ENERGY INFRASTRUCTURE MATERIALS MAPPING

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ACKNOWLEDGEMENTS

Wood Enviromental & Infrastructure Solutions for their contribution to this report.

EXECUTIVE SUMMARY

Scope and purpose

This report has been produced for the purpose of understanding the types and quantities of materials needed for construction of, and generated by the decommissioning of, energy infrastructure during Scotland's transition to Net Zero by 2045. Currently, Scotland imports many of the raw materials and products needed to build renewable energy assets, and subsequently exports much of the recyclable waste arising from the maintenance and decommissioning of these assets. However, this approach does not support Scotland's vision of a circular approach to the energy transition.

Zero Waste Scotland commissioned Wood to consider the material types and quantities currently required and projected to be required up to 2050. This report forecasts, through high-level analysis, the generation capacity of seven low carbon technologies[1], as well as onshore electricity transmission and distribution (T&D) and decommissioned oil & gas (O&G) infrastructure, to understand the scale of this sector to 2050. The authors have considered materials for each technology, End-of-Life (EoL) processes and potential technological advances that may impact materials. This report also presents high-level findings for the proportion of selected materials required for installation and life extension of assets by 2050, as well as those generated from decommissioning and life extension by 2050. Research to understand supply and demand of these materials in support of Scotland's Material Flow Accounts (MFA) is presented to highlight current, and potential future, material supply issues.

In 2020, Scotland generated the equivalent of 97% of its electricity consumption and 6.4% of its non-electrical heat demand through renewable sources.

Capacity forecast

In 2020, Scotland generated the equivalent of 97% of its electricity consumption[1] and 6.4% of its non-electrical heat demand[2] through renewable sources. The 2017, Scottish Energy Strategy[3] set a target for 50% of Scotland's heat, transport and electricity to be generated from renewable sources by 2030, with full decarbonisation of the energy system by 2050. As such, all of the seven low-carbon energy technologies studied are projected to increase up to 2050. As low-carbon technologies are often situated in remote locations, significant upgrades to the electrical T&D infrastructure will also be required up to 2050, while O&G decommissioning is expected to near completion by 2065[4].

The technologies that are currently in earlier stages of development (i.e. offshore wind, hydrogen, heatpumps (mature technology, but with limited deployment) and electric vehicles (EVs)) are expected to generate the greatest increase in capacity from their current levels over the coming decades and they will also see the greatest increase in materials requirement.

Material requirements

In 2018, Scotland directly consumed nearly 65 million tonnes (Mt) of materials in total across all sectors[5]. This report has identified that to meet increasing renewable energy demands in Scotland, up to 241 Mt of materials, including up to 230 Mt of materials of interest (or "selected materials"[2]), could be required in Scotland by 2050. This is equivalent to at least 12% more materials each year by 2050 than were directly consumed in Scotland in 2018; and potentially 40% more per year up to 2030. This is primarily driven by the large capacity of hydropower that is due to be commissioned in Scotland by 2030; although, as caveated later in the report, further investigation is needed to better understand the material requirements in the hydropower sector.

According to this analysis, those technologies expected to experience the most growth up to 2050 will require large increases in problematic materials such as neodymium and lithium-cobalt (Li-Co) which have not previously been extracted at scale[6]. This study estimates that by 2030, Scotland may require up to 150% more LI-Co oxide per year than was imported into the entire UK in 2020. This deficit is projected to increase to over 400% by 2040 and over 500% by 2050. Materials with more established sectors such as steel, and aluminium, will also require significant, though less pronounced, increases in production to meet demand from the renewable energy sector up to 2050. Scotland (and the UK) has capacity to reprocess some of these materials, including a proportion of steel, iron and aluminium, lithium (and more recently neodymium[7]), although the bulk of these resources are exported for reprocessing at EoL[8, 9].

Environment, Social and Governance and supply issues

Apart from the raw materials required for concrete, the raw materials investigated in this report are mostly extracted outside of Europe and processed beyond the UK. Scotland also exports most of the decommissioning materials identified within this report, with very little captured for recycling or reprocessing domestically. As such, there is a heavy dependence on foreign supply chains for energy infrastructure materials.

Whilst the earth technically contains enough metal ores to meet projected global demand for most anticipated purposes , extracting and processing them into the form required for energy infrastructure, poses economic, environmental and social challenges[190]. Furthermore, whilst processing capacity for many materials can be expanded within a few years; extraction capacity can take 10+ years to develop. In addition, producers of some materials, particularly rare earth elements, have been known to restrict their output; which has caused their value to soar and countries to begin stockpiling[11]. The UK Government is expected to consider this within the UK Critical Minerals Strategy (to be published later in 2022) under the UK Net Zero Strategy[12].

Material generation and recovery

The decommissioning at End of Life (EoL) of the energy technologies assessed in this report is expected to generate up to 290 Mt of selected materials in Scotland by 2050. Of this total, 94-96% (272-279 Mt) comprises concrete; primarily generated through hydropower decommissioning between 2030 and 2050. Further study is required to determine the quantity of materials that can be feasibly recovered.

Recovery of materials from used equipment can yield far greater quantities than those extracted through the mining of raw materials. For example, it is reported that 30 tonnes of recycled Li-ion batteries could provide the same quantity of usable material as 250 tonnes of Lithium ore, or 900 tonnes of cobalt ore[75].

The renewables sector has demonstrated elements of circular practices to reduce the dependence on imported materials, particularly critical materials, through substitution, material reduction, and better design for circularity. For example, the development of rare earth element-free generators is underway to reduce the dependence on rare-earth elements in wind turbines[13] and there are efforts to reduce lithium requirements in Electric Vehicle (EV) batteries through the development of Lithium-Iron Phosphate (LFP) batteries and high-manganese-content batteries[14]. The electricity T&D sector demonstrates better circular design by directly reusing or recycling

more than 95% of materials generated from decommissioned assets within new T&D projects[146].

There is evidence of the reuse of materials and components in other technologies like onshore wind, blue hydrogen, and Oil & Gas. However, where this does take place, refurbished components are often exported for use in lower-income countries[15]. Reuse is preferred EoL treatment in terms of material value retention, however, given reuse is outside of Scotland, it does not support Scotland's ambitions for a circular economy as material is leaked from the Scottish economy. This is particularly pertinent for materials where there are significant supply risks, such as neodymium.

Some materials such as Platinum Group Metals (PGMs), chromium and nickel cannot be directly substituted and there will always remain a proportion of material that cannot be directly substituted, refurbished or reused[16]. The UK has the capacity to reprocess and recycle some of the materials generated at EoL; including a proportion of steel, iron and aluminium (and more recently neodymium); although the bulk of these are exported for reprocessing when the energy assets containing them reach EoL[17, 18]. Nevertheless, UK industry is recognising the importance of securing supply through the development of domestic material reprocessing capacity and the recovery of materials such as lithium. This is demonstrated by the installation of the Fenix Battery Recycling facility in Kilwinning near Glasgow, Glencore-Britishvolt and Veolia's announcements to develop domestic Li-Co recycling capacity[19, 20], and Birmingham

UK industry is recognising the importance of securing supply through the development of domestic material reprocessing capacity and the recovery of materials such as lithium.

University's neodymium recycling plant[21].

The negative ESG impacts and supply constraints outlined above can influence public support for the renewable energy transition. As the International Energy Agency (IEA) notes in a recent report[22], policy makers need to provide clear signals about their climate ambitions to boost investor confidence in committing to new projects. Such efforts should be accompanied by a broad strategy that includes supply chain resilience and sustainability standards.

Limitations and recommendations

This study was commissioned to provide a high-level understanding of the material needs of the Scottish energy sector. It is recommended that, as part of a separate further study, a more detailed analysis for the technologies with low confidence (see Appendix B) should be undertaken to determine more accurate material requirements.

This study has identified the following key limitations and recommended areas of future research:

- The generated materials reported in this study are not all necessarily recoverable. Further analysis must be undertaken to determine the proportion of each material that can be viably recovered, along with further study to identify the capacity that can be recycled in Scotland. Further study should also differentiate between the quantities of raw materials needed for domestic production of infrastructure and those that are embedded in imported products.
- The requirement for nickel and chromium within steel should be investigated further as data were insufficient to quantify this in this study. A more detailed study is also required to understand the requirements of future Scottish energy infrastructure for individual PGMs, and the supply chain risks associated with this.
- Given the early stage of development of the hydrogen economy in Scotland, confidence in the hydrogen assessment is low. A detailed study into the material demands for the wider hydrogen network including hydrogen hubs, transmission etc. should be investigated given the large quantities of rare materials that may be required in this sector.
- A more detailed study of T&D networks, particularly subsea cables, sub stations and battery storage infrastructure, is needed to better understand the materials usage in this sector up to 2050 as they will play a vital role in connecting offshore energy to Scotland, the wider UK and Europe.
- The materials requirement for hydropower should be more thoroughly investigated. Hydropower makes up 80-85% of overall materials and more than 90% of the concrete needed up to 2050 in this analysis[3]. Whilst this assessment supports other literature[23]. A detailed study should be undertaken to understand more accurate concrete estimates for current and planned hydropower assets in Scotland.
- Opportunities for cross-sector collaboration in the treatment of materials should also be investigated. For example, the use of the aggregate generated from hydropower assets could be considered as a direct replacement for the quarried rock that is currently used for rock-dumping decommissioned O&G pipelines.

Key assumptions made in the models and throughout this project are outlined in Appendix D. Data was obtained via a desk-based review of existing literature as well as data supplied by the client and on input from technical experts within Wood.

GLOSSARY OF TERMS

Term	Definition
Alkaline water electrolysis	A water electrolysis technology that involves the use of an aqueous solution of potassium or sodium hydroxide
Allotrope	One or more forms of a chemical element that occur in the same physical state
Blue hydrogen	Hydrogen generated using traditional hydrocarbon-based technologies with carbon capture
Fixed offshore wind assets	Turbines that are installed on platforms secured to the seafloor by concrete or steel pillars
Floating offshore wind assets	Turbines that are installed on floating platforms constructed from concrete or steel and tethered to the seabed
Gearbox (wind turbine component)	A mechanical component that is used to increase or decrease the rotational speed
Generator (wind turbine component)	A device consisting of a moving magnet surrounded by a conducting coil that converts mechanical energy into electricity
Green hydrogen	Hydrogen produced via electrolysis using renewable energy sources
Hydrometallurgical metal reclamation	Method metal recovery from ores or alloys using an aqueous solution
Jacket (wind turbine component)	Subsea structures that fix the turbine platform to the seabed. Monopile jackets are single tubular steel designs that are buried in the seabed. Lattice structures are less dense steel structures similar to traditional electricity transmission pylons
Mattress	A protective cover made of concrete blocks to protect cables or pipelines on the surface of the seabed.

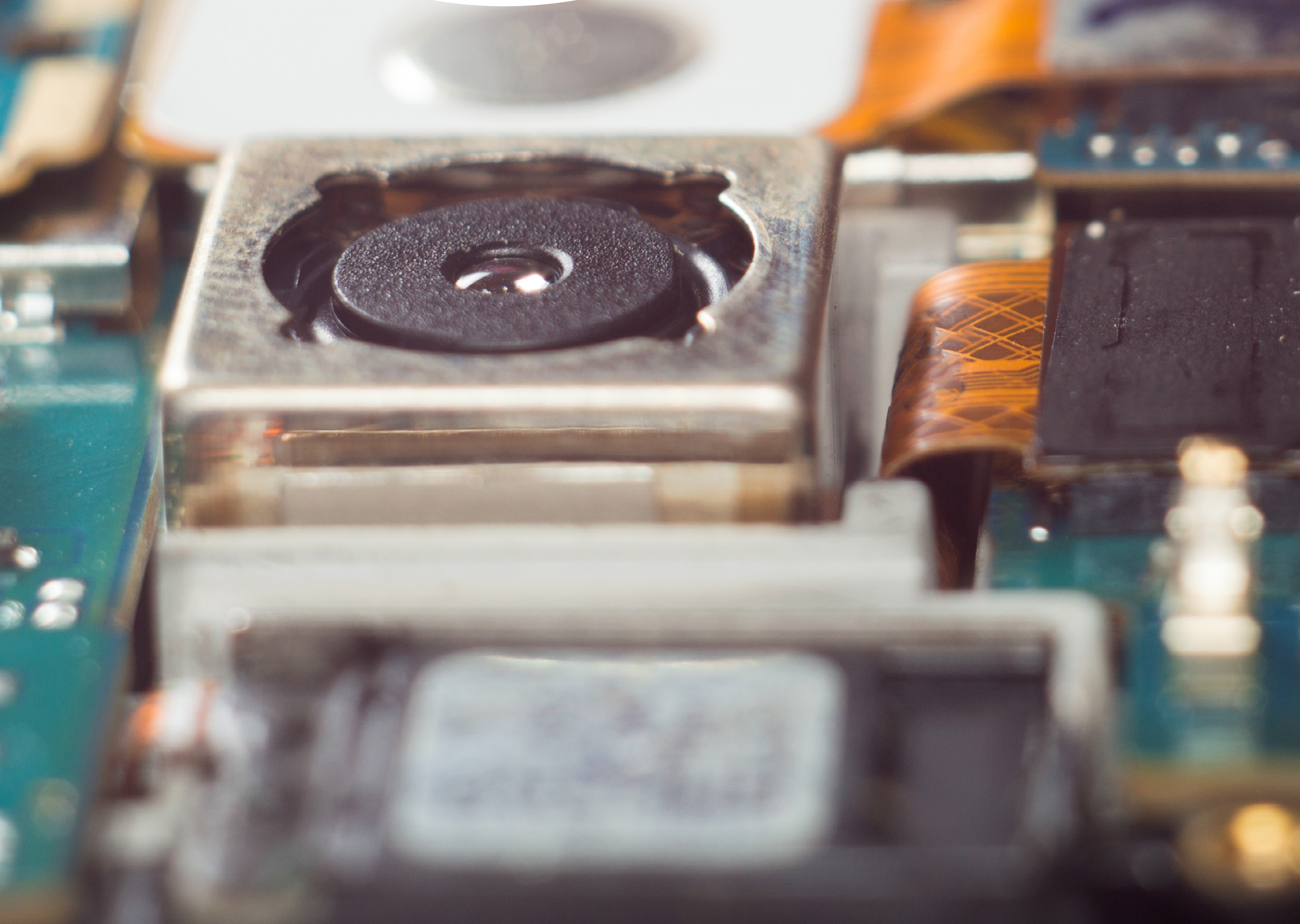
Nacelle (wind turbine component)	Housing that contains the generating components in a wind turbine, including the generator, gearbox, drive train etc.
Physical materials separation	A method that converts a mixture of materials into two or more distinct product mixtures
Pyrometallurgical recovery	A branch of extractive metallurgy that consists of the thermal treatment of minerals, ores, and/or alloys to enable recovery of valuable metals
R-410A	A hydrofluorocarbon refrigerant
Rebar (wind turbine component)	Steel bars used to reinforce structural concrete
Solid oxide electrolysis	A water electrolysis technology that involves the use of a solid oxide, or ceramic, electrolyte to produce hydrogen gas (and/or carbon monoxide) and oxygen
Sulphur hexafluoride	A gas insulator with high GWP used to prevent electrical jump in high voltage applications
Tower (wind turbine component)	The tower supports the structure of the turbine
Ultramafic rock	Igneous and meta-igneous rocks with a very low silica content
Water electrolysis	The process of using electricity to decompose water into oxygen and hydrogen gas

ACRONYMS AND ABBREVIATIONS

Term	Definition
BOP	Balance-Of-Plant
BEV	Battery Electric Vehicle
BGS	British Geological Survey
CdTe PV	Cadmium Telluride Photovoltaic
CCS	Carbon Capture and Storage
CCC	Climate Change Committee
CCP	Climate Change Plan
DLA	Defence Logistics Agency
DRC	Democratic Republic of the Congo
BEIS	Department for Business, Energy & Industrial Strategy
EV	Electric Vehicle
EoL	End of Life
EIA	Environmental Impact Assessment
ESG	Environmental, Social and Governance
GW	Gigawatt
GWh	Gigawatt hour
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HPMS	Hydrogen Processing of Magnet Scrap
IEA	International Energy Agency
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hour
LTO	License To Operate
LFP	Lithium Iron Phosphate
Li-Co	Lithium-Cobalt
Li-ion	Lithium-ion
MFA	Material Flow Accounts

Term	Definition
MW	Megawatt
MWh	Megawatt hour
m	Metre
MHEV	Mild Hybrid Electric Vehicle
Mt	Million tonnes
MPA	Mineral Products Association
ORE	Offshore Renewable Energy
O&G	Oil & Gas
OGA	Oil & Gas Authority
OWIC	Offshore Wind Industry Council
PV	Photovoltaic
PGM	Platinum Group Metal
PHEV	Plug-in Hybrid Electric Vehicle
PEM	Polymer Electrolyte Membrane
PSA	Pressure Swing Adsorption
SEPA	Scottish Environment Protection Agency
SMR	Steam Methane Reforming
SIF	Strategic Innovation Fund
SF6	Sulphur hexafluoride
TCFD	Task Force on Climate-Related Financial Disclosures
TW	Terawatt
TWh	Terawatt hour
T&D	Transmission & Distribution
TEP	Tyseley Energy Park
UKCS	UK Continental Shelf
WEEE	Waste Electrical and Electronic Equipment
yr	Year
ZWS	Zero Waste Scotland

Recovery of materials from used equipment can yield far greater quantities than those extracted through the mining of raw materials.



CONTENTS

1. INTRODUCTION

This section provides the project background, current challenges faced by Scotland with respect to materials during the transition to Net Zero, the scope of the project and introduces the purpose of this report.

1.1 Background to study

To meet its target of net zero greenhouse gas emissions by 2045, Scotland requires an extensive and rapid deployment of renewable energy infrastructure[24]. Of particular consideration is the materials required to achieve this transition. The associated infrastructure for low-carbon transport, energy storage and transmission also require large quantities of minerals that have not historically been extracted at large-scale. There is no doubt that these technologies are highly mineral intensive, although the production and operation of low-carbon technologies account for a relatively small fraction (6%) of the total emissions compared to those generated by the production and operation of fossil fuel technologies[4].

Currently, Scotland imports many of the raw materials and products needed to build renewable energy assets, and subsequently exports the recyclable waste arising from decommissioning activities. However, this approach does not support Scotland's vision of a circular approach to the energy transition. Scotland has, and will continue to grow, a portfolio of material assets from energy infrastructure. Many of these materials could be recovered during maintenance or decommissioning, to support a more circular approach to the transition and minimise the impacts of material extraction and processing. An increase in circularity through better design, that considers the entire lifecycle including opportunities for life extension, refurbishment, reuse and improved material recovery, has the potential to generate economic, social, and environmental benefits for Scotland and safeguard against future shortages of critical materials[25].

1.2 Scope of the study

The aim of this study is to understand the supply of materials generated by decommissioning energy installations and the material demands of Scotland's transition to Net Zero carbon 2050. This study forms part of initial research to understand supply and demand of these materials, in support of Zero Waste Scotland's Material Flow Accounts (MFA) and highlights potential material supply issues. The study considers 12 core materials required in the technologies of interest:

- Aluminium
- Copper
- Neodymium
- Carbon
- Iridium
- Nickel
- Chromium
- Iron & steel
- Platinum
- Concrete
- Lithium-Cobalt Oxide
- Titanium.

