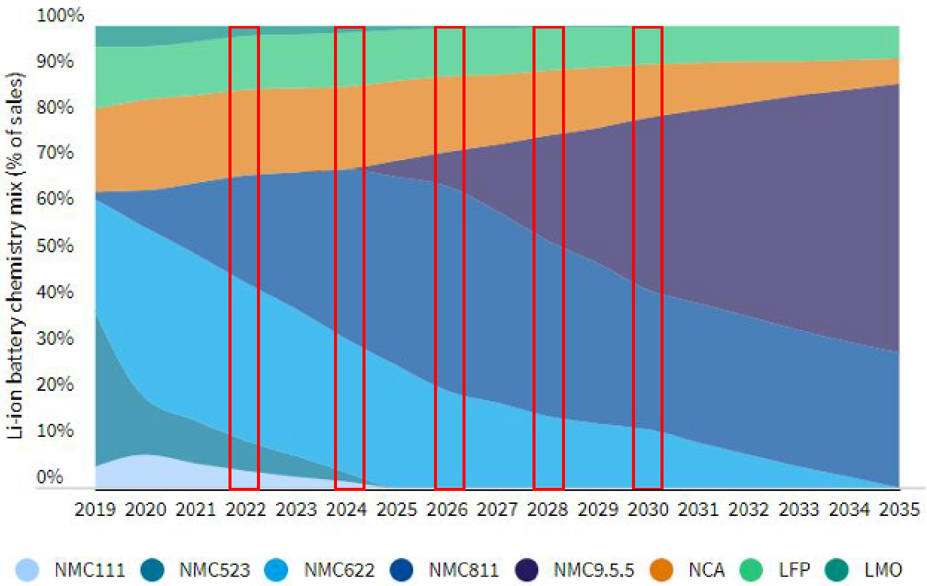


Figure 7.3 Average battery sales composition, modified from Mathieu and Mattea (2021). Red bars indicate the market share splits used in calculation of material demands in this report.

The market share of the various battery chemistries based on the above examples is detailed in Figure 6.4.

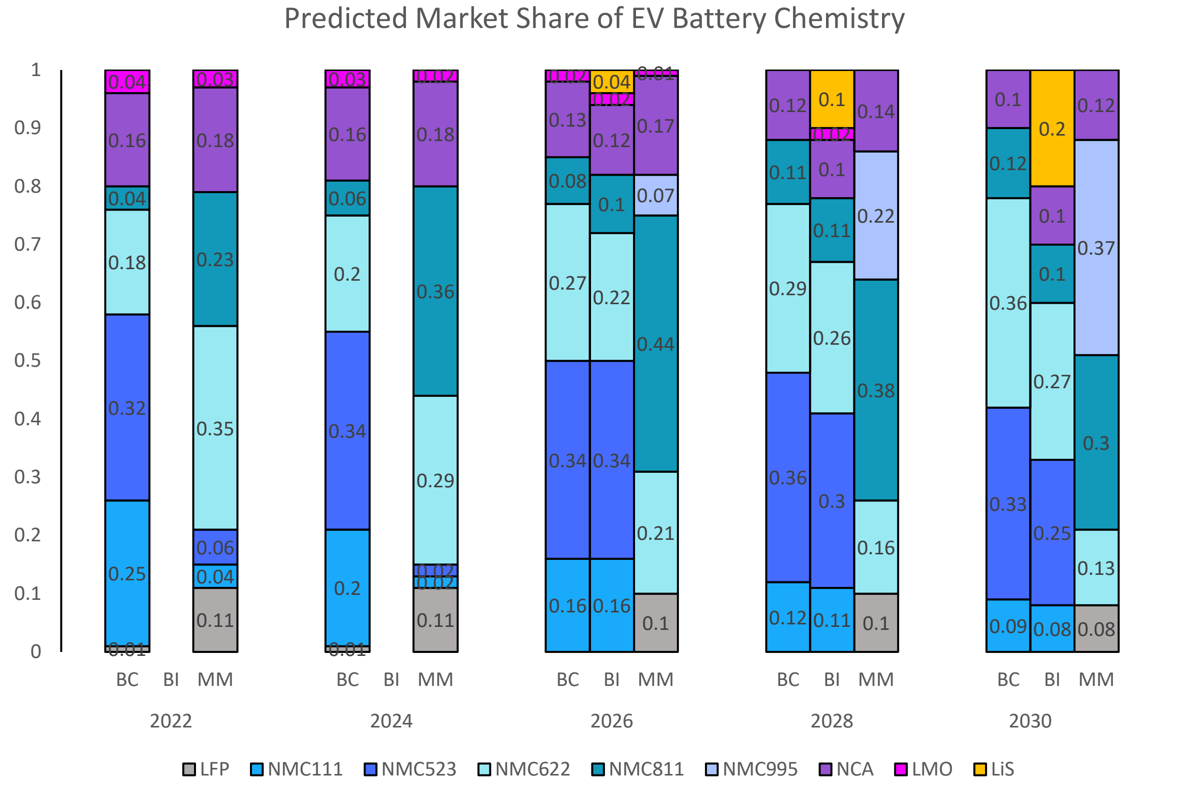


Figure 7.4 Market share projections of battery chemistries from present to 2030 from various sources: Bongartz *et al*. (2021) – (BC Bongartz Conservative; BI Bongartz Innovative); Mathieu and Mattea (2021) (MM).

The material intensities associated with battery chemistries is expressed as kg/kWh (Table 7.2; Bongartz *et al.*, 2021; Mathieu and Mattea, 2021; Porzio and Scown, 2021). The total capacity of an EV battery is measured in kilowatt-hours (kWh) and relates to how much electricity can be stored in the battery pack. The capacity of small EVs vary widely but average values of 66 kWh for BEVs and 12 kWh for PHEVs have been used as average values of battery car capacities to 2030 (Xu *et al.*, 2020).

Material	Material Intensity (kg/kWh)								
	Lithium C	Cobalt C	Nickel	Graphite	Manganese	Copper	Steel	Aluminium C	Iron
LFP	0.09			1.1		0.43	0.43	0.73	0.69
NMC111	0.12	0.34	0.34	0.94	0.32	0.36	0.36	0.62	
NMC523	0.11	0.19	0.47	0.88	0.27	0.34	0.34	0.58	
NMC622	0.11	0.18	0.53	0.83	0.17	0.32	0.32	0.55	
NMC811	0.08	0.08	0.64	0.76	0.08	0.29	0.29	0.5	
NMC9.5.5	0.07	0.04	0.66	0.69	0.03	0.27	0.27	0.46	
NCA	0.1	0.13	0.7	0.81		0.31	0.31	0.55	
LMO	0.09			0.793	1.405	0.486		0.44	
LiS	0.2					0.39		0.21	

Table 7.2 Material intensities associated with different battery chemistries.

To reconcile the rate at which electric cars are produced per two-year period to 2030 the projected rate of European car battery supply has been used as a guide (Fig 6.5). The incremental percentage growth of battery supply between 2020 and 2030 was used to inform the percentage growth each two-year period in electric car production required to meet Ireland's CAP target to 2030. i.e., in this report the rate of car production required to meet the CAP target by 2030 reflects the rate of growth in European supply.

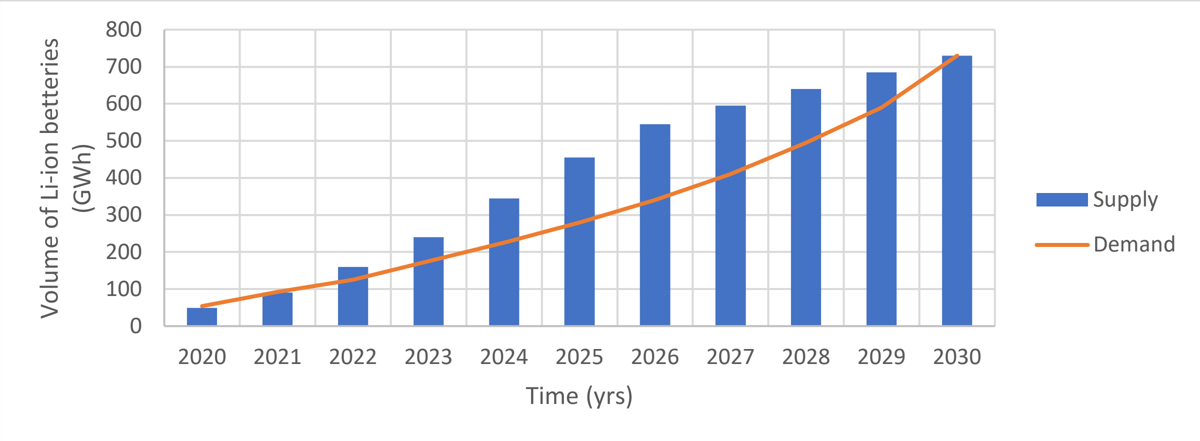


Figure 7.5 European EV battery supply and demand growth to 2030, from Mathieu and Mattea (2021).

Year	Supply (GWh)	Demand (GWh)	Percentage increase in supply (cumulative)	Percentage increase in supply (incremental every 2 years)	Rate of electric car production to meet CAP target
2020	49	54	4	4	45,000*
2021	91	92	12		
2022	160	125	22	18	165,043
2023	240	175	33		
2024	345	225	47	25	238,219
2025	455	280	62		
2026	545	340	75	28	257,234
2027	595	410	82		
2028	640	495	88	13	122,329
2029	685	590	94		
2030	730	730	100	12	115,890

Table 7.3 Percentage increases in EV battery supply between 2020 and 2030, from Mathieu and Mattea (2021).

* cars already on the road prior to 2022 (Dept. of Transport, 2022)

7.1.2 Battery Electric Vehicle Motors

Traction motors in EVs, similar to generators in wind turbines, place growing demand on Rare Earth Elements (REE), a group of chemical elements with similar properties that are used in a range of high-tech applications. Key REEs include neodymium, praseodymium, dysprosium, and terbium, which are used in the manufacture of neodymium-iron-boron (NdFeB) permanent magnets. These magnets are components of traction motors for electric vehicles (Alves *et al.*, 2020). Commercially available traction motors are mostly permanent magnet synchronous motors, with market share reaching 90-93% (Bloomberg NEF, 2020; Alves *et al.*, 2020; Nordelof, 2019). To date this type of motor has been strongly preferred because of its higher efficiency. The material demand for REEs in permanent magnets and other magnet components are detailed in Table 7.4, figures are from Blagoeva *et al.* (2016) & Pavel *et al.* (2017). These estimates are based on the weight of the permanent magnet (1-2 kg) and the percentage weight of the permanent magnet each material takes up and are applicable to small and large electric vehicles. In calculations for small vehicles an average PM weight of 1.5 kg is used.

REE in EVs	Kg/Motor
Neodymium (Nd)	0.340
Praseodymium (Pr)	0.113
Dysprosium (Dy)	0.113
Boron (B)	0.012
Iron (Fe)	0.785

Table 7.4 Material demands per small EV traction motors (Blagoeva et al., 2016).

7.2 Small Electric Vehicles - Metal and Material Demand

Considerations when calculating the material demands to meet CAP targets for electrification of small vehicles:

- Number of vehicles is 845,000 passenger vehicles and 95,000 vans giving a total target of 940,000 small vehicles. 45,000 EVs are already in use in Ireland, resulting in a total shortfall of 895,000 small vehicles.
- The average battery capacity of BEVs and PHEVs as well as the proportion of BEV to PHEV use prior to 2030.
    - Capacity 66kWh for BEV and 12 kWh for PHEV used in calculations.
    - Ratio starts at 70:30 BEV to PHEV and gradually evolves to 80:20 by 2030 in calculations.

- The cathode battery chemistry variations through time to 2030 are incorporated into calculations reflecting the scenarios proposed by Mathieu and Mattea (2021) and Bongartz *et al.*, 2021).
- The rate at which cars are produced to meet the demand by 2030 progresses at the same rate as European battery production is projected to occur.

Incorporating these factors introduced in section 6.1, the following material intensities emerge to meet demands laid out in the Climate Action Plan for the electrification of the passenger and van fleets in Ireland by 2030.