During the scoping phase of this study, some materials were scoped out. This included resources removed or extracted as a result of peripheral activities related to construction or decommissioning of energy infrastructure (e.g., aggregate used for building of access tracks or natural resources arising from the clearance of land). In addition, materials used during operation of energy assets, including SF_6 and oils/lubricants have not been quantified in this study.

Cross-industry data on capacity, life span, material requirements and End of Life (EoL) treatment were collated and analysed for nine core energy technology sectors (see Table 1.1) to illustrate the potential scale and spread of materials required to achieve Scotland's energy transition up to 2050 and beyond.

Table 1.1 List of technologies investigated during this study

Energy technology	Commissioning	Decommissioning
Onshore wind	✓	✓
Offshore wind (fixed and floating)	✓	✓
Electric vehicles (EVs) & refuelling infrastructure	✓	✓
Heat pumps	✓	✓
Hydrogen	✓	✓
Hydropower	✓	✓
Solar	✓	✓
Electricity distribution & transmission	✓	✓
Offshore oil & gas	X	✓

1.3 Purpose of this report

This document constitutes the Final Report of the study "Energy Infrastructure Materials Mapping", commissioned by Zero Waste Scotland. The report includes the following sections:

- **Section 1 Introduction** – project background, scope and the current materials challenges faced by Scotland during the transition to Net Zero.
- **Section 2 Capacity forecast** – an overview of the technologies assessed in this study including their role in Scotland's transition to Net Zero. Capacity forecasts to 2050 are modelled and impacts on material demands assessed.
- **Section 3 Materials** – discussion and analysis of the materials needed for development of renewable infrastructure to support Scotland's transition to Net Zero.
- **Section 4** - Conclusions and recommendations.
- **Appendices A-D** – Methodology and supplementary information.

The methodology for modelling and the assumptions made throughout this project are outlined in Appendix A and Appendix D respectively. The data used was obtained via a desk-based review of existing literature, data supplied by the client, and from technical experts within Wood.

2. CAPACITY FORECAST

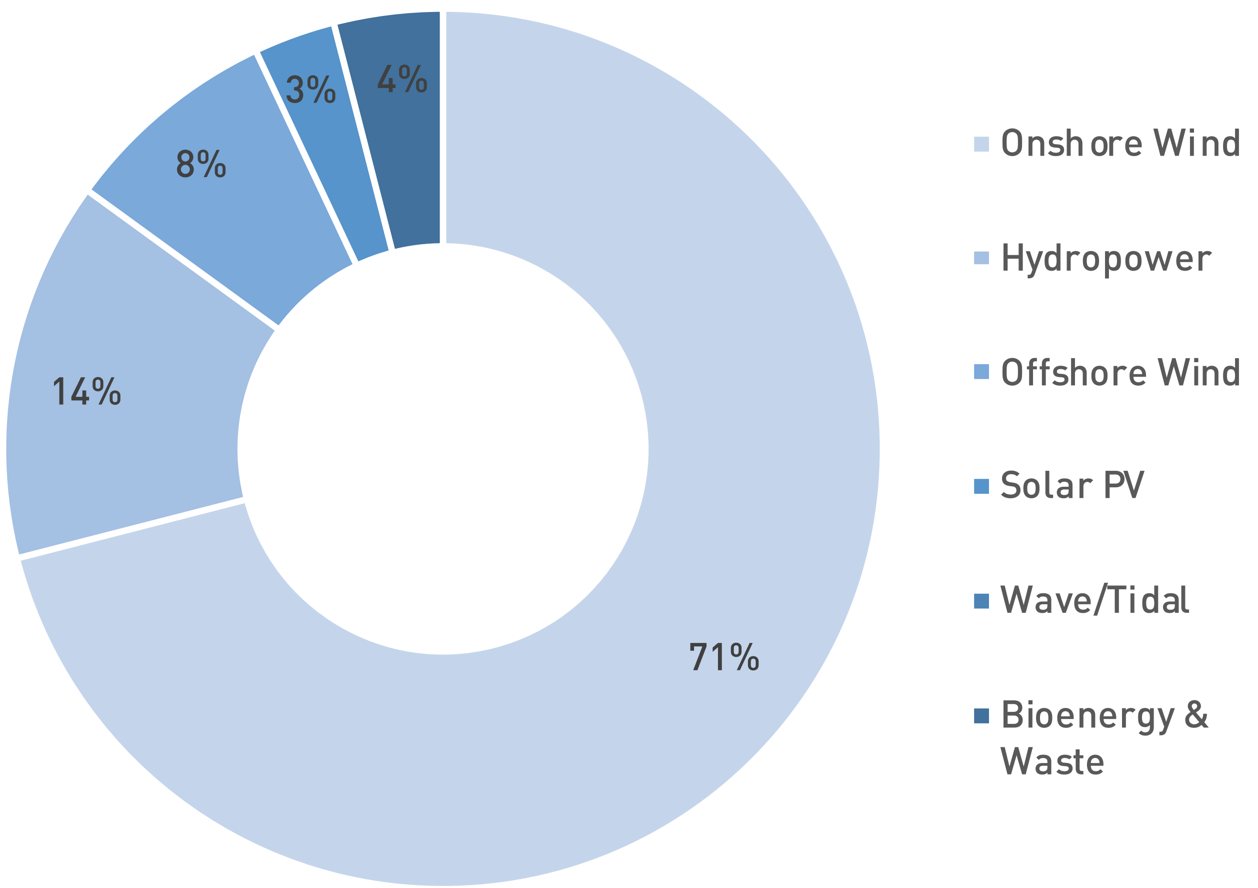
This section outlines the technologies assessed in this study. For each technology it includes a brief introduction of the technology including its role in Scotland's energy transition, a capacity forecast (carried out as part of the study), assessment to 2050 and qualitative assessment beyond 2050, current & potential future locations, advancements in technology and construction methods and their effect on materials use, and EoL options including life extension.

2.1 Introduction

Scotland's vision for a diverse, well-balanced energy supply portfolio or 'energy mix' by 2050 is laid out in the Scottish Energy Strategy (2017)[26]. The strategy includes heat and transport, alongside electricity and energy efficiency. Scotland's Economic Strategy to improve productivity aims to make better use of all resources including people, infrastructure and natural assets[26].

Total energy consumption in Scotland has slightly decreased in the last decade from almost 170,000 GWh in 2010 to 155,000 GWh in 2020[28], aided by improved building energy efficiencies[27]. According to Scottish Renewables (2020), 52% of the energy consumed in Scotland in 2020 came from the heat sector, while transport and power sectors accounted for 25% and 21% respectively[28]. Renewable electricity capacity has been growing steadily (at around 700 MW annually) since the end of 2009, although this growth slowed in 2021[28]. Scotland's electricity supply today is largely decarbonised; Figure 2.1 shows Scotland's current energy mix of renewable electricity[29].

Figure 2.1 **Scotland's energy mix of Renewable Electricity (Q4 2021)**



As Scotland continues to decarbonise its economy, energy sources are becoming increasingly decentralised away from large thermal power plants towards smaller-scale, distributed sources of renewable energy generation[30]. Heating, both domestically and industrially, is becoming decarbonised through introduction of heatpumps and hydrogen as an energy carrier. At the same time, transport is becoming decarbonised through the emergence of electrified vehicles. Furthermore, Scotland is increasing becoming a net exporter of electricity[31]. All of these present major immediate and long-term changes to the way we distribute and consume energy in Scotland.

This section presents the forecast models developed during the study. Nine technologies (listed in Table 1.1) were assessed to demonstrate and the impact that achieving their potential capacity (to 2050) could have on material assets. The outputs project the capacity of each technology to 2050 as elaborated in Appendix A. The key assumptions made are listed in Appendix D. Full workings of the materials composition and references are contained within the accompanying Excel models. It should be noted that the quantity of nickel and chromium required in each technology are likely underestimated due to the quantity that is embedded within high performance and stainless steels. This could not be identified with any certainty from the available material composition data.

2.2 Onshore Wind

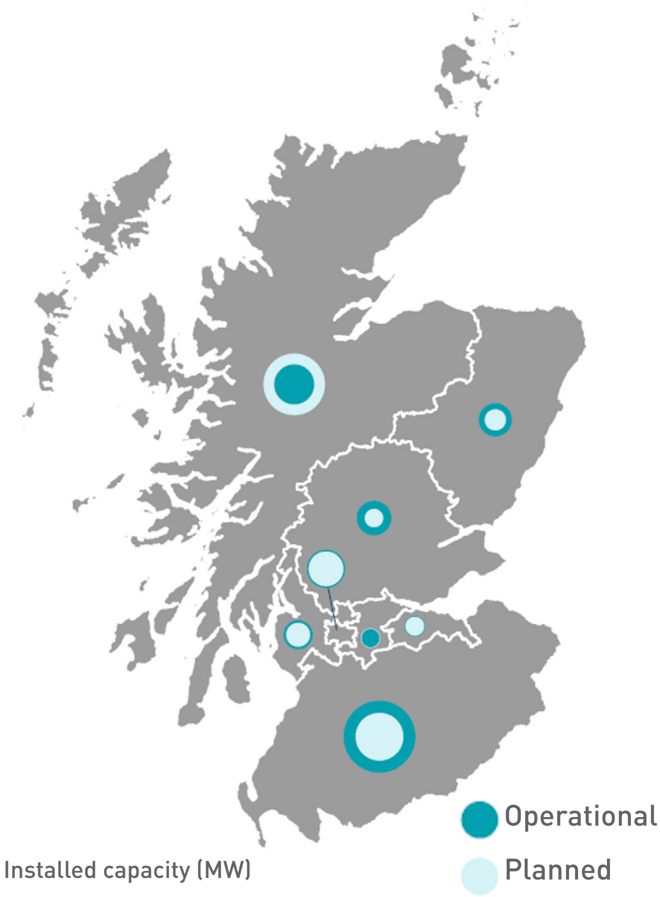
Onshore Wind forms an important part of Scotland's Energy Strategy[32]. It provided 71% of Scotland's generation capacity in 2021[25], playing a key role in Scotland's transition to renewable electricity to date[34].

Figure 2.2 shows the current and planned capacity for onshore wind by region up to 2027[5, 35]. Typically, onshore wind capacity is located in more remote areas in the north and south of Scotland and energy is transmitted to more populous regions.

2.2.1 Capacity forecast

Onshore wind capacity in Scotland stood at ~8.4 GW in 2021 and is expected to reach between 16.4 – 20.4 GW by 2030 and between 22-29 GW by 2050[33]. Onshore wind assets have a typical lifetime of between 15-35 years with the ability to extend asset lifetime by an average of 9 years through replacement of parts[36].

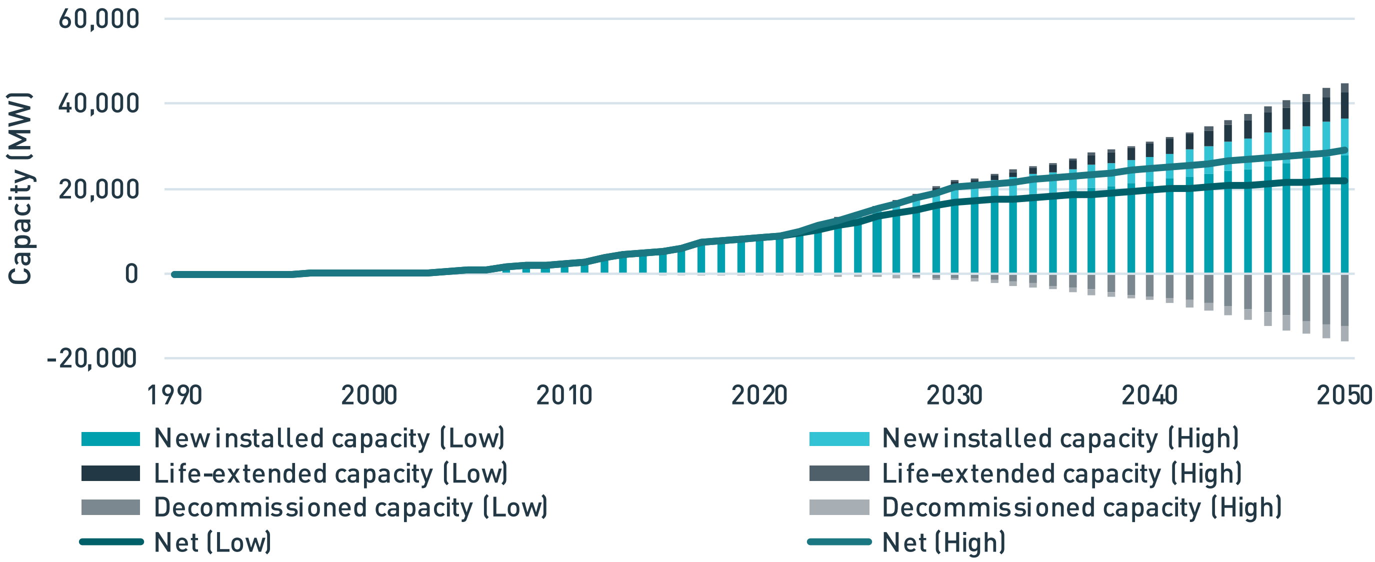
Figure 2.2 Capacity of existing and planned onshore infrastructure, by region to 2027



As shown in Figure 2.3, large-scale Scottish onshore wind capacity that came online in the mid-1990s[37] reached EoL by 2015 and were either decommissioned (~40%) or had their life extended (~60%)[38].

New wind capacity is required to replace EoL turbines and to meet the increasing net energy demand for onshore wind under the modelled scenario.

Figure 2.3 **Onshore wind capacity forecast to 2050***



Under this scenario, this additional capacity is expected to come from new onshore wind developments supplemented by life extension of existing assets.

Currently, life extension of onshore wind assets is not widely practiced, and by 2030, life-extended assets are expected to make up less than 5% of operational capacity as shown in Figure 2.2. Life extended capacity is expected to grow to around 23% of onshore wind assets in operation by 2050 and will continue to grow beyond 2050 to 2075.

Current projections suggest that as onshore wind targets are reached, net capacity should begin to plateau beyond 2050 and up to 2075 as new capacity will only be required to supplement capacity that comes offline. True equilibrium is not likely to be reached in practice because of increasing electricity demand and rebound effects discussed in Section 3.7. Nevertheless, fewer materials are likely to be needed beyond 2050 as growth settles.

2.2.2 Material composition

On average, concrete and aggregate used in the foundations[39] make up 83% (by weight) of an onshore wind asset. This is followed by steel (14%), which is used as rebar[6] in the foundation, in the turbine tower and in components within the nacelle[7]. Iron and steel are both major components in the gearbox. Copper is used in the generator and cabling; and rare earth elements such as neodymium and dysprosium are used in the generator. The quantity of Neodymium used in turbines can vary significantly[40] but typically makes up <1% of the overall mass (including foundations). Blades are typically composed of lightweight composite materials including carbon fibre, fibreglass and aluminium. Nickel is an alloyed component of safety-critical stainless-steel parts.

Significant quantities of sulphur hexafluoride (SF_6) are used in high voltage applications (such as in wind turbines) as a highly effective gas insulator with no direct replacement[41].

SF_6 has a global warming potential (GWP) of at least 22,800 times that of CO2 over a 100 year period and is known to leak from equipment[41]. In addition, hazardous oils and lubricants need to be replaced at intervals during an asset's lifetime and are therefore generated during maintenance activities. Hazardous materials such as SF_6 and oils/lubricants need to handled carefully at EoL. Quantities of SF_6 and oils/lubricants have not been quantified in this study.

In addition to the materials used directly within onshore wind and transition and distribution assets, large quantities of aggregates are required to build access tracks for use during construction, maintenance and decommissioning activities. These tracks are often considered to be temporary, with large volumes of aggregate material and geotextile grid transported to, often remote, locations for short periods of time, after which they are often disposed of. Construction of these tracks requires removal and subsequent reinstatement of natural resources, including vegetation, topsoil and peat. This activity can be very resource intensive, however quantification of these ancillary materials was out of scope for this study.

2.2.3 Technology advancements

The first generation of turbine blades, of which many are currently in operation, were not designed with recyclability in mind. Improvements in thermal, mechanical and chemical recycling techniques, as well as the reprocessing of materials, means that recycling turbine blades is becoming more efficient[43]. Technical advancements could also improve the financial feasibility of the recycling process and it is estimated that the sale of recovered materials could recoup up to 20% of the decommissioning costs[43]. Manufacturers are starting to design blades with EoL treatment in mind[44] and Vestas, the world's largest manufacturer of wind turbines, has become the first company to commit to producing 100% recyclable turbines by 2040[45].

Wind turbines are increasing in size due the increased efficiency of larger swept areas[46]. Whilst this requires a greater quantity of materials per turbine, the energy produced also increases. As a result, fewer materials are required per unit of energy generated[47]. In a 2021 Onshore Wind Policy statement refresh, the Scottish Government acknowledges that tip-heights for onshore wind farms are increasing, and welcomes the resulting efficiencies in generation that this enables. However, it also notes that some developments are unsuitable to accommodate such large turbines[48].

Concerns over the large quantities of rare earth elements such as neodymium required for the wind sector has resulted in the development of rare earth element-free generators; Under an Innovate UK grant, UK-based GreenSpur Wind, and US-based Niron Magnetics have developed a 15 MW generator though it is yet to be proven at scale. Rare earth element-free generators have historically raised concerns among developers due to their weight which requires additional materials to provide structural support but this design is able to meet the mass and efficiency targets required by the market[49].

2.2.4 EoL

The foundations, tower and nacelle components remain in use throughout the entire asset life. Life extension for onshore wind is expected to involve replacement of gearbox parts and blades as direct replacements of material[50]. During decommissioning all materials are recoverable except for the foundations. These are typically left due to the cost of removal and low value of materials. Reuse of the foundations as the base for new assets has been investigated, but this has not yet been undertaken at scale due to concerns over-loading fatigue[39].

According to technical experts engaged during this study, life extension of 15 years is possible, although this depends on engineered tolerances and site conditions. Older turbines currently reaching EoL were built with large engineering tolerances and thus are more suited to life-extension than modern turbines which are often designed to reach EoL at the end of the land-lease term.

According to industry experts consulted in this study, condition monitoring[8] is becoming standard practice in modern turbines to guide this due to its benefits in predicting failures in advance[51]. Industry experts advised, life extension of onshore wind assets is not yet commonplace and currently, there is no standardised approach for achieving it.

Octopus Energy Generation is partnering with turbine manufacturer EWT to repower existing UK onshore wind turbines with more powerful and tech-enabled equipment. 1,000 turbines have been identified as suitable for an upgrade which will extend the life of some components. The type and scale of upgrade will depend on the existing structure and the upgraded turbines will range from 250kW - 1MW and is expected to be completed by 2030[52].

At EoL, materials are currently recycled or exported for reuse, often in lower-income countries. Whilst 85-90% of components are theoretically recyclable, approximately 60% of turbine blade waste including fibre reinforced plastic is currently landfilled and the remainder is generally incinerated for energy or recycled for lower value applications[42, 53]. Repurposing techniques for turbine blades have been reported, including use as structural components in bridges[54]. Furthermore, a domestic market for refurbished wind components is emerging. Renewable Parts, based in Argyllshire, is expanding operations to meet the growing demand from UK wind farms for refurbished wind turbine components[55].

2.3 Offshore Wind

Offshore wind provided 14% of Scottish renewable energy generation in 2021[56] and will play an increasingly pivotal role in Scotland's Energy Strategy[57] and hydrogen economy[58] up to and beyond 2050. Scotland has great potential for offshore wind, particularly in shallower east coast regions[59]. However, opportunities to install offshore wind farms in shallower waters are expected to decrease up to 2050, resulting in the need to explore opportunities to develop sites located further offshore using floating turbines[59].