Battery Materials (tonnes)	Bongartz *et al.* (2020)		Mathieu and Mattea (2021)	Average
	Conservative	Innovative		
Lithium C	5,100	5,386	3,952	**4,813**
Cobalt C	9,057	8,675	4,324	**7,352**
Nickel	23,496	22,509	23,921	**23,309**
Graphite	40,662	39,079	35,691	**38,478**
Manganese	10,706	10,477	4,125	**8,436**
Copper	15,838	16,211	13,851	**15,300**
Steel	15,317	14,667	13,550	**14,511**
Aluminium C	26,853	26,309	23,653	**25,605**
Iron	139	139	3,253	**1,177**

Table 7.5 Material demand, in tonnes, arising from battery production to meet CAP targets for small EVs

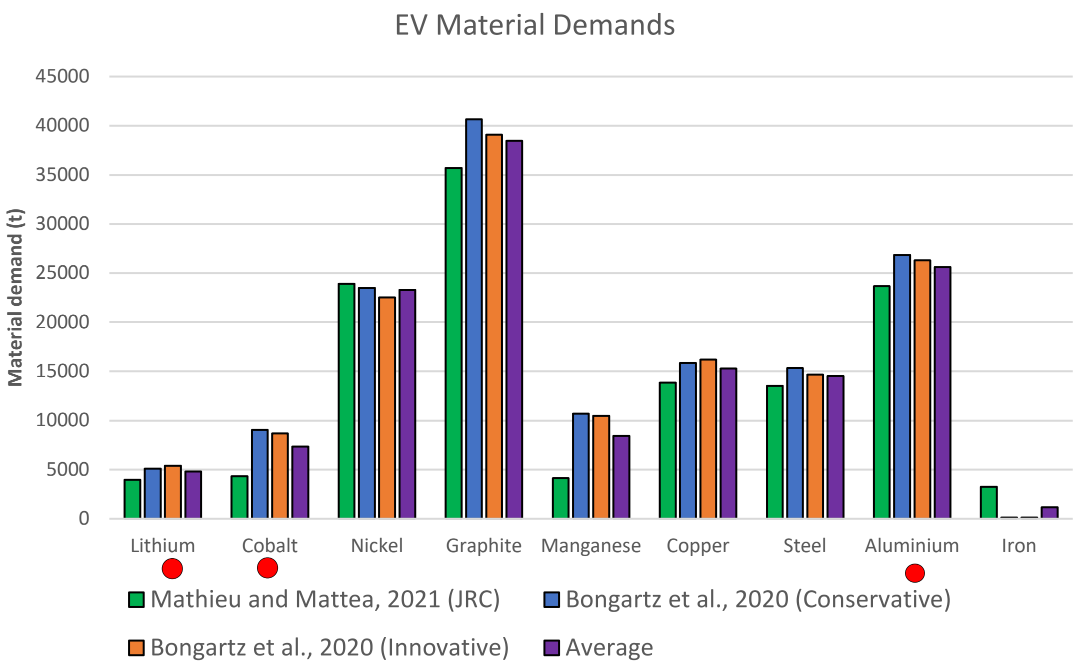


Figure 7.6 Demand for materials and metals to meet CAP small EV targets. Note red dots denote critical raw materials.

Further to battery supply, the level of REE and other material required for traction motors in small electric vehicles is detailed below.

Material	Demand (t)
Neodymium C	319.37
Praseodymium C	106.46
Dysprosium C	105.75
Iron	752.79
Boron C	11.21

Table 7.6 Demand for REE and other materials within permanent magnets of traction motors.

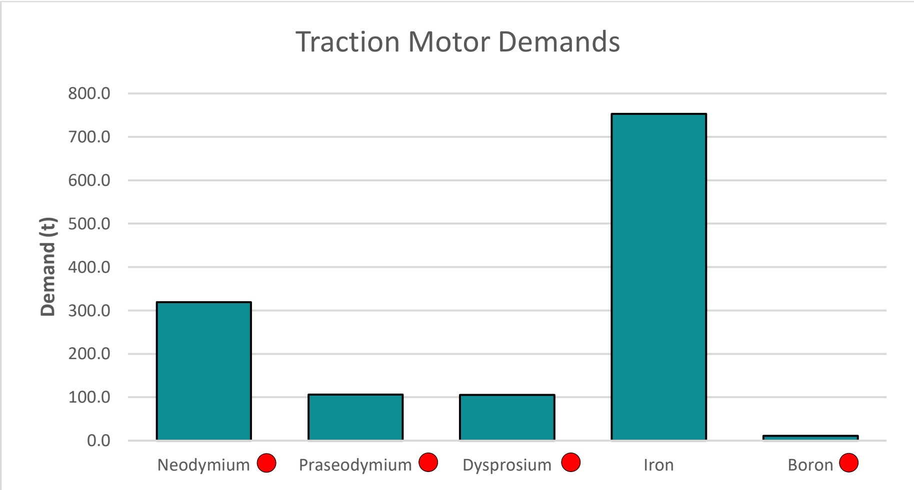


Figure 7.7 Material demand arising from traction motors in small EVs. Note red dots denote critical raw materials.

7.3 Electric Buses – Metal Demand

The Climate Action Plan aims to have 1500 electric buses in use by 2030. Different battery chemistries have different advantages, and the choice of battery chemistry for small vehicles does not currently suit the requirements of larger vehicles such as buses. LFP batteries are the preferred option for larger EVs such as buses (Wen *et al.*, 2020). While having lower energy densities compared to NMC batteries, LFP batteries are suited to use in high population density areas where regular stopping and starting of the bus occurs. In less densely populated areas, greater energy density and longer range available from NMC batteries is better suited, such as is used in the US (sustainable-bus.com, 2019). Battery packs in electric buses are much larger with capacities in battery electric buses (BEBs) around 340 – 450 kWh (BYD ADL, 2021; Wrightbus 2022), and Plugin Hybrid Elecric Busses (PHEBs) of 30 kWh (Sustainable-Bus, 2020; Xie *et al.*, 2020). Metal demand stemming from electric bus batteries considered here initially looks at sole use of LFP batteries in all 1500 buses, as well as considering a mix of LFP and NMC batteries.

The split of BEBs and plugin hybrid electric buses (PHEBs) is uncertain, but the BEBs are expected to dominate the market, considering these are the lowest emission options and will be in use in Ireland in 2023. The scenario considered herein reflects this expectation and details the metal requirements for the CAP target being met solely by BEBs. As the level of material and metal required for PHEBs is less that BEB due to lower capacity batteries, the estimates below can be considered as maximum demand. With inclusion of PHEBs in the mix material and metal demand would be reduced.

Ireland has entered into a deal with Wrightbus to supply up to 800 electric buses which make use of LFP batteries (340 – 454 kWh) and permanent magnet direct drive traction motors (Wrightbus, 2022). The reported figure for BEB battery capacity (340 kWh; Wrightbus, 2022) and the number of buses required to meet the target (1500) combined with the metal demands (Table 7.2) make it possible to estimate the metal demand that will arise from the rollout of 1500 BEBs in Ireland (Table 7.7; Fig. 6.8).

Material (tonnes)	LFP	LFP & NMC
Lithium C	45.9	46.3
Cobalt C	0	20.3
Nickel	0	95.2
Graphite	561	509.7
Manganese	0	22.8
Copper	219.3	198.6
Steel	219.3	198.6
Aluminium C	372.3	337.9
Iron	351.9	237.6

Table 7.7 Material demand, in tonnes, arising from battery production to meet CAP targets for electric buses.

Further to battery supply, demand for REE and other material required for traction motors will exist for BEBs. It is difficult to discern the volume of material required in the traction motors associated with buses, or indeed the preferred motor. The power of the motor in some electric buses (280 kW) is comparable to the upper end of passenger vehicles (250 kW BMW i4; 300 kW Volvo C40; SEAI, 2022). As such the upper PM weight of 2 kg per vehicle can be used to calculate a rough estimate on potential REE demand from electric bus traction motors. This assumes that all motors are permanent magnet and do not use alternate technology. Electric buses also tend to have dual motors located on the front and back axels (Unnikrishnan & Panda, 2020) which may use different motor technology and have both a permanent magnet motor and an induction motor. Table 7.7and Figure 6.9 detail an estimate on the demand arising for REE in meeting electric bus targets.

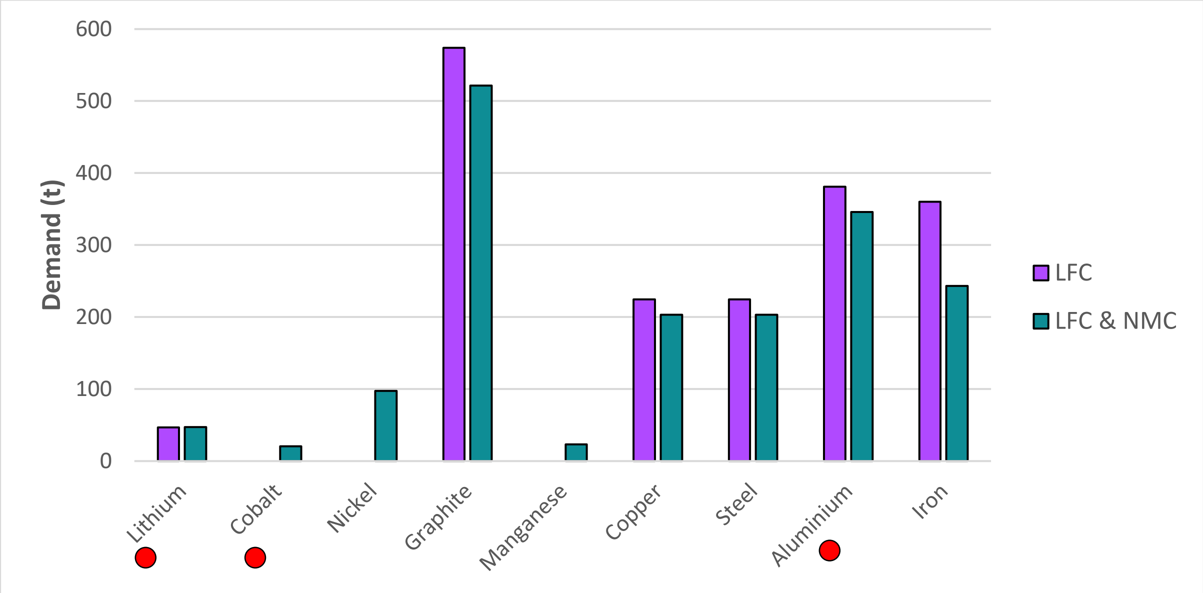


Figure 7.8 Metal demands arising from Climate Action Plans for provision of electric buses. Note red dots denote critical raw materials.

Material	Demand (kg)
Neodymium C	679.5
Praseodymium C	226.5
Dysprosium C	225

Table 7.8 REE in BEB traction motors.

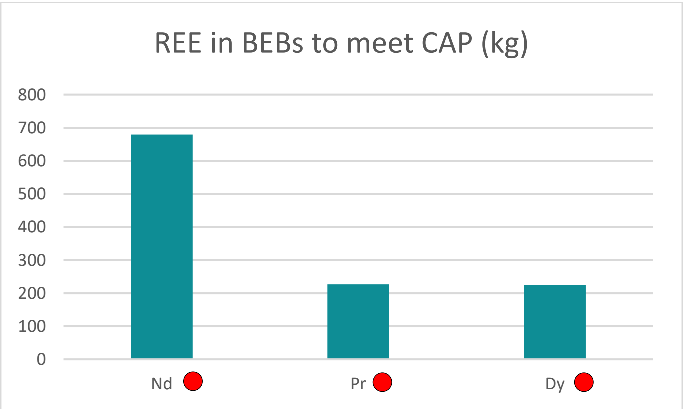


Figure 7.9 REE demands arising from Climate Action Plans for provision of electric buses. Note red dots denote critical raw materials.

7.4 Low Emission Heavy Goods Vehicles (HGVs)

Targets relating to heavy good vehicles determine the increased use of 'low emission' vehicles. Since the publication of the Climate Action Plan fully electric HGVs are in use on road in Europe. The battery capacity of such vehicles is 315 kWh (DAF,2020). This information can be used to deduce potential material and metal demands stemming from these vehicles (Table 7.9; Fig. 6.10). LFP lithium-ion batteries again are thought to dominate the market for electric HGVs, but the prevalence of NMC Li-ion batteries is expected to increase in the market before 2030 (Mathieu and Mattea, 2021). The figures below reflect a continued dominance of LFP batteries, and an alternate scenario whereby an increased use of NMC batteries is seen.

The traction motor used in these vehicles will again use permanent magnet or induction technology. The intensity of material in the motors can again be estimated as used previously by knowing the mechanical power that is used (210 kW; DAF, 2020) which again is in the range of passenger vehicles.

Material (tonnes)	LFP	LFP & NMC
Lithium C	99.23	100.60
Cobalt C	0.00	67.53
Nickel	0.00	316.97
Graphite	1,212.75	1,041.86
Manganese	0.00	75.80
Copper	474.08	405.17
Steel	474.08	405.17
Aluminium C	804.83	690.44
Iron	760.73	380.36

Table 7.9 Material demand arising from introduction of 3500 electric HGVs reflecting the dominance of LFP or a combination of LFP & NMC Li-ion batteries.

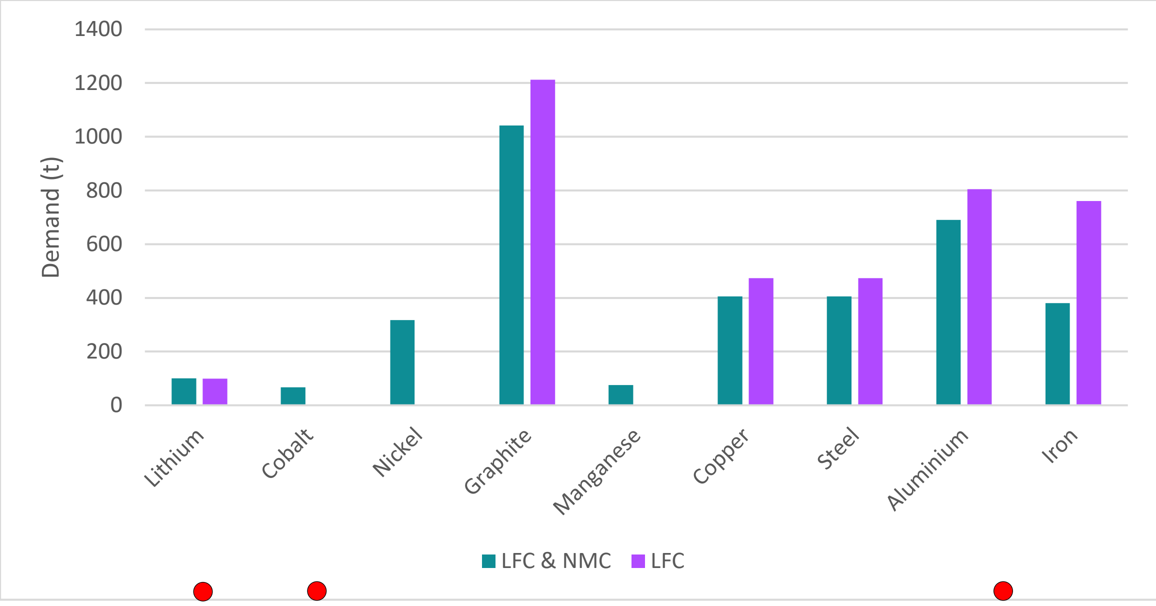


Figure 7.10 Metal demands arising from Climate Action Plans for provision of electric HGVs. Note red dots denote critical raw materials.

Material	Demand (kg)
Neodymium C	1,585
Praseodymium C	528
Dysprosium C	525

Table 7.10 REE in HGV traction motors.

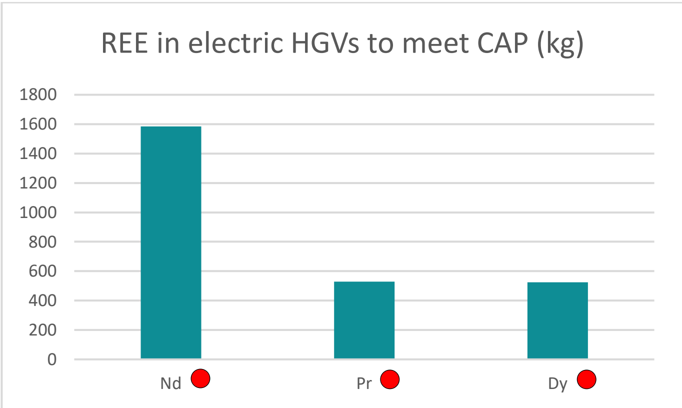


Figure 7.11 REE demands arising from Climate Action Plans for provision of electric buses. Note red dots denote critical raw materials.

7.5 Points to Note

As demand grows for certain critical materials, particularly rare earths used in permanent magnet motors, car manufacturers are attempting to reduce their use or move away from REE intense motors completely and use instead induction motors, which demand high amounts of copper (Reuters, 2021). While the permanent magnet remains the optimum electric traction motor, and used for calculation of material demands herein, there is potential for reduced use of dysprosium or greater use of induction motors in the realisation of 2030 targets.

8 Energy Storage

Generation profiles of renewable sources of energy are highly fluctuating and dependant on season and weather conditions. One way to offset the variability of renewable energy generation and facilitate the necessary flexibility of the electricity system is by the integration of concepts for energy storage. Electricity storage projects have been designated as EU priority electricity infrastructure and will receive preferential treatment (CAP, 2021). Energy storage methods that are currently utilised in Ireland include grid-scale batteries and green hydrogen. These methods can store excess energy and avoid curtailment of renewable energy sources. These methods act as buffers between times of high and low variable renewable generation and provide low carbon alternatives for the almost 50% of energy demands that will not be electrified (GDG, 2022).

The extent of battery storage and green hydrogen deployment in the Irish electricity storage market and their respective material demands are estimated as best possible below.

8.1 Grid Scale Battery Storage

It is predicted that to reach 70% renewable generated electricity by 2030, 1.7 GW of installed battery capacity will be required (Wind Energy Ireland, 2018). Currently there is 2.5 GW (2,500 MW) of grid scale battery in the development pipeline in Ireland. EirGrid have assumed that 1.45 GW of storage will be operational in 2030. At the end of 2021 there were 6 projects operational providing 350 MW of operational battery storage on the market (Energy Ireland, n.d.). The difference between current capacity (350 MW) and the potential planned 2,500 MW can be used to arrive at an estimate for material and metal demands that will arise to make up the 2150 MW shortfall.

Lithium-ion batteries dominate the Battery Energy Storage System (BESS), making up 90% of installed capacity in the USA in 2018 (Energy Information Administration, 2020). Their applicability results from their high-cycle efficiency (they don’t lose much energy between recharge and discharge) and fast response times. Of the different Li-ion chemistries a mix of NCA; NMC; LMO and LFP are reportedly used (IRENA, 2017).

Using the remaining planned grid scale capacity and battery composition knowledge detailed above (Sect. 6.1.1), an estimate can be made on the metal and material demand arising from further deployment (Table 8.1; Fig. 7.1).

Material	Demand (t)
Lithium C	209.6
Cobalt C	172
Nickel	628.9
Graphite	1,925.9
Manganese	900.3
Copper	841.7
Steel	580.5
Aluminium C	1236.3
Iron	370.9

Figure 8.1 Metal demand arising from grid scale battery storage.

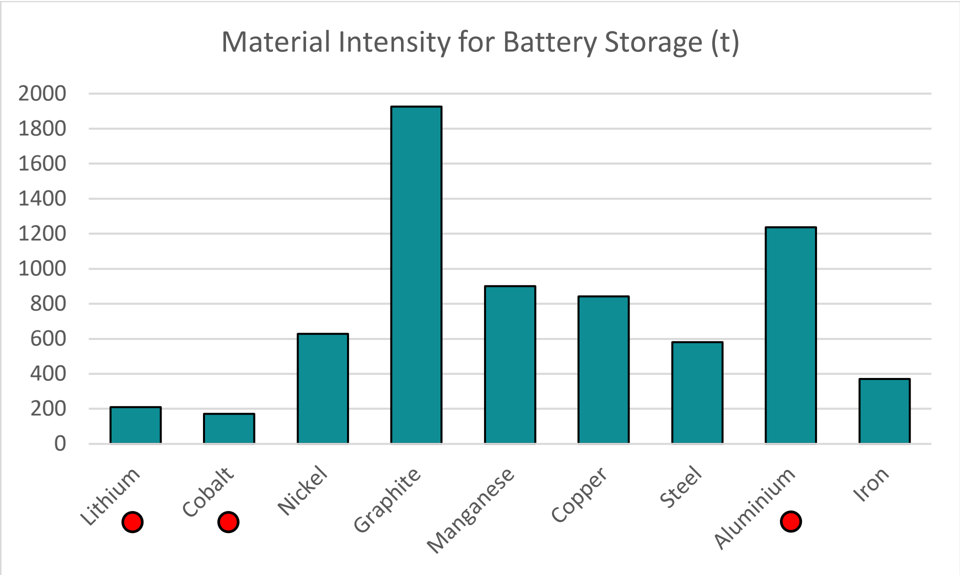


Table 8.1 Metal demand arising from deployment of grid scale battery storage. Red dot denotes critical raw material.

The future of stationary battery storage is likely to involve zinc-air batteries, which may be the solution to long duration discharge, due to their low cost, non-flammable, safe, and abundant materials. Zinc-air batteries are currently in the demonstration phase of development and are proving their ability to provide multi-day backup power and compete economically with Li-ion batteries (Daniel-Ivad, 2022).

8.2 Green Hydrogen

Green hydrogen has been identified in the Government of Ireland Climate Action Plans as having the potential to support decarbonisation across several sectors including heavy goods transport, high-temperature heat for industry, and electricity generation. Hydrogen is a versatile energy carrier that may store excess renewable energy from the grid. This may overcome a significant challenge to the energy sector as back-up for intermittent renewables; seasonal storage of renewable energy to replace today's fossil fuel storage systems; and to ensure security and resilience in energy supplies.

Green hydrogen uses excess energy produced from renewable sources to power the electrolysis process and can be installed in tandem with a renewable energy source such as at Kilathmoy (Statkraft, 2019). Electrolysis is a sustainable process which uses electric current to split water into hydrogen and oxygen. Once produced the hydrogen can be stored as a gas under high pressure in underground stores, at very low temperatures, as a liquid, or adsorbed to specific molecular complexes. The hydrogen can then be used later to produce electricity by way of a fuel cell which, like a battery, reacts across an electrochemical cell to produce electricity, water, and heat (US Energy Information Administration, 2021). This process is particularly potent because hydrogen gas has the highest energy content per unit of mass of any fuel, making it great for holding and thus distributing energy (Hydrogen Ireland, n.d.).

Electrolysis by a process called Proton Exchange Membrane (PEM) is increasing in prevalence due to its ability to accept fluctuating power input, such as is available from solar and wind, and deliver hydrogen at high purity. Water oxidises, forming O_2 at the anode and releasing protons, which pass through the proton exchange membrane and are reduced to form H_2 at the cathode. Materials required in PEM include platinum-based catalysts for the cathode and iridium-based catalysts for the anode (Carmo *et al.,* 2013). Costs related to these materials are the main drawback of this technology (David and Martinez, 2020). While platinum has excellent stability in the generation of hydrogen, other platinum group metals are also used, including palladium (Adams and Chen, 2011). Other technologies for electrolysis include Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis (SOE). PEM is expected to makeup 30-60% of electrolysers, however recent breakthroughs reducing the use of iridium is expected to increase the dominance of this technology (h2bulletin, 2021).

The main material intensity that arises from green hydrogen electrolysis is the platinum group metals (PGM) – platinum and palladium in the cathode catalyst, and iridium in the anode catalyst. All these materials appear on the EU list of critical raw materials. Intensities for Platinum and Iridium from various sources as well as the published predicted reduction in intensities has been used here (Carmo *et al.*, 2013; Kiemel *et al.*, 2019; Haraeus, 2020; h2bulletin, 2021; Table 8.2).