In 2020, Scotland had 829 MW of operational offshore capacity with 4.9 GW of consented projects and 4.4 GW in the pipeline[60]. Figure 2.4 shows the locations of planned and existing installations based on the BEIS planning database up to 2030[61] which does not include the regions announced for developments by the Crown Estate (Scotwind and INTOG) in February 2022. This announcement included almost 32GW of additional offshore wind capacity. Offshore Renewable Energy (ORE) Catapult ELMWind report focusses on materials required for offshore wind[62].

2.3.1 Capacity forecast

According to ORE Catapult, capacity is expected to reach between 32-35 GW by 2050[62]. Offshore wind assets have a typical design life of between 25-35 years with the ability to extend asset lifetime by up to 20 years[60].

Figure 2.4 Capacity of existing and planned offshore infrastructure by location to 2030

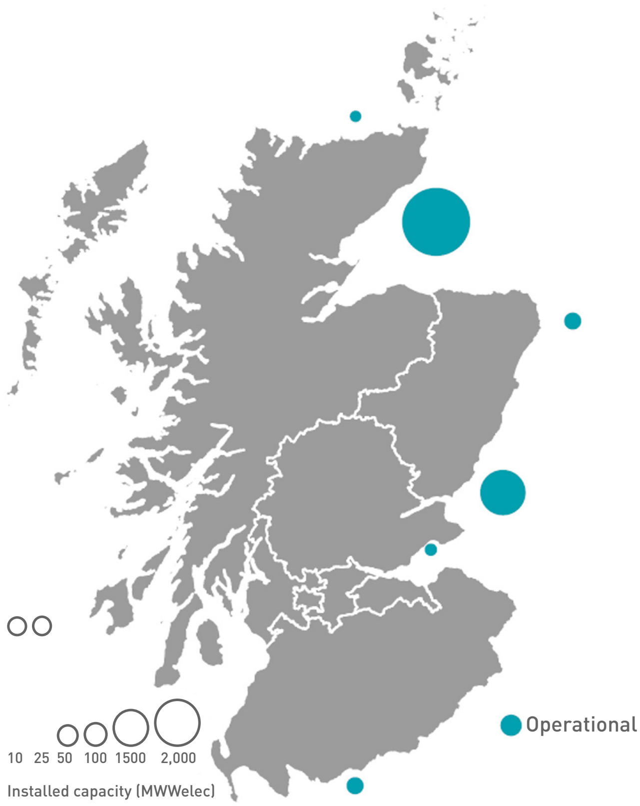
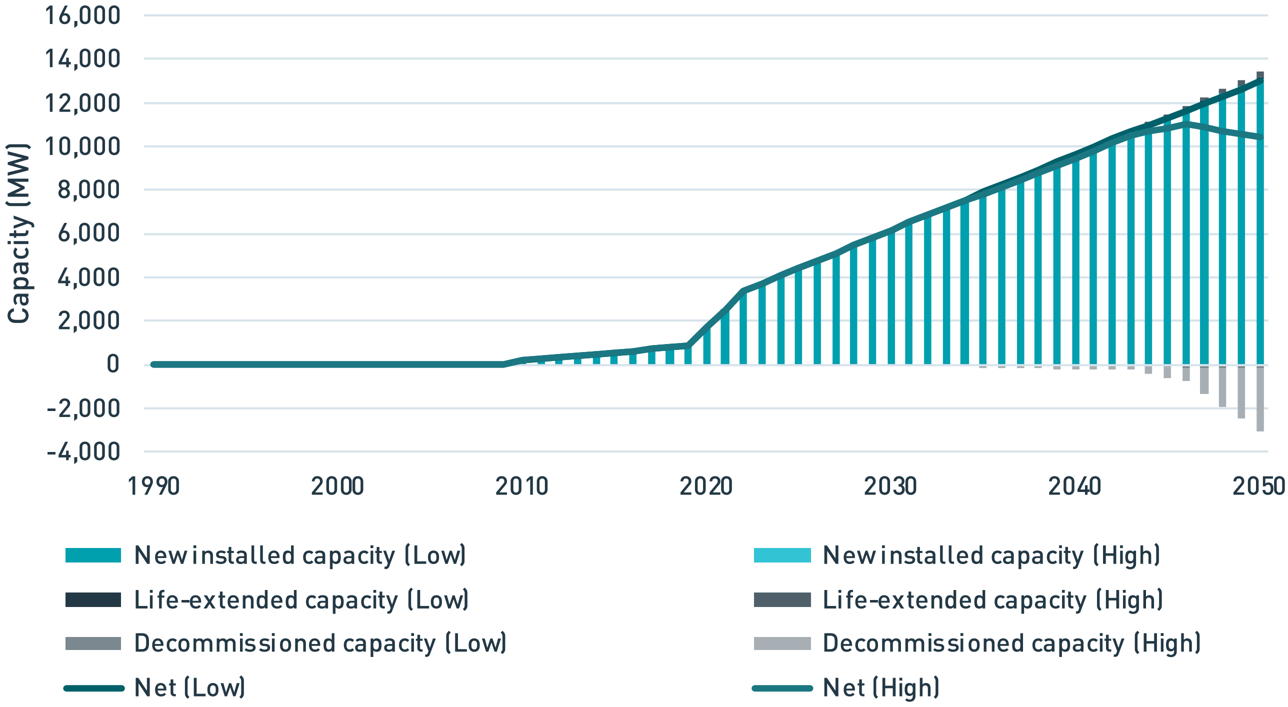


Figure 2.5 Offshore wind capacity forecast to 2050*



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity.**

One of the first offshore wind farm (Hywind Scotland) came online in 2017 (though small-scale projects came online shortly prior to this[60]). Using the assumptions in Appendix D, the first of these turbines are expected to reach EoL in the 2030s at which point, it is assumed that the life of 90% of these assets will be extended. Decommissioning of offshore wind assets at scale is not expected until the 2040s, although it will be required by 2050. It is expected that decommissioning will continue to increase to 2075 and beyond.

Net capacity is assumed to increase approximately linearly up to 2050, although it is recognised that some large windfarms may come online sooner. As with onshore wind, growth may begin to plateau beyond 2050 as targets are met, at which point the demand for new materials will decrease whilst the materials preserved from life extension and decommissioning increase.

2.3.2 Technology advancements

Currently, most offshore installations are 'fixed'[9]. However, the proportion of fixed offshore installations is projected to shrink to 46% in 2040 and a smaller proportion in 2050 as further offshore locations are explored. Most current 'floating'[10] capacity is steel based. However, concrete-based floating assets are expected to account for 50% of floating capacity by 2040 as concrete is becoming proven as a cheaper alternative to steel floats[62].

Offshore turbine blades are increasing in length at a faster rate than onshore wind which allows for greater power generation per unit of material[47]. Other technology advancements include those discussed in section 2.2.3 though offshore wind has been developed more recently.

2.3.3 Material composition

Offshore wind assets are exposed to harsher marine conditions. Partially as a result of this, they have different material requirements to onshore wind assets, including the use of more resistant materials. Iron, steel, copper, neodymium and aluminium are generally required in similar proportions in both types of asset. However, the platforms for fixed and floating offshore wind technology can vary. Neither floating nor modern fixed offshore wind infrastructure require concrete for foundations at the seabed.

As with onshore wind, hazardous oils and lubricants also need to be replaced at intervals during the assets lifetime. SF_6 is also used as a gas insulator[41]. These hazardous materials must be handled carefully at EoL. Quantities of SF_6 and oils/lubricants have not been quantified in this study.

Fixed

While the first offshore wind farms used concrete-based foundations, they have been superseded by steel monopile and lattice jacket[11] structures which do not require concrete foundations[63]. Currently on average, steel and iron make up 97.4% of 'fixed' offshore assets.

Floating

Currently on average, steel and iron make up 90% of total 'floating' assets. However, some floating offshore wind designs employ concrete as a buoyancy platform which makes up 83% of their overall mass. As steel makes up only 12% by mass of concrete-based floating assets, the proportion of total steel required for floating technology will decrease as concrete-based floating capacity increases.

2.3.4 EoL

As noted above, decommissioning at scale is yet to be undertaken, so it is uncertain as to the quantity of substructure steel and cabling that can be commercially recovered. Furthermore, from offshore Oil & Gas decommissioning experience, some materials may lose value as a result of extended exposure to the marine environment (e.g. rust, protective paint and marine growth)[64]. As with onshore wind assets, decommissioned wind turbines are expected to be sold as parts for recycling or exported for reuse to lower-income countries.

The jackets, tower and nacelle components are expected to remain in use throughout the entire asset life. According to an industry expert, as with onshore wind, life extension likely involves the replacement of gearbox parts and blades. According to technical experts, reuse of the substructures as the base for new assets is being considered but is yet to be investigated in detail. If viable, this would reduce the quantity of steel required for replacement of assets.

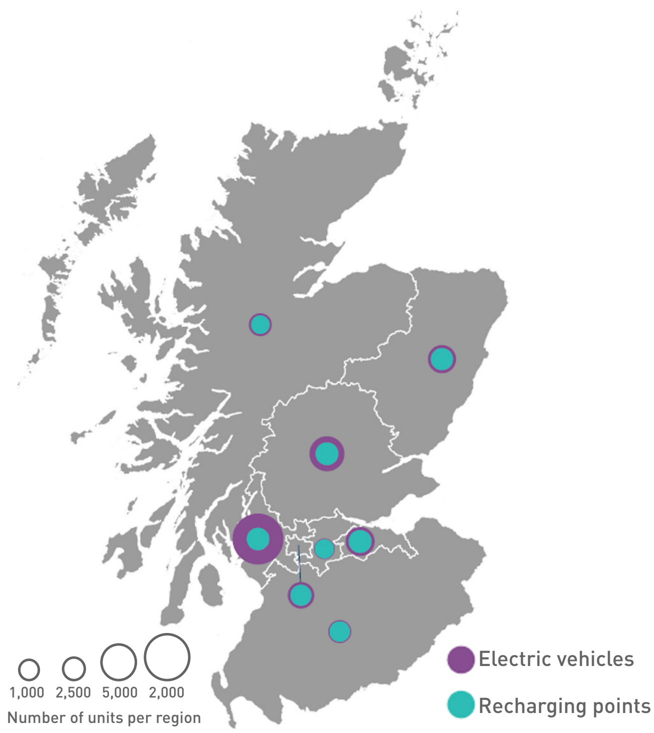
2.4 Electric Vehicles Infrastructure

Supporting the uptake of EVs is an important component of the Scottish Government's Climate Change Plan (CCP). The CCP aims to phase out new petrol and diesel cars & vans by 2030, and all vehicles (including heavy-goods vehicles) by 2050[65, 66].

The two EV types assessed in this report are battery electric vehicles (BEVs) and plug-in hybrid electric vehicle (PHEVs)[62]. They have been combined as a single figure in this assessment. As of 2020, there were approximately 14,808 BEVs and 10,640 PHEVs in Scotland[67] and there were approximately 7,910 public charge points and 91,300 home charge points as of 2021[65].

There is greater demand for EVs in more populous regions of Scotland (see Figure 2.6). This figure shows current EVs and charging points in Scotland[65].

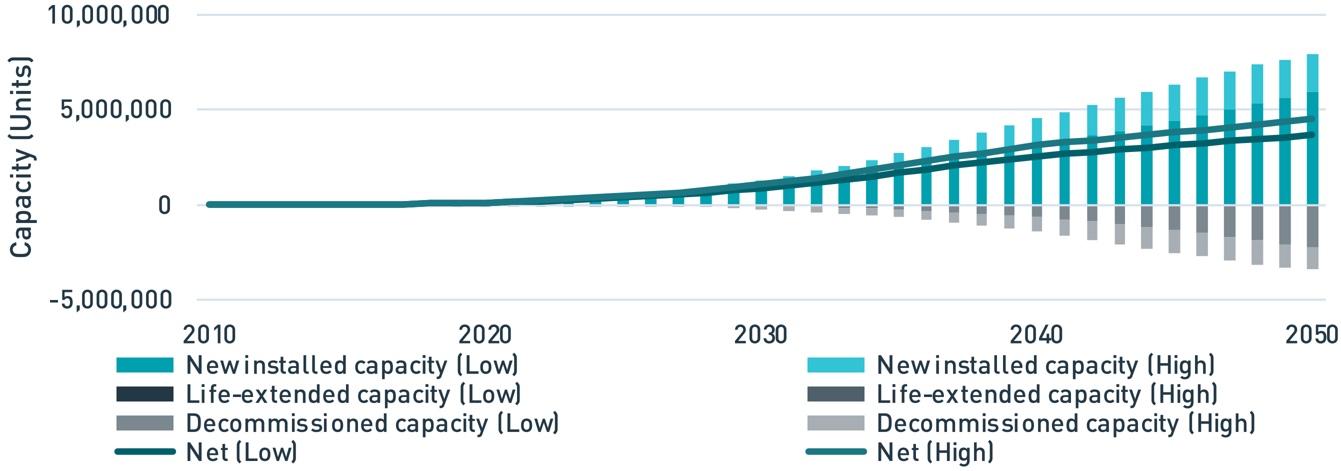
Figure 2.6 **Current location of existing EVs and charging infrastructure by region**



2.4.1 Capacity forecast

Transitioning to zero-carbon mobility will require an increase from 26,000 to approximately 579,000 EVs (including BEVs and PHEVs) by 2030 and up to 3.4 million by 2050[m]. PHEVs are likely to be phased out, with consultations in place to bring forward the phase out of hybrids in the UK to 2035[68]. According to the analysis in this report, Scotland will also require 385,000 home and public charge points by 2030 and 730,000 by 2050[n]. The sum of charge points and EVs are shown in Figure 2.7. The typical lifetime of EVs was taken as 8-12 years but can reach 20 years. Charger lifetime was also taken as 8-12 years[69].

Figure 2.7 **EV and EV infrastructure forecast to 2050***



***Forecast includes a high and low forecast for new capacity (i.e. no. of EVs and chargers), life extended capacity and decommissioned capacity.**

Government data for registered EVs and EV chargers is available from 2015. Net capacity was assumed to increase approximately linearly up to 2050, as shown in Figure 2.7. Currently EV batteries have a lifespan of roughly 100,000 to 200,000 miles with warranties issued for between five and ten years[70]. Although the average age of EVs at scrappage has been increasing since 2009[70], EVs are increasingly being scrapped through the 2020s and their batteries recovered. Additional EVs are required to compensate for this and maintain the projected net capacity.

Once targets have been met, the material requirements for EVs and recharging infrastructure may begin to plateau once all cars on the road are EVs. Nevertheless, there will remain strong materials demand for new vehicles beyond 2050 and up to 2075 as current vehicles reach their EoL. However, advancements in the low-carbon mobility sector are fast-paced so it is difficult to predict the sector landscape beyond 2050. Improvements in life extension would reduce the quantity of materials required for new vehicles but, as noted in Appendix D, this has been excluded from modelling as there are currently no known opportunities and it is uncertain what materials would be included. However, future life extension opportunities can be incorporated into the model as they become available. Once the BEV reaches its EoL, 100% of the vehicle was assumed to be decommissioned and broken down for parts/recycling including the battery.

2.4.2 Material composition

Batteries make up 30% of the weight of a BEV and 14% of a PHEV, tyres account for 3% and the chassis/body making up the remaining 67-83% for the weight by weight[71, 72, 73].

Across both BEVs and PHEVs, steel and iron make up the majority composition (~54%) of the overall EV weight. Other metals and alloys' make up 20% of the overall EV weight; plastic & rubber make up 10% followed by copper (6%), graphite (5%) and aluminium (4%). Lithium-Cobalt (Li-Co) Oxide accounts for ~10% of the weight of BEVs and ~5% of PHEVs. EVs also contain small, but significant, quantities of other metals including manganese, brass, lead, magnesium, and zinc (all <1%)71,72,73.

Tyre composition varies by vehicle but is roughly rubber (47%), carbon black/silica (24.5%), metals (16.5%), textiles (5.5%), zinc oxide (1%), sulphur (1%) and other additives (7.5%)[74].

EV charging infrastructure varies depending on type but are typically composed of steel (45%), plastic (17%) aluminium (10%), titanium (5%), nickel (2%), chrome (1%) .

2.4.3 Technology advancements

New battery technologies expected to be commercialised over the next 10 years are largely based on Lithium-ion (Li-ion) and seek to improve performance and reduce the use of rare metals. Other advancements include Lithium-air batteries, solid-state batteries and non-lithium-based batteries such as hydrogen fuel cells[75] and hemp batteries[76]. Lithium iron phosphate (LFP) batteries and high-manganese-content batteries are also in development reduce the quantity of lithium required in batteries[77].

Improvements in battery technology also require in improvements to battery charger technology. As charging speed increases, greater currents may be required which require more materials such as gallium, silicon and others[78, 79]. Rapid and ultra-rapid chargers currently make up a small proportion of public chargers but are expected to dominate by 2030. Future innovations could include wireless charging using induction and under-floor chargers in areas with limited space[80].

Hydrogen fuel cells are likely to play a key role in the decarbonisation of transport. Hydrogen fuel cell vehicles are EVs that generate electricity on board at relatively high efficiency, avoiding or reducing the need for critical materials used in EV batteries today[81]. As of 2021, there were over 300 hydrogen fuel cell vehicles on the road in the UK and under the UK hydrogen strategy[P], "hydrogen is likely to be fundamental to achieving net zero in transport, potentially complementing electrification across modes of transport" particularly in long-distance car and heavy goods transportation. However, there is a question as to whether they are suited to all forms of road transport[81]. Widespread uptake requires the development of a UK-wide network of hydrogen fuel stations which depends on how the energy system evolves with respect to hydrogen as discussed in 2.6[81].

2.4.4 EoL

Significant questions remain over EoL options for EVs and their batteries. A battery is deemed to have reached EoL when capacity has reached 80%[82]. The used battery can be reused either through refurbishment or directly reused on another vehicle or other application which demands lower performance[82].

EoL batteries can be disassembled, and the cathode materials are restored for battery manufacturing directly without further processing[82]. Alternatively, a number of technologies have been developed to extract valuable raw materials from the spent battery cells, including pyrometallurgical recovery, physical materials separation, hydrometallurgical metal reclamation, and direct recycling[75]. It is reported that 30 tonnes of recycled Li-ion could provide the same quantity of usable materials as 250 tonnes of Lithium ore, or 900 tonnes of cobalt ore[75].

The cost of battery collection is primarily driven by proximity to supply therefore, domestic recycling capacity is vital for maintaining material security. Fenix Battery Recycling opened a Lithium-ion battery recycling facility in Kilwinning near Glasgow in 2021 with capacity to recycle 10,000 tonnes of batteries (with future expansion to 20,000 tonnes)[83] and Veolia and Glencore-Britishvolt have both announced plans to develop battery recycling facilities in the UK[84, 85].