Hydrogen electrolysis material intensity (t/GW)					
	Carmo *et al.* (2013)	Kiemel *et al.* (2019)		Haraeus (2020)	h2bulletin (2021)
		2019	2035		
Platinum	0.43	0.33	0.0375		0.18
Iridium	1.39			0.42	

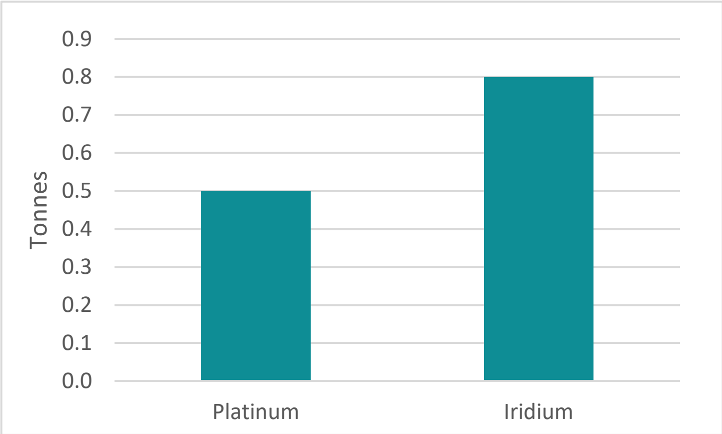
Table 8.2 Published figures of PGM intensities for Hydrogen electrolysis.

Green hydrogen can act as an effective energy storage medium, linking the electricity market to other sectors and competing with solutions like batteries, but with much more complex interactions. Ultimately the extent of this role will depend on there being sufficient demand for the hydrogen produced, such as in sectors including gas grid injection; transport fuels; and chemical feedstock. Studies have shown that the presence of electrolysis both increases the feasibility and reduces the overall cost of decarbonising the energy systems it connects. The EU's hydrogen strategy also underlines the need for an integrated energy system to achieve climate neutrality by 2050. General agreement on the role hydrogen storage can play in providing crucial energy storage exists but the size of that role in the near term is uncertain (GDG, 2022). Recent additional measures announced as part of the sectoral emissions ceilings to further decarbonise the energy sector has targeted 2 GW of green hydrogen energy storage by 2030. Prior to this, the Climate Action Plan had no fixed target. Aside from official targets, potential use of hydrogen in Ireland has recently been estimated to 2030 (GDG, 2022) and a total capacity required to decarbonise various sectors also deduced (Table 8.3). The uses include gas grid injection; transport fuels; and chemical feedstock. A total of 11.78 GW of electricity dedicated to hydrogen production is required (GDG, 2022).

Uses in Ireland to 2030 (GDG, 2022)	Equivalent of energy required (GW)
HGVs – replace diesel in 25,000 largest vehicles	1.4
Aviation – 50% of aviation demand	4.2
Shipping – 50% of shipping demand	1.2
Fertiliser – supply national demand	0.78
Natural Gas - displace 20% of natural gas demand	4.2
Total	**11.78**

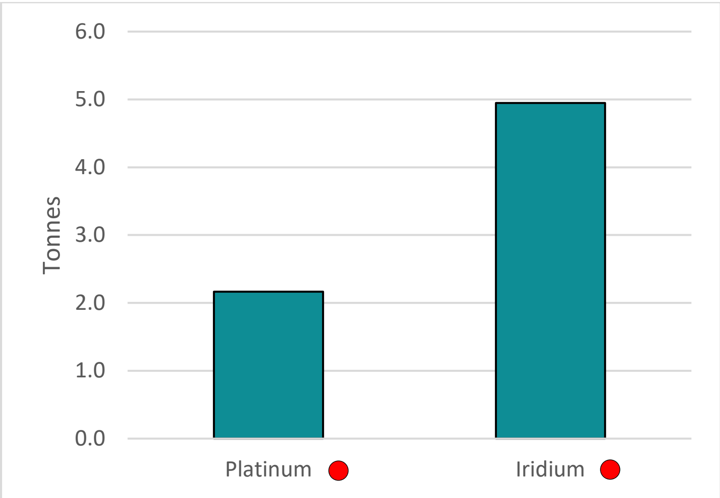
Table 8.3 The potential role of green hydrogen in Ireland's energy transition

While highlighting the wide-ranging impacts green hydrogen can have across sectors for the purpose of this report the official governmental target is used here to estimate the total potential material required (Fig. 7.2). The level of material that would currently be required to meet the target outlined for across sector impact (11.78 GW) is also presented below (Fig. 7.3) but is not included in total material calculations (Sect. 9). Note: platinum and palladium are interchangeable and are both commonly used in electrolysis so the demand could be shared across these two metals.



Material	Demand (t)
Platinum C	0.5
Iridium C	0.8

Figure 8.2 Estimated PGM demand arising from sectoral emission ceiling target for hydrogen production of 2 GW.



Material	Demand (t)
Platinum C	2.2
Iridium C	4.9

Figure 8.3 Estimated PGM demand arising from integration of hydrogen across sectors in Ireland by 2030.

9 Transmission Network Upgrades

EirGrid maintains and plans upgrades to the electricity transmission network. As demand or generation changes, or as the transmission network becomes more interconnected with neighbouring transmission networks, the flow of electrical energy throughout the transmission network changes. To accommodate these changes in power flows, it is necessary to modify or strengthen the transmission network to ensure performance and reliability levels are upheld (EirGrid, 2021). A major change that the transmission network must undergo is increased integration of renewable energy sources (RES). In light of this, EirGrid has put in place a roadmap to support the transition to increased renewable electricity generation by 2030 and identifies the transmission network reinforcements needed to manage renewable energy generation.

Details of general maintenance and grid upgrades that will be performed in the coming years are detailed in the Transmission Development Plan (EirGrid, 2021) including those specifically required for integration of RES. Information on RES integration projects include the length and voltage of cable requirements, some upgrades however, are in the earliest stages of planning and do not include detail of the length of cable required (EirGrid, 2021; 2022). The plans that currently have length and voltage detailed are used here to understand the metal demand arising from transmission network upgrades related to integration of RES (Table 9.1). As there are other projects in early stages of planning without established lengths, the figures determined here are a minimum metal demand and will certainly increase as planning matures over the coming years.

Cable Voltage	Cable Length (km)	Conductor	Conductor Cross Sectional Area (mm2)	Demand (t)
110 kV	666.26	Aluminium C	630	1,137.3
220 kV	139	Aluminium C	1,200	451.8
400 kV	143	Copper	1,000	1161

Table 9.1 Projects identified in the Transmission Development Plan 2020-2029 that are directly related to RES integration. Cable specifications from ESB Networks (pers comm.).

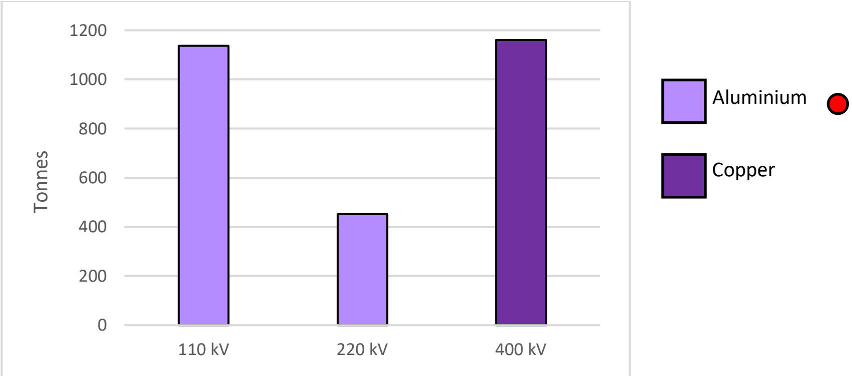


Figure 9.1 Demand arising from current planned grid upgrades directly related to integration of RES.

10 Metal and Material Demands

The material and metal demands that have been deduced in Sections 4 to 8 are summed in order to provide a total potential demand that will arise from achieving the Climate Action Plan 2021 targets, inclusive of subsequent modifications, for the Energy and Transport sectors (Table 10.1; Fig. 9.1).

Cumulative Demand (t)	
Concrete	3,902,488.0
Steel	1,665,485.2
Polymers	62,252.0
Plastic	83,453.5
Glass/carbon comps	71,555.3
Aluminium (Al)	55,018.8
Boron (B)	48.2
Chromium (Cr)	6,318.0
Copper (Cu)	68,379.8
Cobalt (Co)	7,612.5
Dysprosium (Dy)	219.8
Iron (cast)(Fe)	241,665.0
Manganese (Mn)	19,057.1
Molybdenum (Mo)	1,314.0
Neodymium (Nd)	1,427.3
Nickel (Ni)	28,597.8
Praseodymium (Pr)	300.8
Terbium (Tb)	39.0
Zinc (Zn)	67,100.0
Silica (Si)	4,927.4
Silver (Ag)	24.6
Germanium (Ge)	0.2
Cadmium (Cd)	1.9
Tellurium (Te)	2.0
Indium (In)	0.5
Gallium (Ga)	0.1
Selenium (Se)	1.0
Graphite	41,967.7
Lithium (Li)	5,170.2
Platinum (Pt)	0.5
Iridium (Ir)	0.8

Table 10.1 Cumulative metal and material demand.

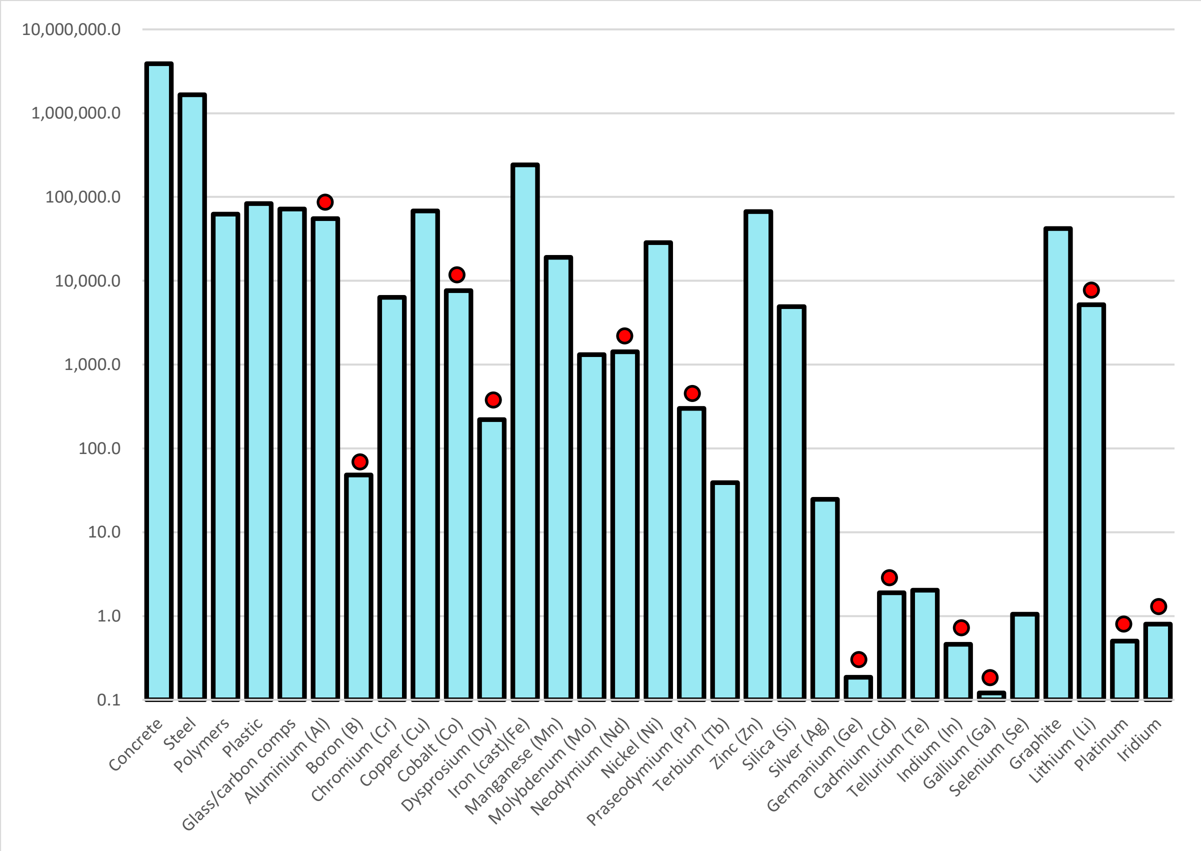


Figure 10.1 Total metal and material demand arising from decarbonisation of energy and transport sectors, inclusive of storage and grid upgrades. Note Y-axis scale is logarithmic.

It is important to contextualise these demands in terms of global supply. For example, the greatest demand exists for concrete, but supply should exist to meet this need. Issues for supply are more likely to arise for critical raw materials and those that may experience supply issues in the near future and thus jeopardise realisation of 2030 targets. This comparison of expected demands to current global supply may also serve to inform selection of technology and infrastructure – i.e., wind turbine drive train assembly considering REE supply, or offshore cabling conductor choice.

In order to do this, a gauge on share of global supply can be estimated by using Ireland's population as a percentage of global population, this method has been used in other supply demand assessments (Viebahn *et al.*, 2015; Habib and Wenzel, 2016).

Ireland makes up 0.06% of the global population. By deducing 0.06% of the global supply of all metals and materials assessed here, it is possible to obtain a theoretical 'Irish allocation'. The demand stemming from CAP targets was compared to the 'Irish allocation' to highlight the metals and material demands that are likely to exceed supply (Fig. 9.2). A value of 100% in this figure indicates that the demand stemming from CAP targets would require 100% of the 'Irish allocation'.

Figure 9.2 highlights only demand stemming from considerations in this report and does not include demand that already exists for some of these materials for other applications.

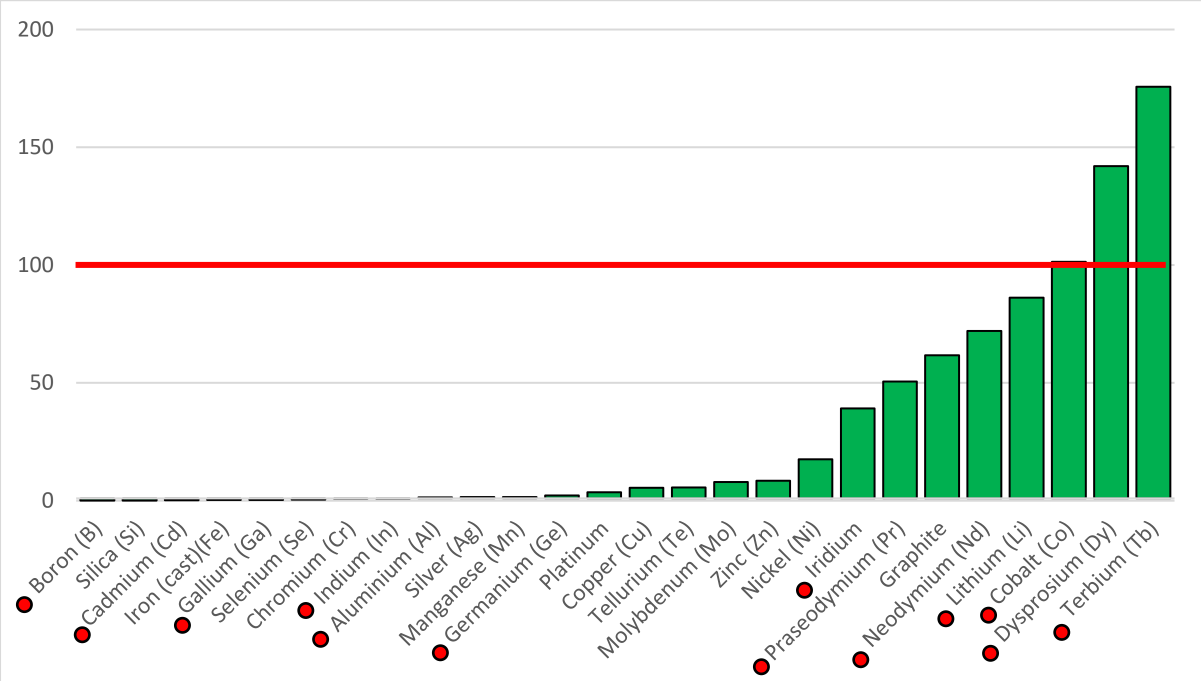


Figure 10.2 Demand arising from CAP targets in comparison to 'Irish allocation', see text for explanation. Red line indicates equal CAP demand and 'Irish allocation'.

The material and metal demand has also been broken down by applications considered (Fig. 9.3). This enables better understanding as to how each application contributes to the overall total demand. Some metals like copper and aluminium have universal use across all applications while others are application or technology specific.

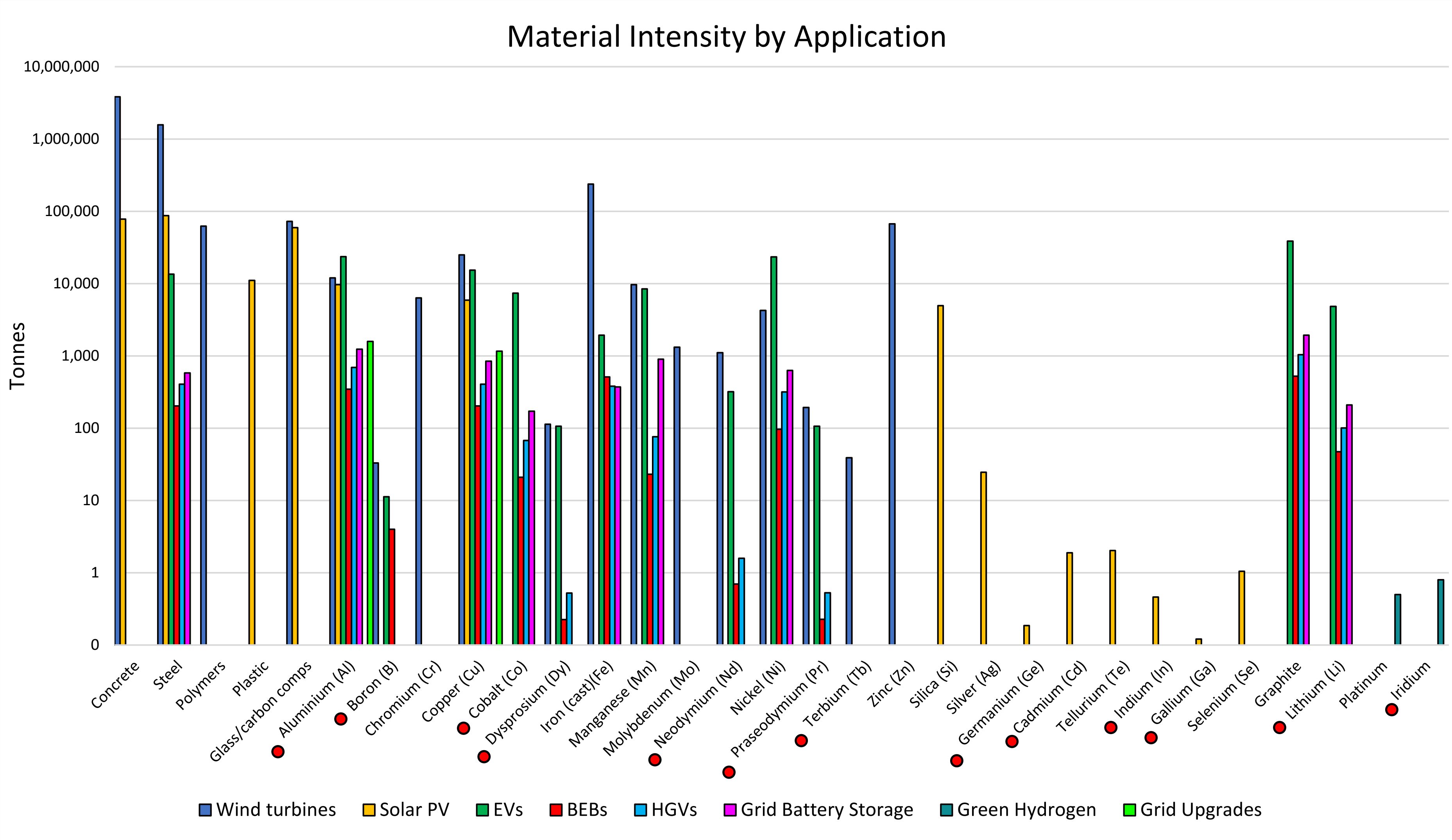


Figure 10.3 Material demand broken down by application. Note Y-axis is logarithmic.

11 Outlook for Critical Raw Materials

The analysis carried out here has identified 13 critical raw materials (CRMs) currently on the European list that are key to meeting CAP targets for energy and transport sectors. The recently updated CRM report compiled by the United States Geological Survey (USGS) in 2022 has also been considered in this section and comprises a further seven raw materials from this analysis that are now considered critical (Fig. 10.1). These raw materials are across the spectrum of technologies required for renewable energy and electrification of transport (Fig. 10.2). The expected demand to feed Ireland's decarbonisation targets (Fig. 10.1) is likely to exceed the supply of these critical materials considering their existing application in other industrial processes and products including aerospace, security, and portable electronic devices. Access to resources is a strategic security question for Ireland and Europe's ambitions to deliver on climate action targets. The outlook for critical raw material demand stemming from global demand as the renewable energy and transport sectors grow is explored in this section. The dynamic nature of this supply relationship is also highlighted with recent political instabilities and conflicts and how this may impact the materials currently on the critical or non-critical raw materials lists. Furthermore, the imperative to decarbonise the global energy economy will result in a widespread increase in demand for the raw materials required. While this outlook focuses on Ireland, similar exercises and raw material requirements will be mirrored across all other economies globally.

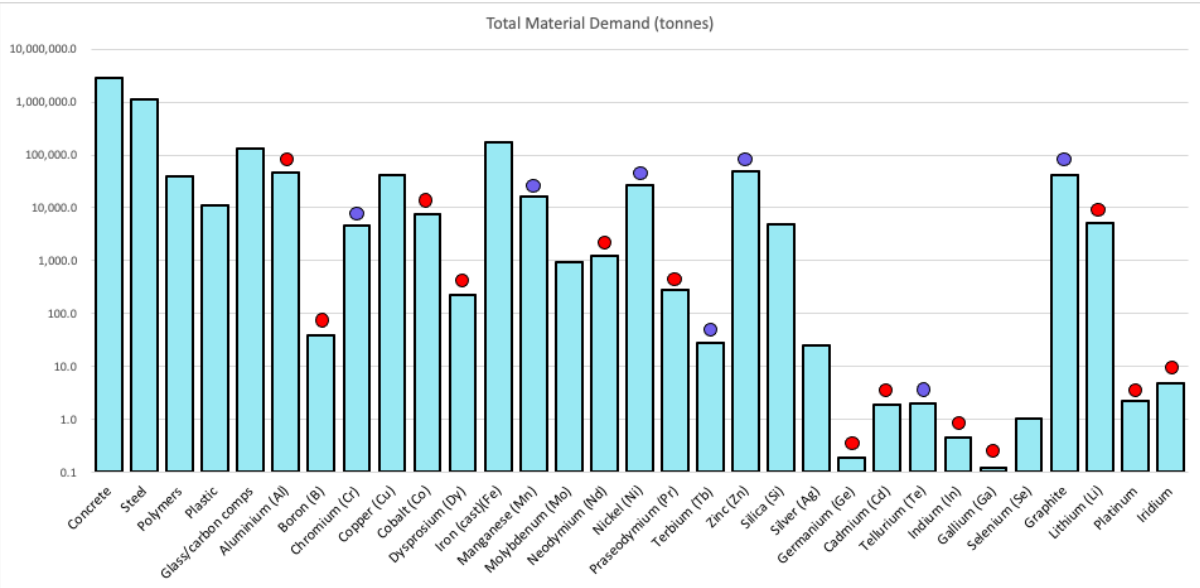


Figure 11.1 Total material demand with CRM highlighted from European list (2020) as red dots, and the additional materials on the USGS list of CRMS (2022) in blue.