2.5 Heatpumps

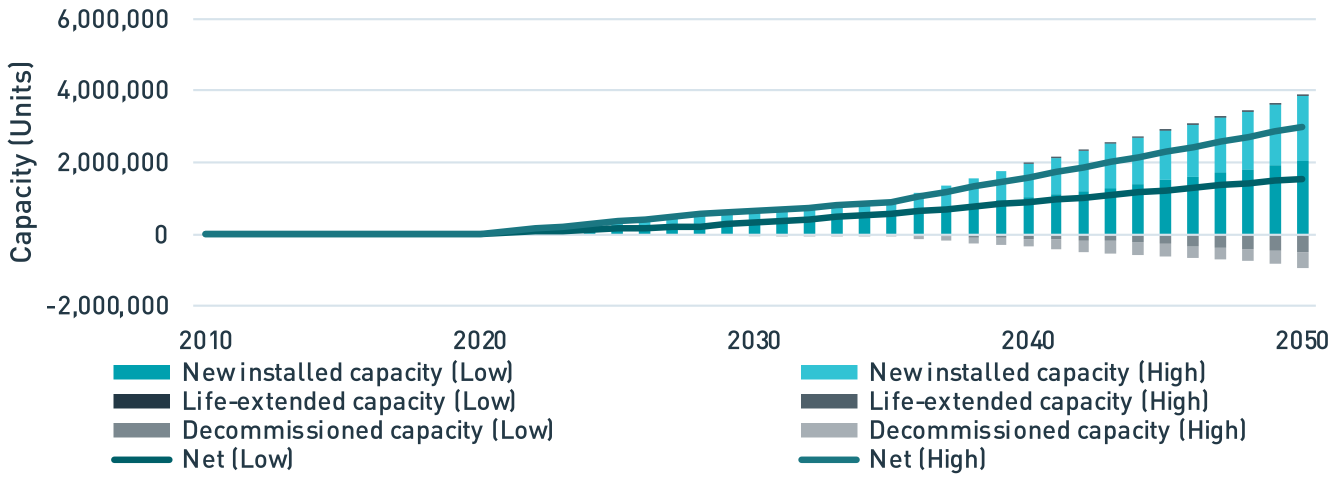
Heating and water heating accounts for ~40% of the UK energy consumption which accounts for approximately 20% of the greenhouse gas emissions[86]. Implementation of low energy heating is therefore essential to achieve net zero by 2045. Heatpumps extract heat from various sources including air, ground and water by exploiting a temperature gradient. They can be implemented on large-scale district heating networks ('utility') or on a smaller, 'domestic' scale. Both utility and domestic heatpumps were considered in this model. Within these types of heatpumps, different sources of heat energy can be taken using air-source, water-source and ground-source heatpumps.

2.5.1 Capacity forecast

A map of current district heating networks can be found at districtheatingscotland.com[q]. Utility heatpumps are most likely to be located in more populous regions as they are used in district heating networks which require high building densities. Domestic heatpumps are located throughout Scotland as they are adopted by households with clusters in more populous regions[87].

In 2020, there were an estimated 14,000 domestic heatpumps in operation in Scotland[88]. According to the model, this is expected to reach ~272,000 by 2030 and between 1.3-2.5 million units by 2050[86, 89]. There are a further estimated 3,000 utility heatpumps currently in operation in Scotland. This is expected to reach 56,000 by 2030 and between 264,000 and 509,000 units by 2050 as shown in Figure 2.8. Heatpumps have a typical lifetime of between 14-15 years[90]. Utility heatpumps can have an extended lifetime reaching up to 50 years[90].

Figure 2.8 Heatpump unit forecast to 2050*



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity.**

Data for heatpumps is available from 2015. At EoL, due to limited available data, 100% were anticipated to be decommissioned. Using the assumptions in Appendix D, the net capacity is assumed to increase linearly from 2020 to 2035. A linear increase is assumed from 2035 to 2050. Life-extended capacity is expected to make up a small proportion of the forecast up to 2050 as most units would be replaced at EoL. Beyond 2050 and up to 2075 we are likely to see improvements in life-extension, reliability, and efficiency; so heatpumps could entirely replace traditional domestic boilers. Once this is reached, net growth will stagnate and demand for materials is likely to decrease.

2.5.2 Material composition

The composition of heatpumps can vary depending on their scale and function. Materials used for heatpumps are typically plastic (1.7%), sand (33.5%), aggregate (44.3%), concrete (7.2%), steel (10%) and copper (2.3%).

The remaining resources used for the production are water, refrigerant, and oil.

A more detailed breakdown of materials used in specific heatpump types is included within the models. Historically, heatpumps have relied on hydrofluorocarbon refrigerants, such as R-410A, but these are being phased out in the EU due to their global warming potential (GWP)[91]. Modern heat pumps commonly employ a water-based system which requires far less refrigerant or utilise low GWP refrigerants[92].

2.5.3 Technology advancements

Standard heatpumps are limited by low efficiencies and the ability to generate the high-temperature water that is required in traditional domestic heating networks. To be effective, the buildings that they are installed in must also be well insulated. High temperature heatpumps do not require the additional insulation or installation of additional radiators that current heatpumps often require, representing a potential replacement for gas and oil boilers in the UK[93, 94]. As a result, the total quantity of peripheral materials required for installation can be reduced although these have not been considered within the modelling carried out for this study.

2.5.4 EoL

Due to the use of environmentally hazardous refrigerants, care must be taken when decommissioning heatpumps to ensure materials are extracted and treated correctly[95]. At EoL, the metal components are recycled and the refrigerant can be extracted and reused. The plastics, brass and cements are typically landfilled[96]. There are trade-in schemes, such as the IVT scheme[97] which offer refurbished parts and ensure that EoL heat pumps are effectively recycled. Further investigation of the heatpump recycling sector should be undertaken to better understand the fate of materials.

2.6 Hydrogen

Under Scotland's energy strategy, hydrogen is set to play a key role in the decarbonisation of the economy up to and beyond 2050[98].

Whilst increased electrification of the energy sector is expected, it is likely that another energy carrier will be required to diversify the energy system and provide energy for industries that cannot be electrified. The scale of, and approach to, hydrogen deployment in Scotland is uncertain and will depend on technology adoption. Nevertheless, numerous hydrogen projects are underway as outlined in the *Draft Hydrogen Action Plan*[99]. This analysis focusses on hydrogen production and excludes T&D infrastructure such as hydrogen hubs and pipelines.

Figure 2.9 Potential locations of hydrogen hubs to 2050

2.6.1 Capacity forecast

Hydrogen production technology was investigated in this study. Peripheral infrastructure including hydrogen hubs and distribution networks were excluded due to data limitations. The following three hydrogen scenarios were used in modelling as the basis for high and low scenarios for both blue and green hydrogen production[100]:

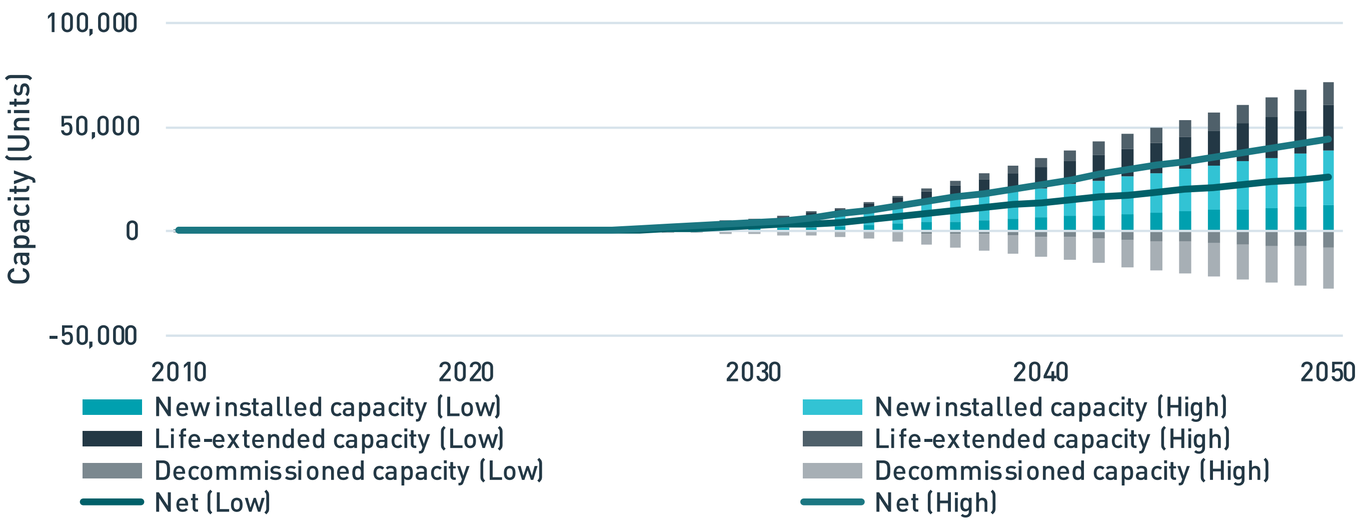
- **Hydrogen economy** – a balanced mix of green (46 TWh) and blue hydrogen (39 TWh) used extensively across all sectors[r].
- **Green export** – renewable resources used to generate large quantities (126 TWh) of green hydrogen for export to European market.
- **Focused hydrogen** – hydrogen plays a supporting role in sectors that are difficult to decarbonise by other means (14 TWh green, 7 TWh blue).

According to technical experts engaged during this study, Polymer Electrolyte Membrane (PEM) hydrolysis was assumed as the dominant green hydrogen technology[101,s]. PEM units have a typical lifetime of 5-10 years with the stack replaced every 2 years.

Also advised by technical experts engaged during this study, Steam Methane Reforming (SMR) was assumed as the dominant technology to produce blue hydrogen. Large-scale SMR units have a typical lifetime of 30+ years with replacement of catalysts and reactor components at least every 10 years.

Blue/grey[t] hydrogen has been the dominant form of hydrogen production since the 1960s. Scotland is currently generating up to 0.3 GW of hydrogen, primarily from blue/grey sources[100]. Under the proposed scenarios, this could increase to 0.5-3.1 GW by 2032 and 1.5-8.6 GW by 2050[u]. Green hydrogen remains mostly in study phase, but some larger projects are moving to maturity. Units are currently deployed at <100 MW scale but output could increase dramatically to 1.5-3.5 GW by 2032 and 11-30 GW by 2050 as energy production and electrolysis technology costs decline[100, 102].

Figure 2.10 Hydrogen capacity forecast to 2050*



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity. Note, model used number of units instead of energy units. Therefore blue/grey hydrogen assets are dwarfed by green hydrogen despite producing more hydrogen per unit.**

As green hydrogen is at an early stage within a fast-paced sector, it is difficult to predict the landscape beyond 2050. If growth were to continue at the currently modelled rate, there will be a vast increase in materials demand for the technology. However, it is anticipated that advancements in life-extension, efficiency and material requirements for technology will improve and reduce the need for materials[103]. Due to the regular replacement of the PEM stack, life extension comes into effect only 2 years from deployment and decommissioned after a further 4-6 years (as shown in Appendix D). Blue hydrogen on the other hand has much longer lifespans and periods between life extension. Due to the short lifespan of green hydrogen assets, materials demand for new assets is high as it becomes the dominant form of hydrogen generation. Therefore, blue hydrogen could be an important short to medium-term solution to meet decarbonisation targets whilst research & development into improving material efficiency in green hydrogen is improved[104].

2.6.2 Material composition

The material composition of each of the current hydrogen-generation technologies varies significantly. In both cases, large quantities of potable water is required. SMR typically requires 4.5 L of water per kg of hydrogen and green hydrogen requires 9 L of water per kg of hydrogen based on the stoichiometric values[105].

Other materials required within each of the asset types are outlined below.

Green hydrogen (PEM)

PEM is composed of 'Balance-Of-Plant (BOP) components' which last the duration of the asset lifetime and the 'stack' which makes up 2.5% of total asset weight and must be replaced approximately every two years. BOP components are composed primarily of steel (51%), copper (22%), concrete (21%) and aluminium (4%). The stack is composed of metals including titanium (77%), steel (15%), aluminium (4%) and copper (1%).

Blue hydrogen (SMR)

Iron and steel make up 90% of the overall mass of an SMR plant, activated carbon used in the pressure swing adsorber makes up 5%, nickel makes up 3% and chromium makes up 1%. Catalysts are composed of iron/chromium oxide and ruthenium/nickel/aluminium oxide. It was assumed that the activated carbon pressure swing adsorber, catalysts and some reactor steel would be replaced at asset life extension.

2.6.3 Technology advancements

Blue hydrogen is a potential short-medium solution to meet Scottish carbon reduction targets[104]. However, in the longer term, it is anticipated that green hydrogen will become the dominant form of hydrogen production. Whilst SMRs are the main technology used for blue/grey, other technologies include Partial Oxidation and Autothermal reforming which both require material-intensive air separation units. Furthermore, Carbon Capture and Storage (CCS) would be necessary for all blue hydrogen technologies as carbon dioxide is generated as a by-product of hydrogen. These peripheral units are material intensive so use of either of the competing blue technologies may increase the associated material requirements.

Within the category of green hydrogen, there are also numerous competing electrolysis technologies in development. Whilst PEM is anticipated to become the dominant form, other technologies such as alkaline water electrolysis, solid oxide electrolysis and microbial are currently viable alternatives in development[106, 107]. Future hydrogen cells are expected to become smaller, more modular and more efficient which could allow for more distributed deployment closer to where is it required and direct replacement/upgrade of modules[108]. Increases in efficiency and lifespan can dramatically reduce the quantities of materials that are needed to produce green hydrogen.

Hydrogen will also require distribution infrastructure including hydrogen hubs and distribution networks. The repurposing of existing gas pipelines is being investigated to distribute hydrogen to businesses[104]. However, significant additional infrastructure will be required depending on the scale of hydrogen roll-out which could require large quantities of materials. The material requirements for this associated infrastructure should be investigated further in future studies.

2.6.4 EoL

Due to the high temperatures of operation in blue-grey technologies, reactor beds, catalysts and adsorbers are replaced at regular intervals throughout the asset's lifetime. According to an industry expert engaged during this study, SMR plants are typically dismantled at EoL, and the materials recovered for recycling; high-value catalysts and adsorbing materials are regenerated[109] and reused. Steel components are typically recovered for recycling. SMRs, and other large process equipment can be dismantled and transferred to a new location at the end of their workable life. According to an industry expert, SMRs in the US have been relocated to the Far East at the end of their economic life.

There is no standardised approach to EoL treatment of PEM. High value materials such as platinum and iridium are the key targets for material recovery. Various hydrothermal, hydrometallurgical and pyro-hydrometallurgical recovery treatments are available for recovery, but they are often material or energy-intensive and require the use of environmentally damaging substances[110].

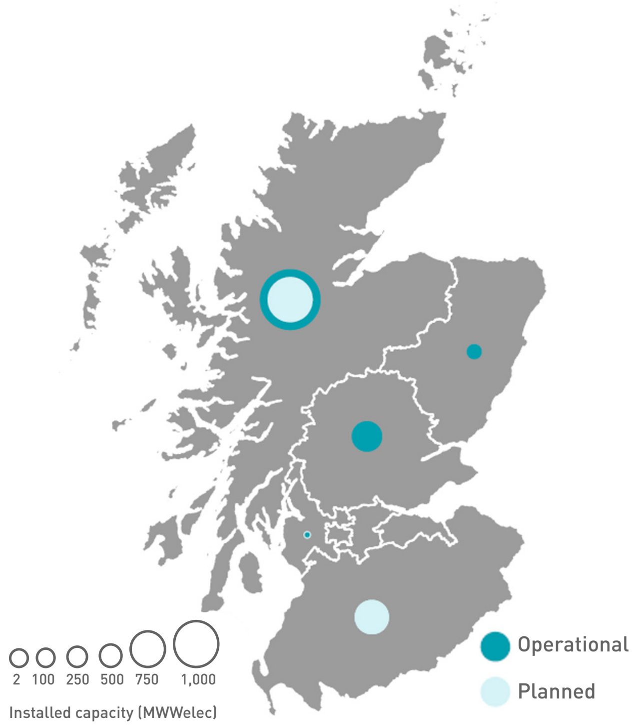
2.7 Hydropower

In 2021, hydropower accounted for 13.5% of installed renewable capacity and 16.5% of renewable power generation[111]. It is a proven and reliable technology though it can have significant environmental impacts if not managed correctly, particularly for larger scale projects[112, 113].

Hydro power in the form of small-scale (<4 MW), large-scale (>4 MW) and pumped-storage facilities were considered in this study. It's estimated that there are 850 to 1550 megawatts of remaining viable hydro potential of in the UK mostly from small-scale installations[114, 115].

Figure 2.11 shows the current and planned capacity for hydropower up to 2030 based on BEIS planning data[116]. Most existing hydropower is located in the north of Scotland although there are opportunities to utilise smaller sites throughout Scotland, particularly in the south[115].

Figure 2.11 Capacity of existing and planned hydropower infrastructure by region to 2030

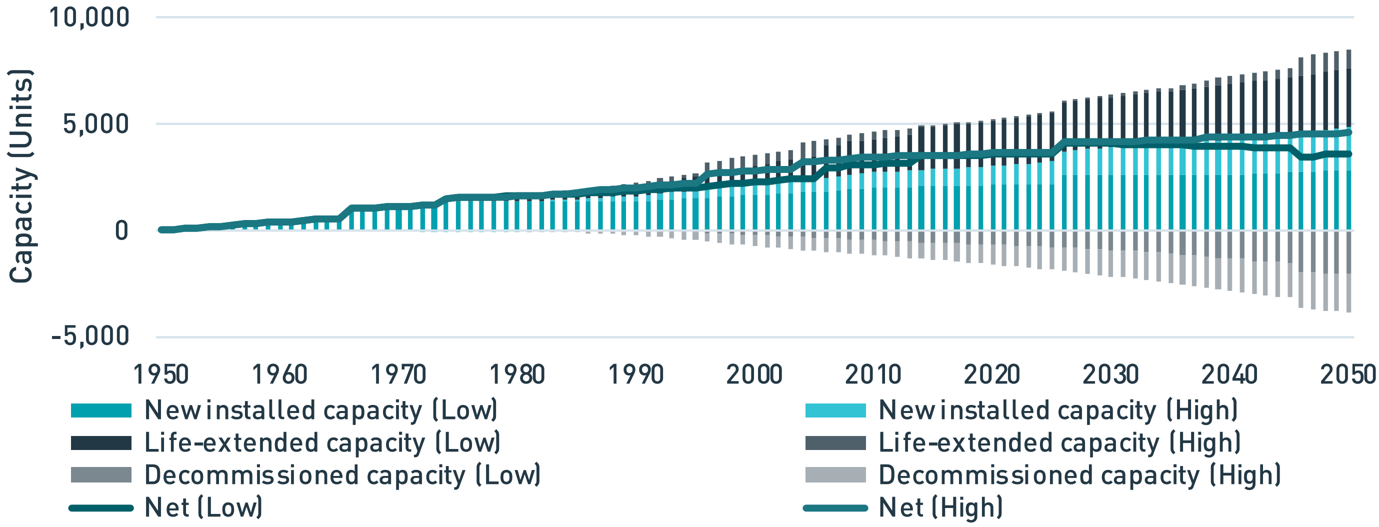


2.7.1 Capacity forecast

Most of Scotland's hydro capacity came online through the 1950 to 1970s and it is unlikely we will see again the scale of development witnessed in this period[114]. Nevertheless, some large-scale facilities came online in the 2000s and pumped-storage facilities have been planned into the 2020s and 2030s such as the Red John Pumped Storage scheme[117] and planned expansion at Cruachan Power Station[118].

The typical lifespan of large-scale and pumped-storage installations is around 80 years, with life extension taking place once or twice throughout its lifetime[119]. The typical lifespan of small-scale installations is around 40 years, with life extension expected at least once in their lifetime[119].