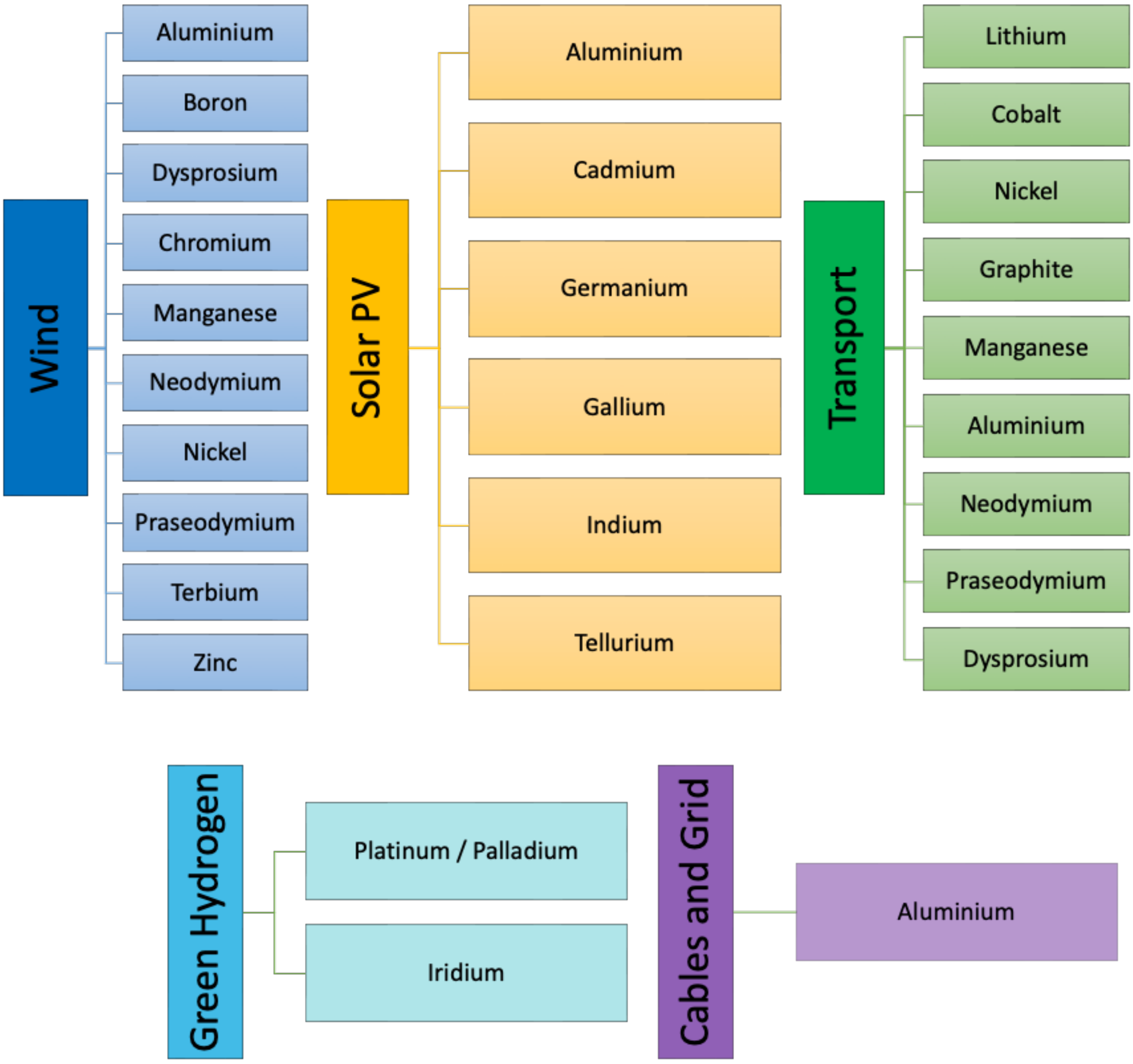


Figure 11.2 Critical Raw Materials (EU and US) across Energy and Transport sectors.

The designation of materials as critical, whether in Europe or the USA, includes economic importance and supply risk. Economic importance considers the allocation of raw materials to end-uses based on industrial applications. Supply Risk considers the country-level concentration of global production or primary raw materials and sourcing, the governance of supplier countries (including environmental aspects), the contribution of recycling, substitution, import reliance, and trade restrictions in third countries (European Commission, 2020; USGS, 2022).

The most up to date USGS CRM includes materials not present on the EU version (Fig. 10.1), which highlights the rapidly changing environment for mineral criticality in the face of political factors and the rapid expansion of the renewable energy and electric automotive industries. Of notable concern for these sectors is the concentration of production of certain metals included in the assessment above, in singular countries (Fig. 10.3). REE are dominantly produced in China, including those required for permanent magnets (Nd, Dy, Pr, Tb); Cobalt is mostly produced in the DRC and refining is concentrated in China and is a key component in batteries; Platinum group metals (PGM) required for production of hydrogen, including platinum, palladium, and iridium, are mainly produced in South Africa and notably a high percent of palladium from Russia (40% of European supply; European Commission, 2020). Many of these raw materials are among the most critical stemming from Ireland's targets for energy and transport sectors (Fig. 9.2).

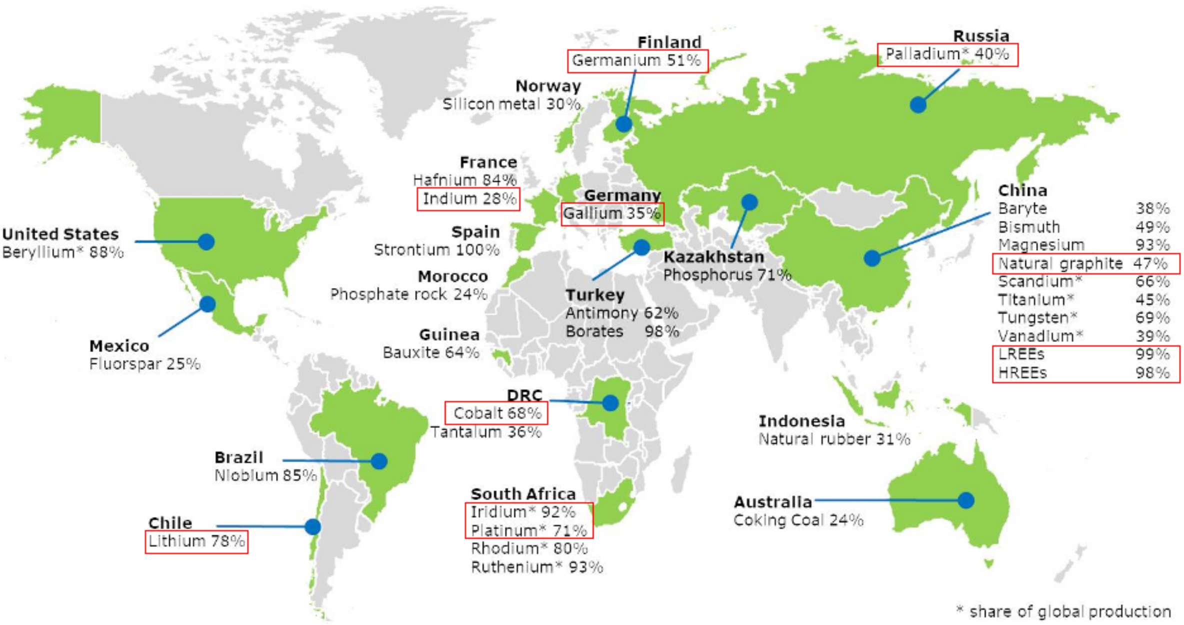


Figure 11.3 Greatest supplier countries of critical raw materials to the EU (European Commission, 2020). Materials required for decarbonisation of energy and transport sectors are highlighted with red boxes.

International, European, and domestic targets for the expansion of renewable energy and electrification of the vehicle fleet will translate into a significant increase in demand for these materials. Current production rates will not be sufficient to meet this demand (U.S. Energy Information Administration, 2021; IMF, 2021). Increasing demand issues are compounded by political issues including conflict in Russia and Ukraine translating into uncertain supply chains of certain materials produced in these countries. PGM necessary for hydrogen production have been mentioned but other metals necessary for the decarbonisation of energy and transport can also be affected, including manganese. China is the primary producer of manganese (82% in 2021; Holman, 2022) and Ukraine was the fifth biggest global producer of manganese in 2021 (Investing News, 2022). Manganese is a key ingredient in steel and used in numerous components in wind turbines (Verma *et al.*, 2022). Inclusion of manganese as a critical raw material in the USGS assessment cited potential for supply disruption as a reason for inclusion. Conflict in Ukraine will undoubtedly impact supply of the metal and potentially impact the production of essential components for wind turbines and electric cars (approx. 20 kg in a typical electric vehicle battery pack: IMF, 2021). Tellurium does not appear on the official EU list of critical raw materials (2020) but the proportion of supply to the

EU in 2019 from Ukraine and Russia amounted to 33%, which would likely add it to an updated EU critical raw material list. The USGS CRM list has included tellurium, noting a growing increase in net import requirements. Demand will particularly grow should market penetration of Cd-Te solar panels occur, as assessed in the HDS scenario for solar energy (Sect. 5).

Metals fundamental to battery production also figure dominantly in the most critical materials for Irish targets considered, including cobalt, lithium, and nickel. Of these metals, cobalt and lithium are designated as critical in the EU and nickel has been recommended for inclusion on the USGS list (USGS, 2022) based on the risks associated with heavy reliance on a single domestic source. While the EU has several domestic sources for nickel ore consumption (65kt), the consumption of refined nickel (375 kt) was largely sourced from Russia (36%) (European Commission, 2020). Nickel is one of the key raw materials for the decarbonisation of the EU, given its use in solar panels and batteries. Demand for nickel in Li-ion batteries is currently only a small percentage of its total demand, but that demand is expected to grow markedly as battery electric cars are experiencing an enormous growth in demand globally. In 2012 the number of electric cars sold amounted to 120,000, whereas in 2021 that many were sold in a week. In 2021 the global stock of electric cars globally was 16.5 million, 5.5 million of which are in Europe evenly split between BEVs and PHEVs (Fig. 10.4). By 2030 the number of electric cars is expected to swell to 250 million (Fears, 2021). This will place pressure on raw material supply to meet demand in manufacture of electric batteries and traction motors used in electric vehicles. Of the most critical materials identified from decarbonisation of Ireland's transport and energy sectors (Fig. 9.2) 9 of the top 10 with greatest supply shortage potential are required for electric car batteries or tractions motors. Figure 9.2 does not include demands on the same materials from other industries and uses such as permanent magnets in heating, ventilation, and air conditioning, which will place further strain on supply of these metals. Considering the continued demand surge there is a push to move away from the use of heavy REE such as dysprosium in permanent magnet motors used in both wind turbines as well as in electric vehicle traction motors. For battery electric vehicles and wind turbines, research and development efforts on motors are currently pushing towards high power density without the use of dysprosium (non-heavy rare earth permanent magnet traction motors) (Pavel *et al.*, 2017; Raminosoa *et al.,* 2020).

12 Domestic Production and prospects in Ireland

Production of raw materials in Ireland is predominantly zinc and gypsum. In 2021 domestic production of zinc amounted to 122,200 metric tons.

12.1 Zinc

Zinc is a key metal for the green transition primarily in galvanising of steel required for wind turbines, electric vehicles, and solar panels. The amount of zinc required per GW of electricity produced by wind turbines is currently 5500 t (Carrara *et al.* 2020). As demand for these key technologies in the green transition grows, so will the demand for zinc. While zinc is not currently on the list of the EU CRM, it was included on the US version in 2022 (USGS, 2022), reflecting the growing need for this metal in green technologies globally. Ireland was the 4th largest producer of zinc in Europe in 2021 (Statista, 2022) and thus is of strategic importance in realising future development of renewable energy and electrification of transport. As well as demand from established technologies, zinc demand could increase from battery technology currently under development. Zinc oxide has attracted attention as an electrode material for lithium-ion batteries due to its low cost, environmental friendliness, and high theoretical capacity (Thauer *et al.,* 2021). The potential for this type of battery is discussed in Section 8.1 above and it is expected that next generation technologies could place further demand on zinc.

The Irish base metal ore field is one of the world's best mineralised zinc provinces and is considered highly prospective for new zinc discoveries. This is coupled with advances in the ability to explore in peatland which cover most of the Irish midlands, techniques including seismic, ground penetrating radar, and directional drilling (Hitzman and Zhou, 2022, pers. comm., 12 July). If demand for zinc continues to grow through the avenues mentioned above there is potential for Ireland to supply considerable volumes to contribute to the green transition, particularly in the sectors of energy and transport.

12.2 Lead

Lead is additionally a key metal for the green transition primarily used in cable sheathing for submarine cables (Carrara et al. 2020), a key component of Ireland's Climate Action Plan. Demand for lead will thus increase commensurate with the rollout of subsea cable networks needed to connect the Offshore Renewable Energy production facilities to the continental grid.

Lead in the Irish Midlands Orefield occurs in conjunction with the world class zinc deposits and has been mined in Ireland for centuries. Ireland is consistently one of the 5 largest producers of lead within the European Union (British Geological Survey, 2022) and can produce lead alongside zinc in an efficient manner. Ireland is well placed to contribute to Europe's sourcing of lead for the Green Transition.

12.3 Secondary raw materials

Potential also lies in secondary yield of minerals and metals from mine waste and tailings, contributing to circularity in mining. Analysis of Irish sphalerites (zinc ore) revealed that germanium was present in moderate amounts, and gallium had a minor presence (Zhou *et al.,* 2021). The growing use of these metals in renewable energy technology (solar PV), as well as other applications such as smart phones and fibre-optic cables has resulted in a rapid increase in their economic importance, and designation as critical raw materials internationally. The presence of these elements represents an opportunity for their extraction from mine waste in Ireland as well as potential recovery as smelting by-products.

Analysis across the spectrum of waste streams can also contribute to altering systems from a linear to a circular pathway, involving multidisciplinary collaboration. Biogenic concentration of zinc in waste and tailings, like that used for gold extraction may be possible (Hitzman and Zhou, 2022, pers. comm., 12 July) as could the removal of rare earth elements from fly ash, and recycling of unused electronics. All methods that have potential to use waste products to attain critical raw materials promote a circular economy.

12.4 Lithium

Lithium, classed as critical in the EU and US, is a key element in the development of renewable energy and electric cars because of its role in Li-ion batteries. Exploration for Lithium in Ireland has been underway since the 1970's since the discovery of spodumene pegmatites in the Leinster Granite. Spodumene contains almost 4% lithium, and historically one of the most significant sources of lithium (Geological Survey Ireland, 2021). This lithium source is preferable to that extracted from liquid brine for battery production as it can be processed or production ramped up faster, the spodumene hosts higher lithium content, and pegmatites are globally distributed which can avoid disruption of supply more effectively. Thus far in Ireland, extensive pegmatites have been identified from surface exposure or near surface drilling activities. The potential for pegmatite presence at deeper depths is yet to be explored but is in the licencing process. As well as the pegmatites themselves, the rock surrounding them is also enriched with lithium but requires a different extraction method as it exists in micas (Menuge, 2022, pers. comm., 26 July 2022; Lee, 2015). This has the potential to increase lithium yield from spodumene pegmatite zones. However, Identification of spodumene pegmatites at depth has been problematic. GreenPeg is an EU Horizon2020-funded research project that aims to improve exploration in Europe for pegmatites in the search for critical minerals and seeks shorter and more secure supply chains for pure silica, lithium, tantalum, caesium and beryllium for the energy transition and emerging technologies. This project is testing geophysical and geochemical methods to better identify pegmatites buried at depth. Pegmatites are showing a higher resistivity in geophysical testing, which may hold promise for deeper exploration in Ireland, and potential to supply some of these in demand raw materials (Menuge, 2022, pers comm., 26 July 2022). Greater de-risking of potential drill locations as well as the extraction of deeper targets can contribute to a reduced surface impact and aid in public acceptance. Ireland therefore is of strategic importance in the continued supply of zinc as well as having the potential to supply other critical materials including germanium, gallium, and lithium.

13 Looking to 2050

Ireland is committed to carbon neutrality by 2050. Net-zero pathways include removal of emitters as well as factoring in carbon removal tactics. Energy, transport, and other sectors that produce the majority of global greenhouse-gas emissions face a steep challenge to decarbonise completely, but research shows that solutions are within reach. A successful transition to net zero will require meeting increased demand for electricity by scaling up renewable, low-carbon power generation and building enough flexibility in power systems to match supply and demand (McKinsey, 2020). To decarbonise transport, new supply chains and manufacturing capabilities are needed, as well as corresponding infrastructure such as charging stations and hydrogen fuelling stations. Innovations in electrifying heavy vehicles will be key to achieving targets.

There are many parameters and variables that exist in achieving carbon neutrality by 2050, including a presumed availability of technology that currently is in its infancy, and as such is currently expensive and likely subject to accelerated technological advances in the coming decades. For power generation by renewable means factors such as future energy demand, increased deployment of renewable energy generation means, and technological advances will all impact the level of infrastructure required and the raw material demand that will occur.

Similarly for decarbonisation of the transport sector technological advances and increased use of next generation car batteries as well as increased penetration of green hydrogen in fuelling heavy vehicles are key to achieving carbon neutrality.

Technological advances will likely result in a reduced demand for critical raw materials and could even result in their elimination as research into renewable electricity and transport technologies continues. In 2019, around 80% of all public energy research and development spending was on low-carbon technologies – energy efficiency, CCUS, renewables, nuclear, hydrogen, energy storage and cross-cutting issues such as smart grids (IEA, 2020) with future increased investment predicted. In Ireland, total public energy R&D budget for 2020 was 27 million USD, of which 13 million USD was for research in renewable energy sources and 0.3 million USD for hydrogen and fuel cells (Fig. 11.1). Commercial vehicle producers and governments are investing heavily in the attempt to produce cheap, efficient, and safe EV car batteries.

Scenarios to 2050 include a potentially significant role for the use of zero-emissions gases (in particular biomethane and green hydrogen) directed towards sectors that maximise emissions abatement in hard to abate sectors, such as transport. Green hydrogen, explored in Section 7.2

above, has been identified as having the potential to support decarbonisation across several sectors, and in particular, in high-temperature heat for industry and in electricity generation. Green hydrogen, produced from renewable energy, has a significant role to play in sector coupling (the increased integration of energy end-use and supply sectors with one another), and minimising the overall cost of decarbonisation across all sectors (CAP, 2021). Advances in green hydrogen technology will undoubtedly occur as it is currently an immature technology. These advances are imperative to the large-scale adoption of this technology and its pivotal role to carbon neutrality by 2050 in renewable energy generation and other sectors. As highlighted above the demand from platinum group metals is currently very high for this technology and if it is to be used to a large extent to achieve carbon neutrality it is imperative that the material intensity decreases.

As a result of ongoing research and development in both the renewable energy and transport sectors as well as certainty in increased demand it is difficult to outline the demand on raw materials that will eventuate on the road to carbon neutrality between 2030 and 2050. It is also likely that recycling will increasingly impact the level of material demands as existing infrastructure reaches end of life.

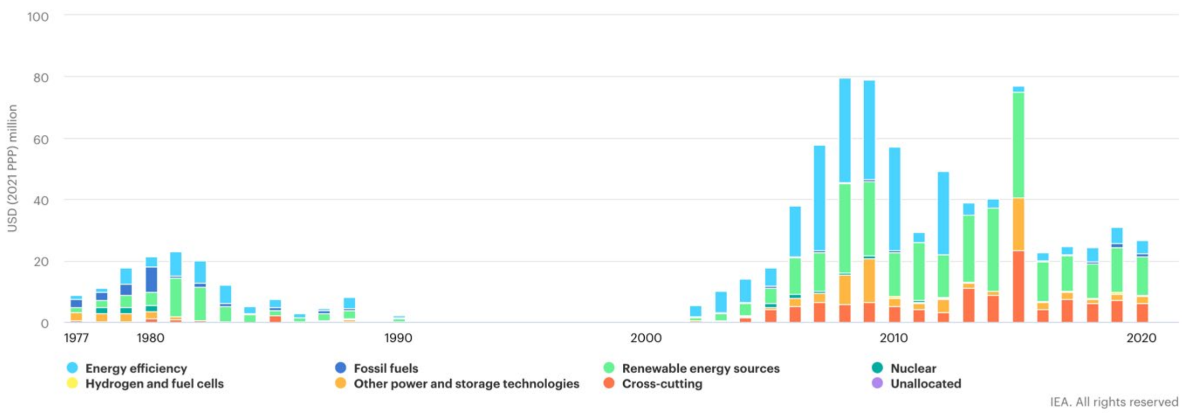


Figure 13.1 Total public energy R&D budget for Ireland (IEA, 2021).

This section will outline some of the predicted and possible pathways to climate neutrality by 2050 in Ireland and the technologies that are believed to be key in this transition. An understanding of the raw material demand that might arise, and key areas of advancement and recycling are also explored in the renewable energy and transport sectors to provide insights into how demand might be offset.

13.1 Carbon Neutral Energy Sector

Over the past decade, the cost of renewable energy generation has dropped substantially—solar power by as much as 80 percent and wind power by about 40 percent—making them economically competitive with conventional fuels, such as coal and natural gas (McKinsey, 2020). Once the renewable electricity share of generation increases above the 2030 targets (80%), however, the system abatement cost becomes very expensive with current technologies. Reducing emissions beyond 2-4 Mt will require the development of a variety of long duration storage technologies and renewable gases. Other market evaluations to carbon neutrality for power generation agree that it is economical and technically possible to reach 50% - 60% decarbonisation. Getting to 90% decarbonisation is technically feasible but will be costly and getting to 100% is both technically and economically difficult (McKinsey, 2020). As we move away from fossil fuels and harness renewable indigenous resources, we enhance our security position, Ireland is currently one of the most dependant countries in Europe on imported fossil fuels. By 2050 this dependence could reduce to less than 5%. To achieve this, a resilient electricity system is required, with adequate flexibility, underpinned by grid development, flexible loads, sufficient capacity, interconnection, and storage (MaREI, 2021).

The path to complete decarbonisation of the power sector is fundamentally about filling longer duration gaps that conventionally would be filled by on demand supply from hydrocarbon-fuelled power plants. This requires extensive carbon-free dispatchable generation to manage periods of low sun or wind. Excess wind and solar can be used to manage this system, resulting in less curtailment when power generation is high. Other methods to ensure flexibility in the power generation system may include all, or a combination of, grid improvements, interconnection, storage systems, smart heating, and flexible EV loads, incorporating zero carbon flexible generation, and adding demand side management (MaREI, 2021).

Required capacity from wind and solar electricity generation that will lead to net-zero targets for electricity generation have been estimated. Greatest estimates for wind generation are 11-16 GW onshore wind; 30 GW offshore wind; and 4 GW from solar PV (MaREI, 2021; WEI, 2021). These assumptions also include enabled capacity such as batteries (3 GW), interconnection (3 GW) and decarbonised gas units (6 GW), which are assumed to run on hydrogen during periods of low wind generation (MaREI, 2021). Fundamentally, these estimates must consider the expected increase in electricity demand to 2050 from data centres, the increased uptake of EV charging, and electrical heating. Using these figures for renewable energy generation capacity it is possible to deduce a potential additional capacity, assuming 2030 targets are achieved (Table 13.1). These calculations assume a mid-range figure for onshore wind capacity of 13.5 GW and includes the repowering of end-of-life capacity as predicted by EirGrid (2019) amounting to 65% of existing capacity in 2019. Some additional minor capacity repowering may be required immediately prior to 2050 of turbines and solar panels deployed prior to 2025, assuming a 25-year lifetime but has not been included here. Assuming the 5.5 GW solar capacity is reached by 2030, the current predictions to 2050 will have been surpassed. Greater deployment of solar farms after 2030 is likely but with no estimate available no further calculation of material demand from further solar PV is considered to 2050.