Figure 2.12 Hydropower capacity forecast to 2050*



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity.**

Using data from Department for Business, Energy & Industrial Strategy (BEIS)[120] and the assumptions in Appendix D, life extension of hydropower assets is evident from in the 1970s, as turbines and generators from the original assets are replaced while the original dam and penstock remain in place throughout the asset's life. Decommissioning of small-scale and medium assets started to occur in the 1980s. By 2020, much of the original large-scale assets remain in use but are expected to come offline over the next decade. Life-extended capacity is expected to account for over a third of capacity by 2030 and 2050. Beyond 2050, and up to 2075, net capacity is expected to stagnate. However, there is expected to be an increasing quantity of materials generated from decommissioning. A similar quantity of materials may also be required to maintain net capacity.

2.7.2 Material composition

There are numerous construction methods for hydropower facilities; each requiring various quantities of material. Micro-hydro facilities[w] can utilise the natural flow of a river to generate power without the need for a penstock[x]. The design of small-scale facilities can take many different forms which each require different quantities and types of materials[121]. For example, small-scale facilities might require the construction of a penstock and/or weir in order to control the flow of water and generate larger power outputs[122]. Based on input from a technical expert, the concrete penstock used in this model (see Appendix D) typically makes up ~90% of the overall mass of small-scale facilities. This is followed by iron and steel (7%), copper (1%) and plastic[123].

Smaller-scale projects require significantly fewer materials per MW than larger scale assets as a result of the concrete and steel needed in the dam and penstock.

Large-scale and pumped-storage facilities require high gravitational potential energy, usually requiring construction of a dam. The construction methods of dams can vary significantly which require varying quantities of materials however, since 1900, concrete has been the dominant material for dam construction in the UK[124]. It should be noted that there is little correlation between the quantities of materials required for dam construction and power output for hydropower facilities. This is due to variations in geography, construction method and turbine size. For example, the 1.61×10^7 MWh Baba dam in Ecuador required 981 kilotonnes (kt) of material (99% concrete and aggregate) whilst the Mazar-Dudas dam in Ecuador required only 128 kt of material (80% concrete and aggregate) despite generating more than 62% of the output of the Baba dam[125]. Therefore, it is recommended that a more detailed study is undertaken to determine a more accurate quantity of materials in existing, and planned, Scottish assets.

Modelling for large-scale and pumped-storage facilities was based on a per MW basis using an existing arch dam for which construction data were available. Using this example, concrete and aggregate makes up 99% of the overall mass. The remaining 1% of materials consist of primarily of steel with some iron and copper[126, 127]. Steel is used in large quantities in concrete reinforcement and the power generation units. Iron and copper are used in the power generation units.

In addition to the materials used within hydropower assets, large quantities of aggregates are required for construction of access tracks to hydropower assets needed during construction, maintenance, and decommissioning. Construction of these tracks also requires removal and subsequent reinstatement of natural materials such as peat, topsoil and vegetation. These ancillary materials have not been quantified in this study.

2.7.3 Technology advancements

The future potential for additional capacity is likely to be single-MW or micro-scale projects, as most opportunities for large-scale hydro in Scotland have been utilised[115]. Micro facilities were excluded from modelling as they could not be discerned from small-scale facilities as defined by BEIS. However, individually they utilise relatively little concrete as they do not require a dam or feedstock. Any additional capacity of micro-scale projects is uncertain and dependent on whether small-scale renewable generation is supported. The introduction of a feed-in tariff[128] in 2010 resulted in an increase in small-scale hydropower generation. However, development has slowed in recent years with the reduction in tariff rates and the removal of the programme altogether[129].

2.7.4 EoL

Global experience in the decommissioning of large-scale hydropower stations is increasing, particularly in the US, as dams built in the 1950s and 60s are reaching EoL. The major reasons for dam removal are environmental concerns and dam failure. Two sources of dam failure are the aging of the construction materials and accumulation of sediment behind the dam impoundment. Engineers typically design reservoirs to incorporate a 100-year sediment storage pool and dams can have their life extended by up to 150 years. However, the cost of repairing a small dam can be up to three times the cost of removing it[130].

At EoL, there is the option of abandoning the dam, allowing silt to build up and reroute the river leading to natural recultivation however, there remains a risk of dam failure[131]. Alternatively, the facility can be demolished, and the land potentially restored to its previous state. This is being increasingly performed via a cut and notch approach which allows for slow draining of the reservoir as demonstrated in the Elwha River dam. This is becoming common practice due to its environmental benefits over other draining techniques[132]. Another, possibility is to reuse the space by deconstructing the original dam and rebuilding a new facility[131].

For facilities that are deconstructed, concrete can be recovered for use as aggregate or sent to 'final disposal'[131]. The remaining metals, including reinforcing-steel rebar can be recovered and recycled[131]. For smaller facilities, recovered plastics and 'other materials' are not easily recycled so are likely to be landfilled or incinerated[131].

2.8 Solar

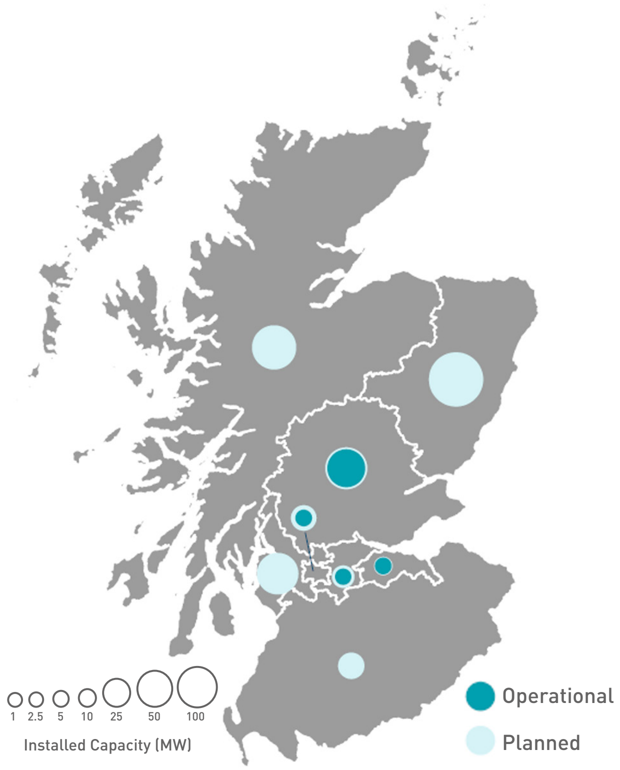
As of, 2021, Solar photovoltaic (PV) accounted for 3% of Scotland's renewable energy generation[133]. It is expected to play an important role in Scotland's Energy Strategy[134] by providing diversification decentralisation of energy assets. There are two major types of solar installations:

- 'Utility' installations are commercial solar farms which require larger land areas to generate electricity on a commercial scale.
- 'Rooftop' installations are typically smaller-scale and can be constructed on top of commercial buildings and domiciles.

Due to the lower levels of solar irradiance in Scotland relative to the rest of the UK, deployment of solar PV has been limited. This is expected to continue to 2050, as developers focus on sunnier regions of the UK[115]. Figure 2.13 shows the current and planned utility solar capacity in Scotland up to 2030 based on BEIS planning data[135].

Domestic and commercial small-scale rooftop cells are located throughout Scotland though it was not possible to identify hotspots.

Figure 2.13 Existing and planned utility solar capacity by region to 2030[135]

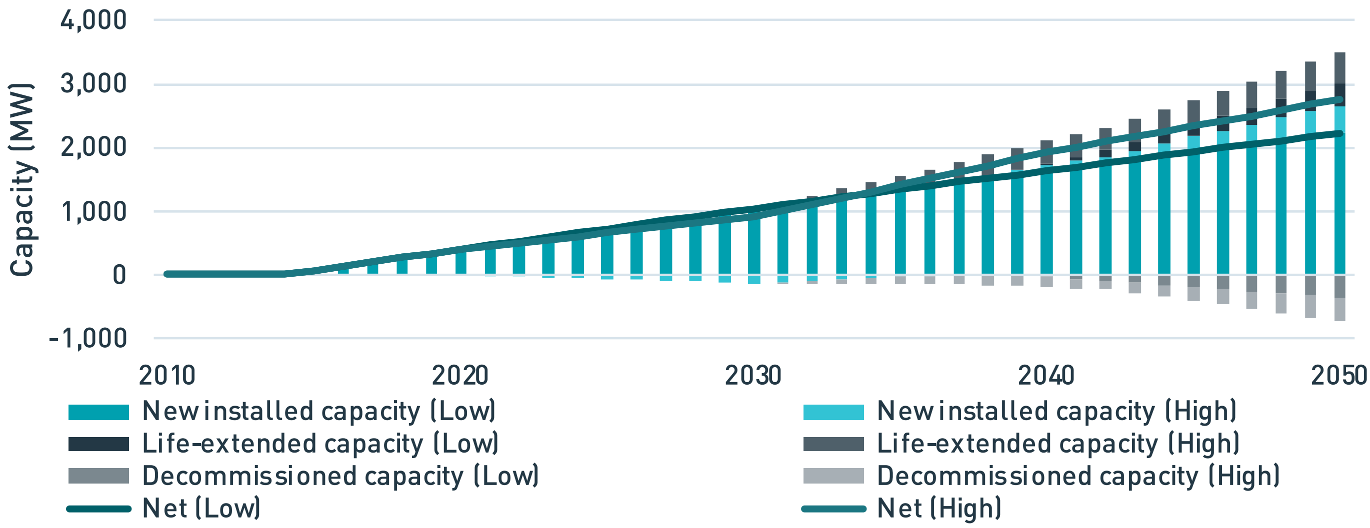


2.8.1 Capacity forecast

Scottish solar capacity stood at 404 MW in 2021. In the absence of any formal solar targets for Scotland, UK build rates were used to estimate a higher and lower linear growth rate up to 2050[136]. Further modelling assumptions are shown in Appendix D. The 2015 building regulations incorporate Solar PV into carbon compliance; as a result, Scotland have increased the deployment of rooftop solar; it was estimated that 60% of Scottish newbuilds had solar PV in 2020[137]. The typical design lifetime of a solar PV panel is 25 years with opportunity to extend the life to up to 40 years. With correct maintenance, solar PV panels do not require refurbishment, however the inverters, which transfer DC current to mains voltage, must be replaced after 25 years according to industry experts.

The proportion of rooftop capacity equalled utility capacity in 2021[138]. However, following the removal of government subsidies such as the feed-in tariff, industry experts anticipate that the utility solar installations will stagnate in Scotland by 2030. Still, utility solar will remain in use until decommissioning and modelling outputs suggest this is expected to make up at least 3% of Solar PV assets by 2050. Re-introduction of government incentives could make utility solar more commercially viable in the future. Small-scale projects (up to 5 MW) may be eligible for the Smart Export Guarantee[139], and beyond the capacity currently in planning it is anticipated that new capacity will primarily be rooftop solar from 2030 onwards.

Figure 2.14 Solar capacity forecast to 2050*



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity.**

BEIS data for solar panels is available from 2015. Although some decommissioning is already taking place, decommissioning at scale is expected to begin from the 2030s. At this point, due to data limitations, it was assumed that 50% of assets were life-extended whilst the remaining assets were decommissioned. The rate of decommissioning is expected to increase from the 2040s as life-extended capacity is decommissioned. Rooftop solar is expected to dominate solar roll-out and despite reductions in subsidies, this forecast assumes a linear growth to 2050 as the cost of the technology continues to decrease. As with other technologies, solar deployment may stagnate beyond 2050 as targets are met and space for utility assets become limited. However, rooftop capacity is likely to correspond with population growth up to, and beyond, 2050[140].

2.8.2 Material composition

As panels are comparatively lightweight compared to other technologies, they require relatively few materials per MW. Utility solar frames are typically steel which account for approximately 42% of overall weight. Solar PV cells (58% of total weight), consist of glass (75%), plastic (10%), aluminium (8%), silicon (5%) and other metals including gallium, germanium, selenium, tellurium, cadmium and indium (total ~1%)[141]. Inverters (<2% of total weight) are required to connect the panels into a solar array. Therefore the number required per panel can vary significantly though they make up a small proportion of the overall weight; They are typically made up of plastics and electronic components which are replaced during life extension according to an industry expert.

2.8.3 Technology advancements

Technology advancements in solar PV are threefold:

1) Land space savings through new deployment techniques such as rooftop

and floating solar[142]– this does not result in material savings but can save on valuable land space which could be better utilised (e.g., for agriculture).

2) Energy efficiency improvements[143] – improves the energy generation per cell which may result in material savings per MW.

3) Material efficiencies[143] – changes in the quantities and types of materials used in cells:

- Silicon cells make up 95% of modules used today. The theoretical maximum solar cell efficiency value for homojunction is about 29%. Silicone structures are popular because silicon is abundant and non-toxic[143].
- The next generation solar cells include perovskite solar cells, organic solar cells, dye sensitized solar cells, kesterite solar cells and quantum dot solar cells[143]. Perovskites can achieve efficiencies of over 29% at low production costs and are the fastest-advancing solar technology. However, there are environmental concerns due to toxicity of lead halides used in perovskite solar cells[143].
- Organic solar cells are thin film cells which use organic semiconductors. These cells are inexpensive, flexible, and lightweight. However, they have low efficiencies compared to silicon-based technologies[143].
- Kesterite solar cells are based on copper zinc tin sulphide or selenide. They do not contain toxic or rare earth elements like cadmium and indium that are required for silicon-based cells however they currently achieve relatively low efficiencies[143].
- Quantum dot solar technologies harness quantum properties to they can be processed to create junctions on inexpensive substrates such as plastics, glass, or metal sheets with promising laboratory performance. They can easily be combined with organic polymers and dyes for alternative applications such as PV paints. They have potential to offer high watt: cost ratio and environmental advantages over traditional cells. They currently remain under development[144].

2.8.4 EoL

The UK produced 650 tonnes of PV waste in 2021 and is expected to reach 30,000 tonnes by 2030 and 1 Mt by 2050[145]. PV waste is categorised as WEEE and falls under the associated legislation. 70% of European manufacturers are part of the global PV CYCE network which offers waste management services and design for reuse guidance[145].

At EoL, silicon-based panels are disassembled and reprocessed. 95% of glass is reused, 85% of silicon is reused and 80% of the modules can be reused for new panels once they have been stripped of their silicone. In total, 96% of materials can be recovered and reused[145].

2.9 Transmission & Distribution (T&D)

Transmission networks enable the bulk transfer of high voltage electricity (direct from power stations) around the country whilst distribution manages the flow of electricity to homes and businesses. There are two transmission network owners in Scotland; Scottish Hydro-Electric Transmission and Scottish Power Transmission. There are also two Distribution Network Operators; Scottish Power Distribution and Scottish Hydro Electric Power Distribution[y]. T&D networks are expected to grow with increased electrification, particularly in the north of Scotland which is projected to increase with growing capacity of onshore windfarms, marine generation, and offshore windfarms[146].

The network is expected to be expanded to link new renewable energy generation from remote areas to the areas of greatest demand. Nevertheless, remote communities in Scotland are calling for local smart grids to reduce their dependence on the central grid by offering 'flexible connections'[147]. These have been successfully demonstrated in Orkney and the Mull ACCESS project[148].

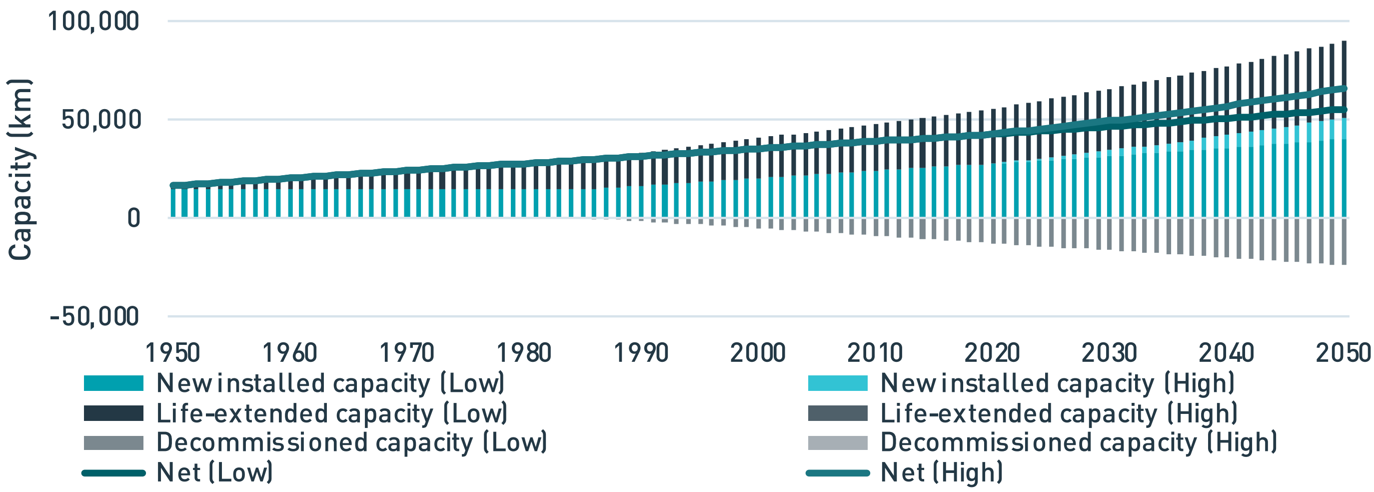
With increasing wind farm construction, Scotland's remote areas are growing in significance for energy production – leading to a series of infrastructure upgrades and replacements across the country[z]. Funding for upgrades is released via the Strategic Innovation Fund (SIF). It is expected to invest £450 million in innovation between 2021-2026[149].

2.9.1 Capacity forecast

As of 2020, there were 9,473 km of above-ground transmission line in Scotland[150] ; an increase from 9,000 km in 2014[146]. In 2014, distribution accounted for 33,010 km[146]. A linear growth for T&D was assumed between 1950 and 2050 by extrapolating the average transmission growth rate between 2014 and 2020.

The typical lifetime of a pylon is up to 80 years[151] and life extension involves replacement of the conductors, insulators, and fittings after 40 years[151]. Life extension is already maximised within the T&D industry so it was assumed that 100% of assets would have their life extended. Modelling in this study focusses on the onshore transmission and distribution network (above ground cables and pylons). It excludes substation infrastructure and subsea cabling which is critical to the deployment of offshore energy generation. Life extension in substation equipment, subsea cables, and associated infrastructure (including battery storage) should be investigated in future studies.

Figure 2.15 T&D capacity forecast to 2050*



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity.**

The T&D network may need to be upgraded to cope with additional connections of heatpumps, EVs and low carbon energy generation[152], particularly in the remote and offshore regions that will experience the biggest increases in renewables capacity up to, and beyond, 2050. If renewable targets are met by 2050, continued expansion of the T&D network may not be required. Therefore, it is possible that net growth may stagnate up to 2075.

The decommissioning of pylons is expected to increase linearly up to and beyond 2050 as an increasing proportion of pylons reach their EoL, resulting in opportunities to recover more material. Parts are also recovered from replaced conductors and insulators from life extension.

2.9.2 Material composition

Of the above-ground T&D infrastructure investigated, concrete makes up 53% of the total mass followed by wood (19%), steel (18%), aluminium conductor (6%). Porcelain, glass & resin insulators make up 4% of the materials. The conductors and insulators are typically replaced during routine maintenance and life extension, whilst the remaining materials remain in use until EoL. Foundations are typically (but not always) removed at EoL.

In addition to these materials, significant quantities of SF_6 are used in high voltage applications (such as in T&D switches) as a highly effective gas insulator which allows for much smaller components[41]. It is thought that up to 1% of SF_6 can leak from aging equipment. Therefore, SF_6 must be handled carefully during maintenance and at EoL. Further to this, large quantities of aggregates are required for construction of access tracks to facilitate construction, maintenance and decommissioning of pylons. Construction of these tracks also requires removal and subsequent reinstatement of natural resources such as peat, soil, stone and vegetation. These ancillary materials have not been quantified in this study.

2.9.3 Technology advancements

'T-pylons' are the first new commercial-scale design for a pylon in Great Britain since 1927. The new design is a third shorter and lighter than existing pylons and has a smaller ground footprint than traditional high-voltage designs[153]. The monopile design uses less concrete and allows for faster construction. Despite being a third shorter, it could not be determined whether this results in a third fewer steel requirement, as reported by The Guardian[154]. It should be noted that Pylon spacing for a T-pylon is about the same as a standard lattice structure (on level ground), but higher numbers could be required in steeper/hillier areas[155]. It should be further noted that introduction of this new type of pylon will eventually reduce the potential for reuse of components from existing pylons across the UK and Scotland.

2.9.4 EoL

Currently, at least 95% of materials are recycled or recovered by the T&D sector[156]. Closed loop recycling, refurbishment and reuse of equipment does occur, particularly through the aluminium alloy cable conductor recovery scheme operated by National Grid[156]. Ceramic insulators can be ground down in the UK for cement, while glass is ground for use in road surfaces. Concrete and steel rebar foundations are removed at the EoL, with concrete able to be used as aggregate[156].

The value of materials can be retained through reuse of equipment. However, there remain several barriers which include[156]:

- Obsolescence of equipment (size, safety standards) inhibits refurbishment or upgrade.
- Long lifetime of equipment prevents direct replacement as a suitable reuse outlet is needed at around the same time that they are de-commissioned.
- The geographical location of much of Scotland's T&D infrastructure can impede reuse.

The future reuse of equipment can be increased through better design, such as planning for easy dismantling of structures and equipment in challenging locations, and through refurbishment schemes[156].

2.1 Oil & Gas (O&G)

The decommissioning of offshore O&G installations and pipelines on the UK Continental Shelf (UKCS)[159] is regulated by the Department for Business, Energy & Industrial Strategy (BEIS) Offshore Decommissioning Unit through the Petroleum Act 1998. Under the act, owners of O&G installations and pipelines are required to decommission their offshore infrastructure at the end of a field's economic life[157]. Offshore decommissioning activity in the North Sea is set to increase as existing field infrastructure approaches EoL[158]. According to industry experts engaged during this study, there is no standardised approach to offshore decommissioning.

2.10.1 Capacity forecast

For O&G, only decommissioning of assets was studied. According to the Oil & Gas Authority (OGA) (2019), the quantities of assets shown in Table 2.1 are yet to be decommissioned. Scottish assets were taken as the proportion of UKCS assets in 'Scottish' waters[aa] in 2014.

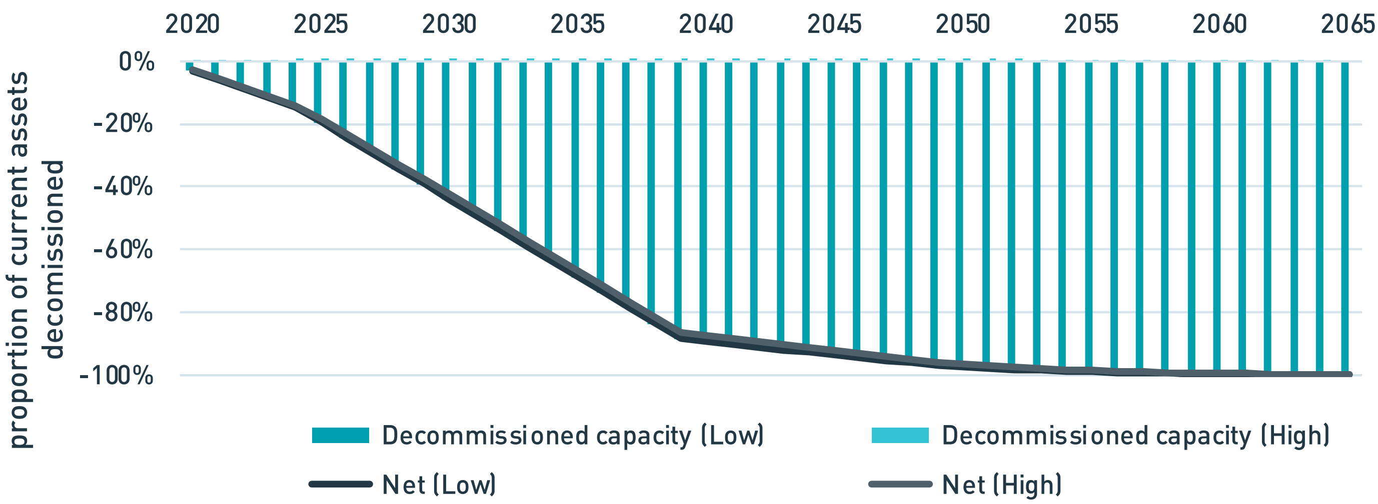
Table 2.1 **Scotland's energy mix of Renewable Electricity (Q4 2021)**

Structure	Units	UKCS assets	Scottish assets*
Topsides	tonnes	2,000,000	880,000
Substructures	tonnes	1,000,000	440,000
Subsea structures	tonnes	75,000	33,000
Wells**	tonnes	466,000	205,040
Pipelines**	tonnes	4,596,226	2,022,340

***Assuming 44% of UKCS assets are in 'Scottish' waters as defined in the assumptions in Appendix D.**
****Calculated using data from BP (2011).**

Figure 2.16 shows the percentage of existing assets removed per annum based on the anticipated spend on decommissioning up to 2065[158].

Figure 2.16 **O&G assets removal forecast to 2065***



***Forecast includes a high and low forecast for new capacity, life extended capacity and decommissioned capacity.**

The OGA predicts a sharp rise in expenditure on O&G decommissioning until 2030 as large numbers of installations reach the end of their productive lives[159]. By 2040, 82% of assets are expected to be decommissioned, with 98% decommissioned by 2050 and close to 100% expected to have been decommissioned by 2065[158]. It should be noted that, existing offshore assets offer the potential to be utilised in Carbon Capture and Storage (CCS) activities which BEIS deems vital to meeting the UK's emissions targets[160]. For example, according to the literature, reuse of O&G assets, may result in some CCS projects saving significant capital expenditure on decommissioning and resultingly fewer materials[160].

2.10.2 Material composition

Concrete makes up 48% of the material in offshore O&G assets, making up the majority of the subsea protective mattresses[bb] and required in pipelines infrastructure. Steel makes up a further 41% of offshore O&G assets and accounts for most of the composition of structures including topsides, substructures, and wells. Offshore assets also contain significant quantities of copper, nickel, and zinc (1.2%, 1.4% and 1.9% respectively) which can be recovered from topside structures[161].

Pipelines that cannot be recovered must be left securely at the seabed. According to an industry expert engaged during this study, approximately 10% of the remaining pipeline must be 'rock-dumped' at either end as well as empty middle sections to prevent floating. An industry expert advised that this requires ~860 tonnes of quarried rock per km of pipeline. The use of recovered aggregates as an alternative to quarried rock requires further investigation in future studies to determine whether materials from decommissioning other energy assets (e.g., from hydropower) could be utilised.

2.10.3 Technology advancements

There is no standardised approach to decommissioning offshore O&G assets. Decommissioning operators continue to find methods to reduce costs through continuous improvement.

As CCS technology improves, subsea pipelines and subsurface storage facilities could be adapted to pump pressurised CO_2 to the seabed[162]. The conversion of offshore infrastructure for use by CCS and offshore renewables industries would however require (potentially significant) investment and condition assessments of existing offshore infrastructure prior to repurposing. In-service and decommissioned O&G assets are also being considered for repurposing as green hydrogen infrastructure. These assets could include[162]:

- Floating and fixed production installations – converted bulk carriers could be well suited to provide a platform to host hydrogen production equipment.
- EoL pipelines could be used to import of natural gas feedstock for blue hydrogen production.

According to an industry expert engaged during this study, some structures are being considered for direct reuse as platforms for offshore wind, however, condition monitoring must be undertaken to ensure the structure is able to support these loads.

2.10.4 EoL

Up to 98% of offshore asset material is suitable to be recovered and recycled following decommissioning[156].

Some small- to medium-sized components, such as valves and generators, can be refurbished and reused directly. However, reuse within the UK is limited partially due to concerns over liability in the industry[156].

Much of the refurbished equipment generated in the UK currently is re-sold overseas including examples of entire topsides[163, 156]. A further barrier is the length of time that many of the assets have been in situ for (around 40 years), and the lack of design features to aid disassembly or reuse. Individual offshore installations often have unique design characteristics that reduce the potential for component interchangeability between installations. Furthermore, the value of some materials is reduced due to marine growth or naturally occurring radioactive material.

Pipelines are typically isolated and cut around platforms at EoL. About 10% of pipelines are removed with the rest left at the sea floor and rock dumped.

3. MATERIALS

This section analyses a selection of materials that are crucial to the development of the renewable infrastructure investigated in this study throughout Scotland's transition to net zero carbon.

3.1 Challenges

As previously discussed, low carbon technologies are often mineral-intensive. As each of the technologies assessed in this study (with the exception of O&G) are expected to grow up to and beyond 2050, it is anticipated that large quantities of materials will be needed during Scotland's transition to Net Zero.

Technically, the Earth contains enough metal ores to meet projected global demand for most metals beyond the next 100 years[164]. This includes 'critical' metals, defined as metals vital for economic well-being, whose supply may be at risk due to geological scarcity; geopolitical issues; trade policy or other factors[164]. In 2020, the European Commission identified 30 critical materials for the European Union including cobalt, rare earth elements (such as neodymium), natural graphite, Platinum Group Metals (PGMs) and lithium[165]. There is, uncertainty as to whether the metals needed to meet foreseeable infrastructure development, can be extracted on time and in an economically viable way, with minimal negative environmental and social impact[166].

The International Energy Agency (IEA) in its recent assessment of critical minerals noted that price volatility, geopolitical influence, and supply disruption could hamper international efforts to tackle climate change through slowing or substantially raising the cost of the process[167]. Similar sentiments have been echoed by a recent World Bank report[164] which also stressed the importance of addressing the sector's environmental and social impacts. Overall, supply chain reliability and sustainability is limited for the minerals needed for the renewable energy transition[166]. This is hampered by long lead times to bringing new mineral production online (typically 15 years) and declining resource quality.

The following limits to extraction have been identified from literature: The potential impacts of these concerns are further explored later in this section[166]:

- **Technical limits:** ability to extract material using current technology and capacity.
- **Economic limits:** profitability of extraction.
- **Social & environmental limits:** The social and environmental impact

The early consideration of material resource availability is therefore essential to facilitate the transition to the net zero economy. As the IEA notes[167], policy makers need to provide clear signals about their climate ambitions to boost investor confidence in committing to new projects. Such efforts should then be accompanied by a broad strategy that includes technological innovation, recycling, supply chain resilience and sustainability standards[98].

3.2 Material composition

Selection of materials for further study was based upon supply criticality and whether their use was cross-cutting (needed across a range of low-carbon technologies) or concentrated (needed in one specific technology). The following materials were selected for analysis in this study:

- Aluminium
- Copper
- Neodymium
- Carbon
- Iridium
- Nickel
- Chromium
- Iron & steel
- Platinum
- Concrete
- Lithium-Cobalt Oxide
- Titanium.

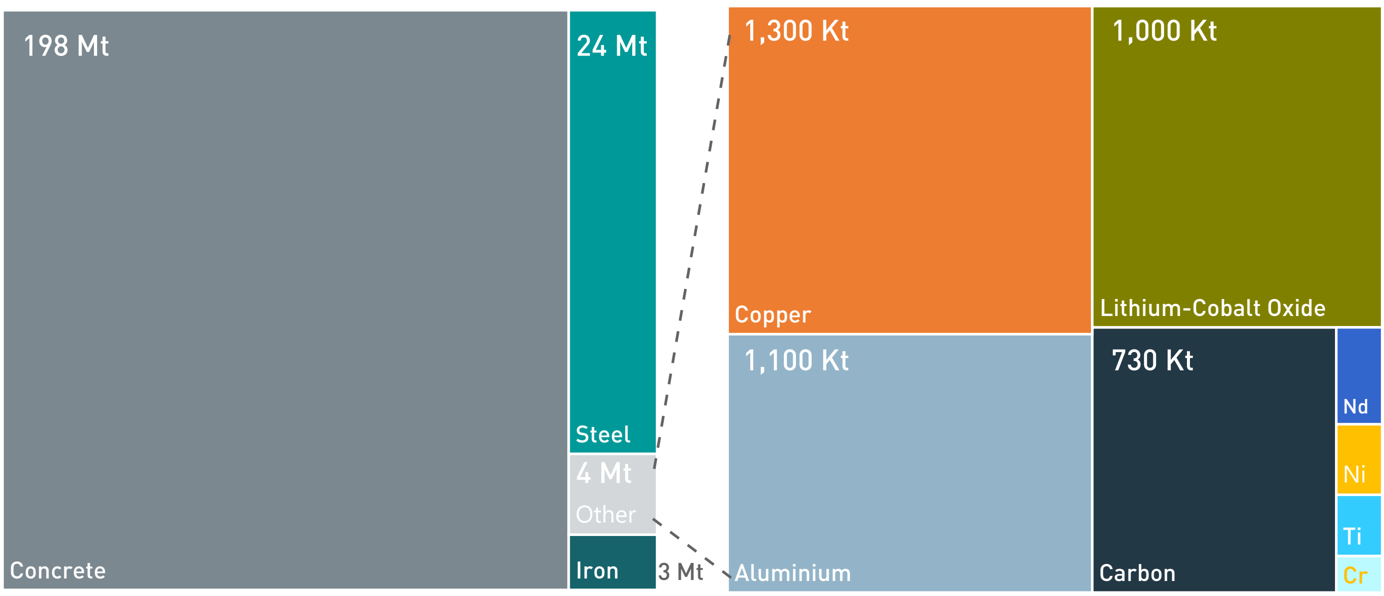
The composition of these materials required and generated across each technology up to 2050 based on our high-capacity estimates in the following sections. The results of this section support Zero Waste Scotland's Material Flow Accounts (MFA) and will contribute towards improving the granularity of the dataset in the low-carbon energy sector.

3.2.1 Required materials

From the high and low-capacity models used in this assessment, between 190-210 Mt[29] and 215-230 Mt of selected materials[168] could be required in Scotland by 2030 and 2050, respectively. By 2030, 13-18 Mt of these will be steel, iron and other potentially recoverable materials. By 2050, this is expected to increase to 22-31 Mt (based on high-capacity estimates). If this growth rate were to continue, up to 255 Mt of selected materials could be needed by 2075.

In 2018, Scotland directly consumed 64.7 Mt of materials in total across all industries[169]. According to the modelling outputs in this study, by 2050, the renewable energy transition may require Scotland to consume at least 12% more materials each year than it directly consumed in 2018, and potentially 40% per year up to 2030. Figure 3.1 shows the proportion of materials that are required for installation and life extension of assets by 2050 based on high energy capacity estimates.

Figure 3.1 Proportion of selected materials required for installation and life extension by 2050



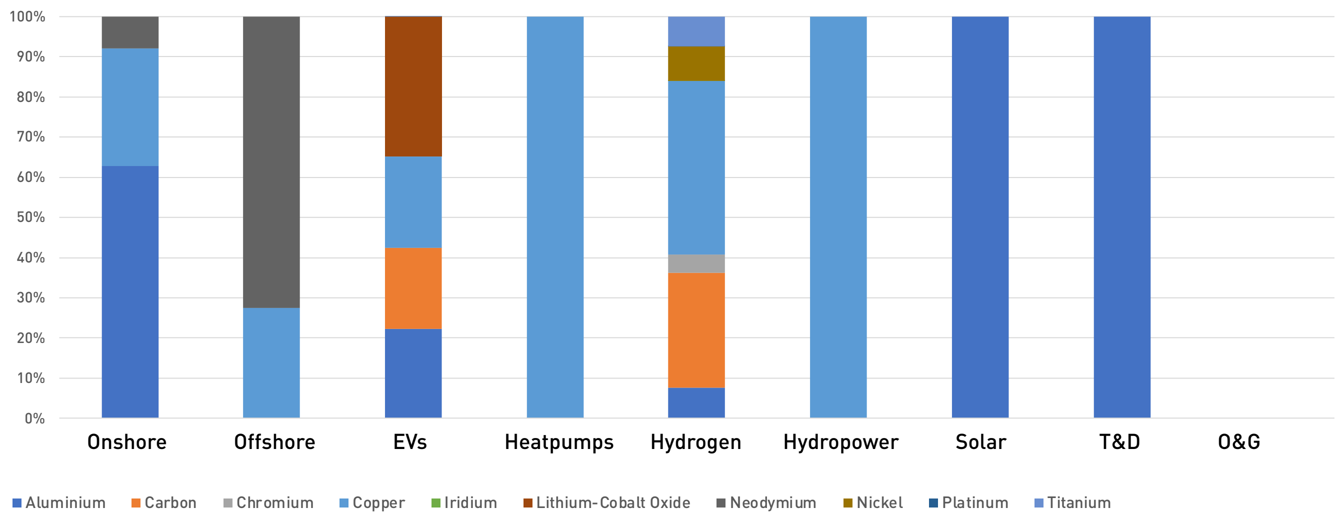
In addition to these materials, up to 43 tonnes of iridium and 4 tonnes of platinum could be required up to 2050 respectively in the technologies assessed in this report. Further, as caveated previously in this report, the quantity of nickel and chromium required are likely underestimated due to the quantity that is embedded within high performance and stainless steels. However, assuming that 10% of the steel used in these technologies is 304 grade stainless steel containing chromium and nickel at 18% and 8% each respectively[170], they could (combined) account for 62 kt or up to 0.3% of the total mass of required materials. Further research is necessary to determine more accurate quantities of these metals.

Concrete, steel, and iron (the 'bulk materials'), account for 87%, 10% and 1% of total materials respectively. A range of 'other' materials make up the remaining 2%; copper (31%), aluminium (25%), Li-Co (24%) and carbon (17%). Neodymium, nickel, titanium, and chromium each account for 1% of the 'other' category, whilst platinum and iridium make up negligible quantities in comparison.

It should be noted that, in this analysis, hydropower makes up 80-85% of overall materials and more than 90% of the concrete needed up to 2050. This estimate is primarily driven by the planned hydropower facilities up to 2030, such as the 450 MW Red John Pumped Storage Hydro Scheme due online in 2026[171, 172]. Whilst the confidence in the hydropower models is low due to design variants discussed in Section 2.7, this assessment supports literature elsewhere which suggests that "concrete stocks are about 20 times larger than metal stocks, primarily due to the large amounts of concrete in hydropower dams"; The findings of this study suggest up to 10 times, using the same materials but assessing different technologies. The material composition of the example dam used in the model is supported by other examples identified in literature[173] and as advised by industry experts within Wood. Nevertheless, as this study provides a high-level assessment of all technologies, a detailed study should be undertaken to understand more accurate concrete estimates for current and planned hydropower assets in Scotland.