	Wind (GW)	
	Onshore	**Offshore**
2030 Capacity	8	7
Additional Requirements	5.5	23
2050 Capacity	13.5	30
Repowering required	2.8	
Total additional Capacity for 2050	**8.3 GW**	**25 GW**

Table 13.1 Additional capacity required by 2050 to assist in reaching carbon neutrality in the energy sector.

Advances in technology and knowledge will undoubtedly impact the outlook for material demands to 2050, most notably will be the substitution and elimination of some rare metals and materials in wind turbines, the transition to floating offshore wind turbines, the increasing impact of recycling, the increased capacity of individual turbines, and the adaptation to supply chain issues as they arise. With estimates available for the capacity that may be required in 2050 it is possible to make an estimate of the metal and material demands. These estimates are highly speculative and largely based on current technology but consider some potential technological advancements that are in the research and development stages. Long term future technological advances will reduce or remove material intensities, but to what extent is difficult to predict. The estimates provided here for material demands do not include potential reductions and as such should be viewed as a maximum for material demand. All further future advances, substitutions, and greater penetration of recycling are likely to reduce these figures. Achieving these targets is also dependant on other factors including conducive policy and necessary upgrades to the transmission network, it is assumed here that these are in place and do not impede the targets set as necessary by 2050.

The split of turbine technology is also speculatively projected to 2050 by Carrara *et al.* (2020) and does not show major change in market share from 2030, possibly reflecting uncertainty (Table 13.2). One major change in turbine material demands will certainly be in the reduction of the level of concrete and steel required for floating offshore wind turbines. There are several different substructures for these turbines and only some incorporate concrete use in the floatation system, of these the material intensity is as low as 30,000 t/GW (Eatough, 2021). As the preferable floatation system to 2050 is unknown this value for concrete use has been used as standard for offshore deployment and therefore assumes all will use some concrete. Otherwise, material intensities have been used from Table 5.6 despite the likely improvement in efficiency and size, with consequent alterations in material demand per turbine (Kim *et al.*, 2015)

2050	DD-EESG	DD-PMSG	GB-PMSG	GB-SCIG
Onshore	0.2	0.2	0.5	0.1
Offshore		0.85	0.1	0.05

Table 13.2 Market share of turbine technology between 2030 and 2050 from Carrara et al. (2020).

Material	Total (t)
Concrete	3,714,520
Steel	3,667,605
Polymers	143,980
Glass/carbon comps	254,673
Aluminium (Al)	24,859
Boron (B)	134
Chromium (Cr)	16,678
Copper (Cu)	80,830
Dysprosium (Dy)	413
Iron (cast)(Fe)	629,487
Manganese (Mn)	24,772
Molybdenum (Mo)	3,456
Neodymium (Nd)	4,217
Nickel (Ni)	9,344
Praseodymium (Pr)	783
Terbium (Tb)	157
Zinc (Zn)	172,150

Table 13.3 Estimated metal and material demand arising from addition wind turbine capacity to 2050.

13.2 Carbon Neutral Transport Sector

Future increased decarbonisation of the transport sector beyond the measures laid out in the CAP (2021) will be highly influenced by innovation and technology. The Climate Action Plan highlights green hydrogen as a horizon development and having the potential to support decarbonisation in the transport sector. It is envisaged from 2025 that green hydrogen will contribute to the decarbonisation of hard-to-abate sectors such as HGVs and shipping. Fuel cells can potentially be an alternative to batteries in electric vehicles, using the same technology for electrolysis of water. The material demands associated with fuel cells and the electrolysers, as laid out in Section 7, are the same as PEM electrolysers are the most common technology used in fuel cells.

In terms of batteries there are likely to be advances in technology that will increase efficiency, range, and decrease material intensity. Many car manufacturers are in a race to produce batteries that are cheaper, faster charging, and less vulnerable to raw material shortages. Most of these technologies reduce metal demand including nickel, cobalt, manganese, or lithium. Such batteries include lithium-sulphur (LiS); lithium-oxygen (LiO); Zinc-oxygen (ZnO); and solid-state batteries (Bongartz *et al.*, 2021; Mattieu and Mattea, 2021). With respect to material composition of these innovative batteries, only limited data are available as these technologies are still under development. It is certain that the LiS and LiO batteries have a lithium electrode so still have similar demand for this metal as seen in current vehicle batteries (Table 7.2).

LiS batteries may displace Li-ion cells because of their higher energy density (Fig. 11.2) and reduced cost owing to their use of sulphur instead of cobalt. Progress has slowed though as there is a lower number of recharge cycles possible. Li-O batteries theoretically can have a specific energy 5 times that possible in current Li-ion battery technologies, however significant electrolyte advances are needed to develop a commercial implementation (Badwal *et al.*, 2014). Other issues to overcome in these next generation batteries include safety concerns, capacity fading, and complicated chemistries and reactions (Younesi *et al.*, 2015). Li-S and Li-O batteries in terms of their material demands will significantly reduce the need for cobalt, nickel, and manganese. In contrast, the materials used in the electrodes of these batteries are comparatively low cost, with sulphur being among the most abundant element on earth (Faraday Institute, 2021).

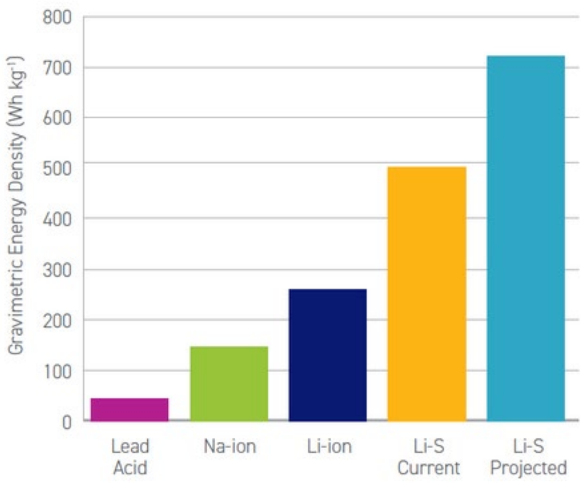


Figure 13.2 Current and projected gravimetric energy density of Li-S batteries compared to state-of-the-art alternative battery technology. From Faraday Institute (2021).

Zinc-air batteries and zinc-air fuel cells are an example of a metal-air battery powered by oxidising zinc with oxygen from the air. These batteries have high energy density, similar to Li-S/O, several times higher than that of commercial Li-ion batteries and are relatively inexpensive to produce, given their use of more readily available materials (Shermann *et al.*, 2018). Grid-scale zinc-air batteries could cost $100 per kilowatt-hour, less than half the cost of today's cheapest lithium-ion versions (Service, 2021). Previously these batteries have been disposable and mainly used in small electrical devices, recent advances however have indicated that these batteries could be used in vehicle propulsion, specifically overcoming their inability to be recharged (Temming, 2021).

Finally solid-state batteries remove the liquid electrolyte and instead use a solid electrolyte is used that can be glass, ceramics, or other solid material, making the battery more dense and compact translating to greater range and less prone to fire risk. Research and development of this battery type for use in vehicles is occurring on a large scale with major manufacturers having announced their use in hybrid vehicles from 2025. While overcoming issues in standard Li-ion batteries, solid-state batteries may not impact the metal demands for critical raw materials including cobalt and lithium.

Exact impacts on the metal demands that will occur after 2030 and to 2050 will be dependent on the future success of research, and commercial viability of next generation batteries in light vehicles. Most next generation batteries aim to reduce the use of critical raw materials, and those that are predicted to be in very high demand which would indicate a reduction in demand for cobalt, nickel, manganese, and to a lesser extent lithium, while increasing demand from the transport sector for more abundant metals and materials including zinc and sulphur.

Large scale recycling of electric vehicle batteries will have an impact on the levels of metal demand in the future. Mathieu and Mattea (2021) estimate that minor volumes of battery related metal demand will be met by recycled EV batteries in 2030 but will increase significantly to 2035 (Table 13.4). Recycling of metals from EV batteries not only lowers future demand but also creates a circular use of the metals and provides employment supporting a just transition. EU battery regulations will ensure the recycling capacity of batteries increases significantly. Recent legislative proposal includes an increase in the weight of a Li-ion battery that must be recycled from 50% to 65% in 2025 and 70% in 2030, and seeking a 90% recycling rate for cobalt, copper, nickel, and lead from 2026. Recyclers will also have to report annually on the quantity of batteries they handle and recycle, and the recycling rates of various materials extracted. If these proposals become law in the EU, it is possible that demand to 2030 may be offset to some extent by recycling of materials. The level of impact of recycling however will be hampered by the supply of end-of-life batteries compared to demand for new batteries. The impact of recycling offsetting demand will grow by the same rate as EV production but offset by 10-20 years, the expected lifetime of an electric vehicle, assuming the recycling capacity exists. Currently only 5% of Li-ion batteries are recycled (Hirschlag, 2022). Europe’s largest battery recycling plant, Hydrovolt Norway, has the capacity to process 12,000 tons of battery packs per year, or approx. 25,000 EV batteries. The plant claims to recover 95% of the materials used in the EV battery (Dow, 2022).

Metal	2030	2035
Lithium	5%	22%
Cobalt	17%	65%
Nickel	4%	22%

Table 13.4 Percentage of required metal demand to make EV batteries that may be met by recycling of end-of-life EV batteries.

A major concern for continued prevalence of electric vehicles to 2050 will also be in the requirements of REE for traction motors, particularly dysprosium, required for the magnet to operate at higher temperatures. Reducing the amount of REE content is the focus of research through two methods: 1) increasing metal efficiency in magnet production, obtaining a magnet with less rare earth content; and 2) optimising motor design, enabling high technical performance while using less magnet (Pavel *et al.*, 2017). Alternatively, motors that do not use permanent magnets can be used, including induction motors and electrically excited synchronous motors, which similar to a turbine motor, does not have a permanent magnet but an electric current magnetises copper windings. The largescale use of these motors is impacted by their lower power density and higher weight compared to PSM (Pavel *et al.*, 2017).

14 Concluding Remarks

The demand for raw materials imperative to the green transition is set to grow at a rapid rate, particularly to 2030 as methods of offsetting demand are not currently present or technologically advanced yet. Supply of these materials will be instrumental in the realisation of decarbonisation targets in Ireland and globally. Potential bottlenecks and roadblocks to supply exist in the form of supply monopolies and rarity of materials. In particular the criticality of raw materials essential to the production of high-tech, low carbon goods such as electric vehicles, wind turbines, batteries, and solar panels will determine if targets are attainable.

Most commonly cited critical materials to the green transition are REE and battery critical elements (lithium, cobalt, nickel, graphite, manganese). This is reflected in the demands stemming from decarbonisation of energy and transport sectors in Ireland, highlighted by comparison with global supply trends. The most efficient technologies in electric vehicles and renewable energy are dependent on critical materials and this trend is not predicted to change in the near future, with a lack of comparable alternatives that comprise less critical raw materials. Considering this the pressing need for domestic production and recycling within the EU of critical raw materials should be at the forefront of policy and investment.

Other materials that are also facing sharp increases in demand include zinc, used for galvanising steel, particularly in offshore wind turbines. Zinc has been designated as critical by the USGS but has not yet been included on the EU equivalent list. Ireland as a major producer of zinc in Europe has the potential to become of strategic importance in resourcing the switch to renewable energy. Other exploration endeavours in Ireland for Lithium and REE may also provide critical materials to the green transition. Increased production from secondary sources also reflects the endeavour to increase circularity in the mineral extraction and use cycle. Increased domestic production in the EU is predicted to attract heavy investment particularly in the areas of geological exploration and mining, and development of effective recycling systems. These systems will likely include the development of recycling technologies as well as infrastructure to collect, dismantle and separate products containing critical raw materials.

Continued decarbonisation and realisation of net zero by 2050 is largely dependent on success in the research and innovation sphere. This includes methods of recycling material already in use once end of life is reached, reduction in material intensities, and substitution of critical materials. Many of these methods are the subject of intense research in academia and corporations alike and will contribute to technology with greater efficiency and reduced material intensities.

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