Figure 3.2 shows the composition of selected materials required up to 2050 for each of the nine technologies examined in this report excluding 'bulk materials'. This figure includes the materials required for installation and life extension.

Figure 3.2 Composition of 'other' materials* required



***Excluding concrete, iron, and steel.**

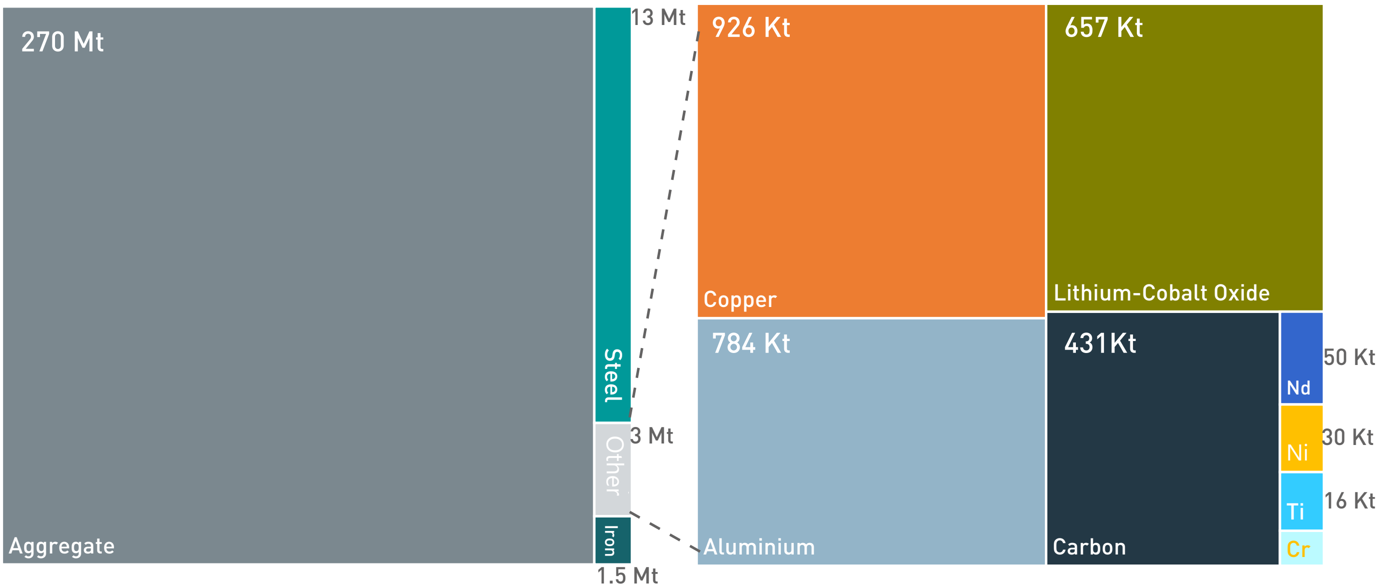
Hydrogen and EVs require the greatest variety of materials of all the technologies studied. High-quality nickel is needed in both EV batteries and green hydrogen production although, as mentioned previously, alloyed nickel is likely to be required in greater quantities across most of the technologies within stainless and high-performance steels. EVs account for all the Li-Co requirements in batteries whilst hydrogen generation requires significant quantities of titanium and chromium in the PEM stack which needs regular replacement. Green hydrogen also requires platinum and iridium in smaller amounts. Carbon is required as an activated carbon adsorber in blue hydrogen and as graphite anodes in green hydrogen and EV batteries.

Neodymium has concentrated uses in offshore and onshore wind. Copper and aluminium are the greatest cross-cutting materials as they are used across most of the technologies. Copper makes up 100% of the selected non-steel and iron metals for heat pumps and hydropower and aluminium makes up 100% of the selected non-bulk materials for Solar PV and T&D.

3.2.2 Generated materials

Figure 3.3 shows the proportion of selected materials that could be generated from decommissioning and life extension of assets by 2050 for each material based on a high-capacity forecast scenario. Up to 41 and 4 tonnes of iridium and platinum could be generated by 2050 respectively from the technologies assessed in this report.

Figure 3.3 **Proportion of materials generated from decommissioning and life extension by 2050**

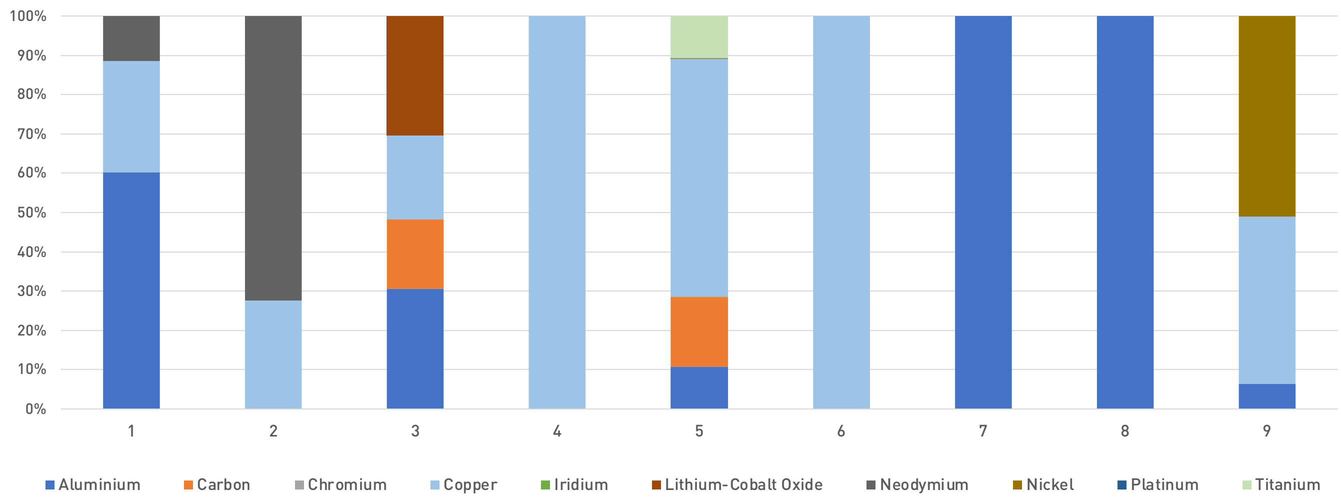


Based on this assessment, up to 72 Mt of selected materials could be generated in Scotland by 2030 and up to 290 Mt by 2050. This total is mostly related to hydropower plants reaching EoL between 2030 and 2050. Concrete-based aggregate makes up to 94% of the total materials generated by 2050 while steel and iron make up 5%. By 2030, 0.2-1.4 Mt of generated materials these will be steel, iron and other potentially recoverable materials; projected to increase to 11-17Mt by 2050. The large quantity of concrete is primarily due to the decommissioning of current large-scale hydropower assets. It should be noted that some of it may not be recovered depending on the decommissioning method (as discussed in Section 2.7) and considering the approaches taken around decommissioning of other energy technologies (e.g., onshore wind)[174]. Unlike other materials, concrete cannot be directly recovered for reuse or recycling. Rather, it is extracted as aggregate for potential reuse as a building material[175].

Other materials make up the remaining 1%, which consists of aluminium (32%), copper (27%), Li-Co (23%) and carbon (15%). Nickel accounts for 2% and neodymium and titanium each account for 1%. Chromium, platinum, and iridium make up negligible quantities in comparison though large quantities of chromium could be required in stainless steel.

Figure 3.4 shows the composition of materials generated from decommissioning and life extension for each of the nine selected technologies up to 2050, excluding 'bulk materials'. This includes the materials required for installation and life extension.

Figure 3.4 Composition of 'other' materials* generated from decommissioning by 2050



*** Excluding concrete, iron, and steel.**

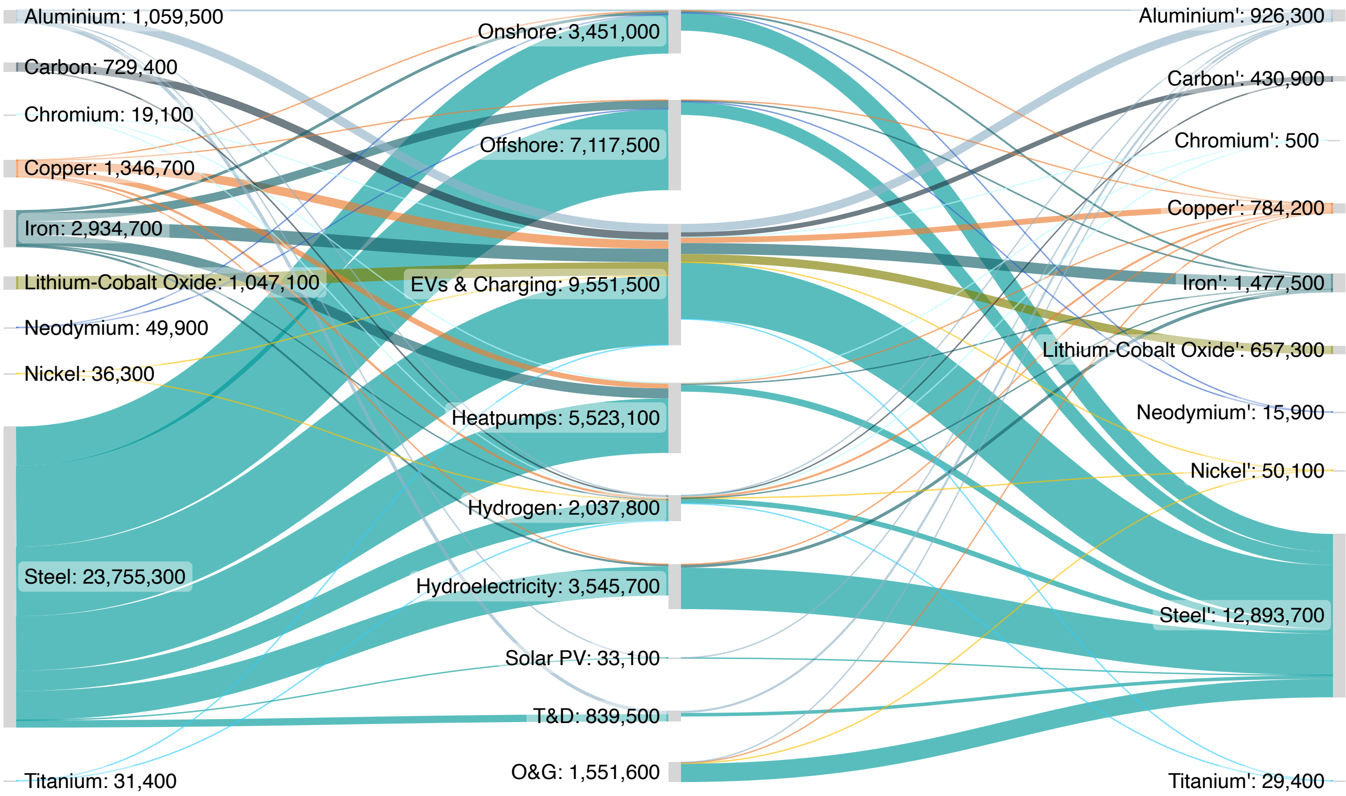
Significant quantities of nickel and copper are available from O&G decommissioning. Otherwise, the composition of other metals is broadly similar to those required for installation. Less nickel is available from hydrogen at EoL as much of it will remain in use within blue/grey assets.

3.3 Material flows

Figure 3.5 shows a high estimate of the materials required for installation and life extension (from left) and the materials generated from decommissioning and life extension up to 2050 (right) based on the high-capacity forecast. Platinum and iridium make up a negligible amount of total materials so are excluded from this figure. Conversely, concrete was excluded due to the enormous quantities required and generated in comparison to other materials.

Note, this figure presents the quantities of selected materials within each technology but does not disaggregate between those materials needed for producing infrastructure in Scotland and also those which are embedded within imported infrastructure that has been produced elsewhere.

Figure 3.5 Sankey diagram of the materials required and generated up to 2050*



***High estimate to 2050. Excludes concrete.**

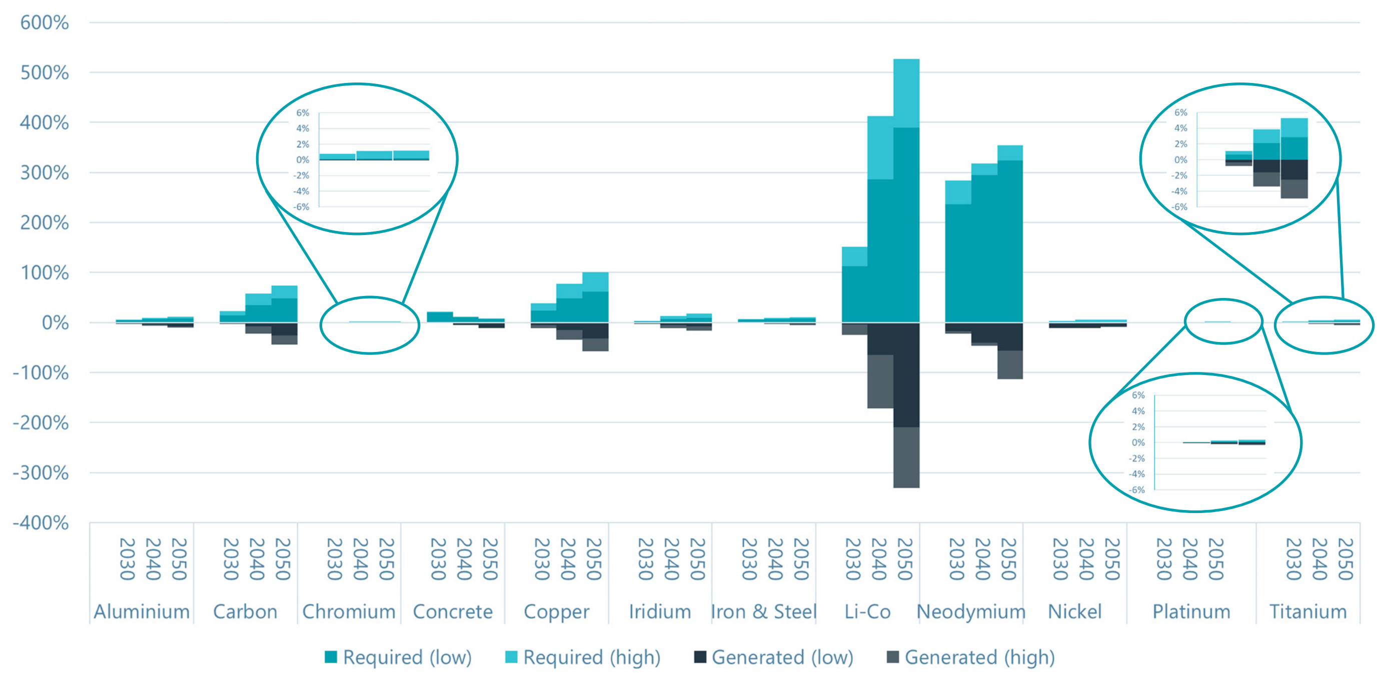
With the exception of O&G, imbalances in Figure 3.5 are due to materials that are anticipated to remain in use by 2050. Note that more materials are generated from hydropower than are needed due to the large quantity of large-scale assets that will reach EoL by 2050.

As shown in Figure 3.5, a significant proportion of the materials for each technology could be generated through decommissioning. Currently, Scotland exports the majority of these materials for reuse, recycling or reprocessing with very few of the materials captured and reprocessed domestically. Typically, Scotland and the UK export materials either as refurbished equipment or as low-value scrap. Imports consist of reprocessed material or newly extracted material for onwards domestic processing[176].

Export figures for selected materials in Scotland were not identified in this study; however, the British Geological Survey (BGS) publishes an annual Minerals Yearbook for the UK which contains estimated imports, exports and consumption of the selected materials[176]. Further information for selected materials is presented this section and elaborated in Appendix C. Although the UK has capacity to reprocess steel, iron, and aluminium, most of these materials are currently exported for reprocessing[177, 176]. There is limited, if any, recycling capacity for the other selected materials as discussed later in this section.

Figure 3.6, below, shows a high and low estimate of the annual quantity of materials required and generated in Scotland as a proportion of current UK imports.

Figure 3.6 **Average annual material requirement and generation as a proportion of 2020 UK annual imports to 2050***



***Concrete is compared against current domestic UK production as 95% of concrete used in the UK is produced in the UK[187].**

Global production, UK import and consumption values for each material are presented in Appendix C. For this analysis, the latest available (2020) figures were used as the basis for comparison, but it should be noted that this was an exceptional year for trade and resulting materials consumption therefore may not reflect typical use in Scotland and the UK.

It should be noted that the annual requirements presented in Figure 3.6 are taken as the average annual consumption between 2020 and the reported year. Therefore, actual annual requirements could be higher than reported towards the end of each decade. It should also be noted that the materials generated are not necessarily recoverable; whilst some material may be recovered and reused in place of primary materials (e.g., aluminium), other materials (including alloys) may be recovered as 'lower quality' secondary materials or not at all due to technical limitations. It is also likely that much of the recovered material will not be directly reused for the same purpose, or indeed within low-carbon technology infrastructure. Further analysis must therefore be undertaken to determine the proportion of this material that is recoverable.

As shown in Figure 3.6, Li-Co and neodymium require the greatest increase in annual imports as they have not historically been extracted or processed in large quantities. Other materials that have an established presence in other industrial sectors; such as iron, steel, and aluminium; will experience less of an increase. Nevertheless, these still represent significant increases in current UK imports due to the large quantities that are currently consumed. The selected materials are briefly analysed below. Further information, including current production, import, and consumption data can be found in Appendix C along with a brief Environmental, Social and Governance (ESG) analysis.

3.3.1 Lithium-cobalt oxide

Lithium-Cobalt Oxide is an oxide primarily used in Lithium-ion batteries. It is expected to play a key role in the transition to zero carbon mobility. This study estimates that by 2030, Scotland may require up to 150% more Li-Co oxide per year than was imported into the entire UK in 2020[dd]. This deficit is projected to increase to over 400% by 2040 and over 500% by 2050. Based on these projections,

a rapid global rollout of Li-Co processing and mineral extraction would be required, including foreign and domestic processing capacity. Whilst production and processing capacity can come online within a few years, development of extraction capacity can take 10+ years to develop[179]. Therefore, to meet future demands, the supply of these primary materials will need to be secured alongside recycling capacity building.

Li-Co oxide requires extraction of lithium and cobalt which are extracted from minerals. Cobalt is produced a by-product of copper and nickel production which are mostly extracted from ores mined in the Democratic Republic of the Congo (DRC)[180]. Lithium is relatively abundant and is mined mostly in South America and Australia in the form of spodumene. China is the largest global processor of Lithium[180]. There is currently no large-scale refining capability in Europe, however Green Lithium has secured funding to become the UK's first lithium refinery, aimed specifically at bolstering supply of battery-grade lithium to the UK and European markets[181].

Li-Co can also be generated domestically through the recovery of materials during decommissioning of assets. By 2030, the equivalent of 24% of 2020 UK imports could be available in the form of EoL EV batteries, and over 300% by 2050. However, it is not enough to meet growing demand so primary materials will be needed up to, and beyond 205. Based on this assessment, the need to further develop domestic recycling capacity for EV batteries is evident. In 2021, Fenix Battery Recycling opened a Lithium-ion battery recycling facility in Kilwinning near Glasgow with capacity to recycle 10,000 tonnes of batteries (with future expansion to 20,000 tonnes)[182]. Furthermore, Veolia have announced that they will provide 20% of UK battery recycling capacity by 2024[183] and Glencore-Britishvolt will provide capacity for an additional 10,000 tonnes of lithium-ion batteries by 2024[184].

3.3.2 Neodymium

Neodymium is a rare earth element. The most important use for neodymium is in an alloy with iron and boron to make very strong permanent magnets[185]. Its main application is in onshore wind, offshore wind and EVs. As shown in Figure 3.6, over 300% more neodymium per year is predicted to be required by 2050 to meet Scotland's onshore and offshore wind infrastructure targets. Although the UK is investing in recycling capacity for rare earth magnets[186], due to the longer lifetime of these assets compared to EVs, much less material will be available for recovery by 2030 and 2050 in comparison.

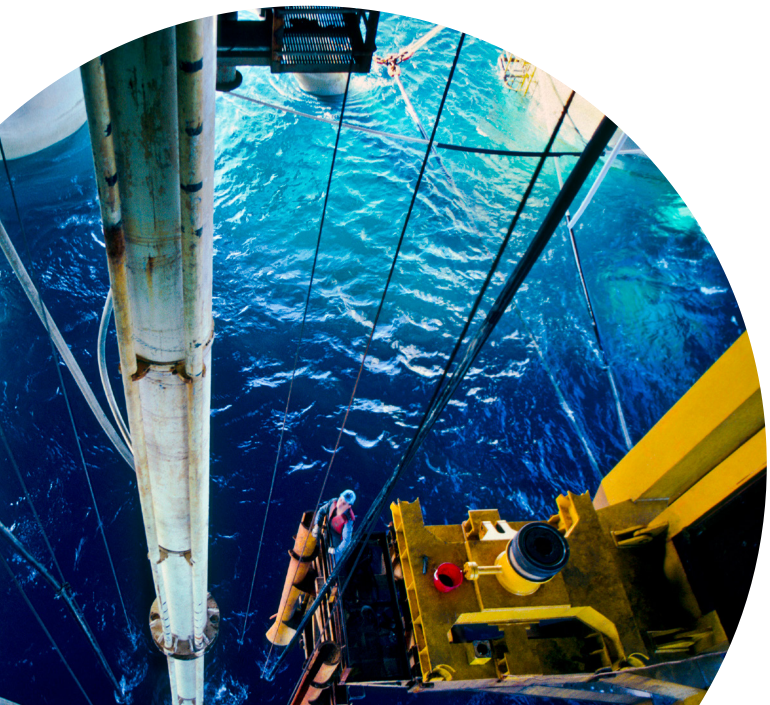
Scotland has historically benefited from its geographical advantages of shallow waters for fixed offshore installations. However, development of floating capacity expands the range for offshore wind, opening the possibility for more countries to develop assets[187]. This is predicted to increase demand for neodymium and other rare-earth materials, leading to further competition.

China is largest producer of rare earth metals including neodymium. It also controls approximately 70% of refining processes[188]. Neodymium is extracted from minerals monazite and bastnaesite which is known to cause widespread environmental pollution[190]. Current substitutes of rare-earth metals are either inferior or still undiscovered [191]. Mixing with iron and other rare-earth elements such as dysprosium and terbium can reduce the quantity of neodymium needed in magnets although they are more susceptible to corrosion and have lower magnetic output[192]. Rare earth element-free generators have historically raised concerns among developers due to their weight, which requires additional materials to provide structural support[193]. 'Nevertheless, UK-based GreenSpur Wind, and US-based Niron Magnetics have developed a 15 MW generator which is able to meet the mass and efficiency targets required by the market, though it is yet to be proven at scale[193].

To meet the projected demand, Scotland will need to secure supplies of neodymium and promote domestic recycling capacity. Recycling capacity for neodymium and other rare earth magnets have been recently brought online in the UK by the University of Birmingham at the Tyseley Energy Park (TEP)[194]. Although still in early stages of development, the Hydrogen Processing of Magnet Scrap (HPMS) process can recover over 90% of the neodymium from electronic waste[195], supporting production of 20 tonnes of recycled rare earth magnets a year. However, the HPMS technology at the TEP is generally applied vehicle motors, audio products and other small electrical devices, and it remains to be seen whether the technology can be upscaled and applied to the decommissioning of infrastructure in Scotland[196].

3.3.3 Nickel

Nickel is a corrosion resistive metal; It is mainly used in making alloys such as stainless steel which is used across all the technologies assessed in this report.



High-quality nickel is also used in the anodes for EVs and hydrogen production[166]. From this assessment, 6% more nickel than is currently imported to the UK may be needed annually by 2050; although, as caveated previously, this study reports a likely underestimate due to the quantities that are included in steel.

As nickel is used in 75% of steel grades[197], it is likely that it could be needed in much larger quantities than is reported in this assessment (as much as 19 kt by 2050[ee], or 8% more per year). To gain a better understanding of the quantities needed in Scottish energy infrastructure, the quantity of nickel used in steel should be investigated further in any future investigations.

The bulk of the mined nickel comes from two types of ore deposits: laterites and magmatic sulphide deposits[198]. Mining and processing of nickel can cause widespread environmental damage; the Russian city of Norilsk, a large producer of nickel is considered one of the most polluted cities in the world[180]. High-quality nickel (class 1) required for EV batteries, is expected to be in short global supply as a result of the surge in demand for EVs[199]. Recycling of nickel is hindered by the difficulty in separating it from its alloy, resulting in only around 17% of nickel being recycled globally[180]. However, it is essential to maximise the recovery of this material to ensure a secure supply[200].

LFP batteries and high-manganese-content batteries are expected to be developed which could reduce the quantity of nickel needed by this sector[77]. Manganese is a promising substitute for use in EVs as its global production is four to five times greater than nickel[201].

3.3.4 Chromium

Chromium is a critical component of high-performance and stainless steels and there is currently no viable substitute. It is used Global resources of chromium are considered ample for the foreseeable future[202]. However, past political and economic events have raised concerns about the uninterrupted availability and reliability of supplies of these commodities[202]. Chromite ore can be found in many countries, but South Africa currently produces 82% of global supply. Worker conditions are an ESG concern in South Africa, particularly for artisanal miners, as chromium has long been recognised as a toxic, mutagenic, and carcinogenic metal[203].

Chromium chemicals are generally consumed in dissipative end uses and thus are often not recycled[204]. Although the projected increases of less than 2% appear small in comparison to other materials, chromium is used across many industrial sectors, so this represents a notable increase in today's consumption. Furthermore, as with nickel, this study reports a likely underestimate due to the quantities that are included in steel, so it is possible that as much as 43 kt more chromium could be needed by 2050[ff] which equates to 4% more per year than is currently imported).

3.3.5 Aluminium

Aluminium is a cross-cutting material needed in most of the technologies studied and use for energy infrastructure is expected to increase; up to 12% of current total UK imports. Aluminium can be obtained from numerous minerals, the most common of which is bauxite. Aluminium is produced from minerals via an energy-intensive electrolytic process[205]. Most of the bauxite used to make aluminium in UK originates from areas such as Jamaica, West Africa, Australia, and South America[206].

The UK has a well-established aluminium recycling industry; however, despite technically having the capacity for recycling 100% of aluminium packaging, nearly half of UK aluminium waste is currently exported due to producers seeking to meet recycling targets at minimal cost[207]. The UK T&D industry already operates closed-loop recovery systems for aluminium and there is potential for this to be extended to other technologies[208]. The ability to recover and reuse this material domestically could reduce the need to import this material and ensure availability.

In some technologies, such as solar PV, demand could be reduced through the substitution of aluminium with other materials such as plastics. However, substituted materials can also have negative ESG impacts.

3.3.6 Copper

Copper is the second most electrically conductive material after silver and is the third most used metal in manufacturing[301]; it is used in all of the technologies assessed in this study. By 2030, Scotland may require up to 50% more copper than is currently imported into the UK and this could increase to 100% by 2050. About half of this deficit could be generated through recovery of materials during decommissioning. Almost half of copper used in the EU already comes from recycling[209].

Large increases in demand would require imports from copper-producing regions outside the EU, particularly in South America [210], although copper mines exist within the EU – notably Poland and Scandanvia[180]. Copper extraction involves the mining of the ore, common types of which are copper oxide and copper sulphide. Whilst a small producer of copper minerals, China is the largest processor of copper[180]. Extraction of copper through open pit mining often results in intensive water consumption, land erosion, sinkhole formation, biodiversity loss and the chemical contamination of groundwater[211]. Large volumes of low concentration sulphur dioxide is often produced by the copper smelting process, which can result in acid rain. Leaching solutions are also known to be disposed of as wastes via land application or other means[180].

3.3.7 Carbon

Carbon as graphite is required for green hydrogen production and in EV batteries and activated carbon is required in blue/grey hydrogen production as a pressure swing adsorbent. From this assessment, these technologies are predicted to be the fastest growing up to 2050 and annual demand for carbon could exceed 74% of current imports by 2050.

Current supply is mostly from China, the US and India[212]. Whilst Scotland was historically a producer of natural graphite activated carbon, there has been no systematic or modern exploration within the UK[213]. Graphite is extracted using open pit method and underground methods including shaft mining whilst activated carbon is usually derived from organic waste products such as wood. Open pit mining can cause environmental damage through habitat loss, dust emissions and water and soil pollution[214].

The purification of battery-grade anode products (graphite) requires high quantities of sodium hydroxide and hydrofluoric acid, which may be harmful to both human health and the environment. Furthermore, the production of anode grade graphite, used in lithium-ion batteries is energy-intensive. Currently, the energy-intensive processing stages within the graphite supply chains are commonly located in regions with low-cost energy. In these areas the electricity grid is often dominated by coal energy, resulting in a high number of embedded emissions[215].

3.3.8 Concrete

Concrete is versatile construction material, used in large quantities for a wide range of groundworks. It is required in all of the technologies assessed in this report except for EVs. This study estimates that up to 184 Mt of concrete may be required by 2030; largely as a result of planned large-scale pumped-storage hydro facilities due to come online by 2026. This would result in an increase in concrete use of up to 20% on current consumption. Beyond 2030, annual concrete demand for installation of renewable energy technology is expected to drop to 7% by 2050. 95% of concrete used in the UK is produced in the UK[216]. It is made by mixing cement with supplementary cementitious materials including sand, water and other admixtures or reinforcement. Aggregates, which make up to 75% of concrete, are extracted from natural deposits, or the mining of underground sediments. Concerns over the sourcing of sand have been raised, with some regions around the world already in short supply although alternatives to mined sand do exist and are being tested in the UK in the form of low-carbon concrete[217, 218, 219].

UK concrete and cement account for around 1.5% of UK carbon dioxide emissions which is five times lower than the global average (7% of emissions)[216]. Clinker is the principal ingredient in concrete and is the main source of carbon dioxide emissions. It is produced by grinding and heating limestone and other raw materials (extracted through mining) to release carbon dioxide before it is mixed with gypsum and other materials to produce cement[216].

90% of UK hard construction and demolition waste is recycled as aggregates but it cannot be directly recycled into new concrete. The UK has the potential to be self-sufficient in the manufacturing of concrete and cement, with all key raw geological materials domestically available[220].

3.3.9 Iron & steel

Steel is mainly composed of iron; it is the most widely used metal in the world and is used in all of the technologies assessed in this report. Based on projections and as shown in Figure 3.6, 11% more iron and steel may be required per year by 2050 than is currently imported to the UK. Half this amount could be recovered from decommissioning and life extension of energy infrastructure. Whilst this is not as significant an increase compared to some of the other materials such as copper, it

still represents a significant increase on the 8 Mt that were consumed in the UK in 2020. Iron is extracted from iron ore at high temperatures in a blast furnace. The top three iron ore-producing countries are Australia, Brazil, and China. Brazil and China largely consume reserves in their domestic economies[221]. In 2020, the UK consumed 8,172 900 tonnes of iron of which 86% was imported: primarily for domestic steel manufacturing[222]. Steelmaking contributes to 15% of the UK's total industrial emissions which can be reduced by 72% through recycling . The use of hydrogen as an energy source for the steel industry is also under investigation as a means to further reduce emissions[225].

Overall, 87% of UK construction steel is currently recycled, 10% is reused and 3% goes to landfill[176]. The UK steel recycling industry is well established, although only 25% of used steel is currently recycled within the UK[224]. Slightly over half of UK steel exports were to the EU, whilst almost two-thirds of steel imports were from the EU[225]. All of Scotland's 820 kt of scrap steel is currently exported for recycling[226]. Modern electric arc furnaces can accept 100% scrap steel, compared to traditional blast furnaces which can accept up to 20%, and can reduce GHG emissions by 60%[227]. Therefore, whilst there is current potential for Scotland to recover steel from decommissioning of energy infrastructure, it could be improved further by increasing domestic recycling capacity using modern electrically powered technology.

3.3.10 Platinum and iridium

Platinum and iridium are PGMs which are required in relatively small quantities for hydrogen production. Based on this assessment, platinum demand is not expected to increase by more than 1% of current UK imports; however, annual iridium demand could increase by up to 17% by 2050. Despite the relatively small quantities needed compared to other selected materials, platinum, and iridium have been included in this study due to their criticality and their lack of substitutability in the technologies assessed in this study. In addition to EV batteries and hydrogen fuel cells, PGMs are used in the automotive industry within catalytic converters (71% of global demand), electronics and medical applications[228]. PGMs are currently produced in relatively small quantities so increases in demand could have significant impacts on the global supply chain[176]. Furthermore, most databases aggregate PGMs so it is difficult to determine current quantities of specific metals within this group. Future Scottish demand for these materials should therefore be studied in greater detail in future studies.

Iridium is extracted from PGM rich ores and as a by-product during the electrorefining of nickel. It is largely unrecycled due it often being used in small quantities that are subsequently deemed to too expensive to recover and recycle[229]. Platinum recycling, on the other hand, is well established, due to the high prices and relatively easy recycling process of catalytic converters[230].

3.4 Geographic spread

3.4.1 Extraction

The materials detailed in Section 3.3 of this report are, with the exception of concrete, extracted as minerals outside of Europe with concentrations in Africa, Asia, South America, and Australasia. Key producing countries for the minerals studied are Australia, South Africa, and China. Australia is the largest producer of aluminium (55% of global supply [231]), iron (81%[232]) and lithium-cobalt (55%[233]). South Africa is the largest producer of Chromium (82%[212]), Iridium and Platinum (70%[212]). China is the largest producer of graphite and activated carbon (75%[212]). Further details for each material are presented in Appendix C. 15% of the UK's aggregates mining in 2019 took place in Scotland although there has been no interest in mineral extraction for the selected materials in this study[234]. In the UK, Cornish Lithium recently reported "globally significant" lithium grades in geothermal waters and is preparing for work on a pilot plant[234]. Cornwall Resources are also progressing with the development tin, tungsten, and copper deposits[234].

The Crown Estate Scotland also manages the seabed and other rights including non-energy mineral rights in Scottish territorial waters and the Scottish offshore zone[234]. There are no currently commercial marine aggregate extraction licenses in Scotland, future proposals would lead to an equivalent process with the relevant seabed manager. Such rights and options can only be exercised once regulatory consent is obtained under Marine (Scotland) Act 2010[234].

3.4.2 Processing

Post extraction, the majority of these raw materials are processed outside of the UK [235]. For example, China accounts for 39% of copper refining globally and around half of lithium concentrates are exported to China where it is used to make battery-grade lithium chemicals. China is also the leading smelter of aluminium (35.45 Mt from January to November 2021[236]).

Of the recyclable materials, there is capacity to recycle many of the materials within the UK. However, in many cases, this capacity is either not sufficient or not used due to cost constraint[237]. As a result, a significant number of materials are exported. Notable examples of this are aluminium[237] and constructional steel[238]. Concrete (aggregates) is the material that is most recycled within the UK, 90% of hard construction and demolition waste is recycled as aggregates[220].Chromium, iridium, cobalt, and nickel are either not easily recyclable or not currently widely recycled due to a lack of financial viability[310, 199].

3.5 Supply chain risks

The risks associated with the material supply chain are varied and include geological scarcity, geopolitics, trade policy and environmental and social concerns. In a recent evaluation of the risks facing their industry, mining companies identified environmental and social issues as the primary risk, followed by decarbonisation and the license to operate (LTO). The LTO of some mining companies is in question as expectations change around the sector's contributions to and engagement with indigenous communities and protection of heritage sites[239].

3.5.1 Predicting supply

Metal supply chains are typically long and complex with historically little transparency in the extraction, refining, transporting and processing stages. As a result, it is virtually impossible to identify all risks leading to a systematic underestimation of supply chain risks[166]. The production of most critical metals is particularly unpredictable as they are often a by-product (companion metal) in the extraction of other metals such as copper, iron, and zinc (major metals)[166]. Thus, the supply chain of these materials must be considered alongside one another with changes in demand for one material having potentially severe impacts on the value of the other. This, in combination with the lack of transparency on unused production capacity, makes predicting the supply of these metals particularly difficult.

The emergence, and rapid rise, of low carbon technologies has led to shocks in the material industry. For example, the surge in demand for EV's and has resulted in the price of lithium carbonate growing by almost 12 times between the start of 2021 and April 2022[240] and the London Metal Exchange recently halted nickel trades due to price volatility[241]. Such rapid scale-up of production cause price spikes and crashes, resulting in instability and uncertainty for both the mining, processing, and renewable energy sectors[242].

3.5.2 Global risks

Europe has historically grappled with geopolitical concerns regarding its supply of resources; There have been disruptions in fossil fuel supply during the oil crisis of 1973 and, more recently, due to the Russian invasion of Ukraine. These geopolitically motivated disruptions are increasingly cited as foreshadowing a future scarcity of critical metals[243]. In the cases of lithium, cobalt and rare earth elements; the world's top three producers control over three-quarters of global output[167]. Examples of recent geopolitically motivated supply chain disruptions include:

- China's export ban on 'rare earth elements' including neodymium, introduced in late 2010, following disagreements with Japan over the Senkaku/Diaoyu islands. As 97% of total global production originated from China at the time, prices rose by more than 1,000%[166].
- Indonesia, a major producer of nickel, implemented export restrictions in 2014 as part of efforts to bring refineries to Indonesia and preserve more of the value chain within the domestic economy. As a result, Indonesia is likely to account for around half of global nickel production growth between 2021 and 2025[244].
- In September 2020, the US declared a Presidential emergency over critical metals and recently announced a task force to strengthen its supply chains following its growing dependence and increasing trade conflicts with China[245].

Other global risks to supply can include decisions by government over environmental or safety concerns; The Philippines, for example, closed 23 mines (predominantly nickel) in 2017 due to concerns over environmental damage - then accounting for around 10% of global supplies[246].

Other, short-term logistic disruptions such as the Suez Canal blockage in 2021 can cause price squeezes on materials such as steel and copper[247]. Extraction and processing South Africa's increasingly expensive and unpredictable electricity supply often limits the production of chromium, iridium, and platinum, which have also been subject to strike action in the country[248]. South Africa accounts for over 70% of the global production of these materials so disruptions could have major repercussions to global supply. China has taken a dominant position in both the mining and processing of many metals, including those extracted elsewhere (e.g., Africa). Not only does this concern extraction and metal production, but also the manufacture and supply of metal products.

Concerns over metal supply chains has led to initiatives in Japan such as a national stockpiling programme with the goal of holding quantities of rare metals[166]. Since 1947, the United States Defence Logistics Agency (DLA) has also managed a national strategic stock of materials (including cobalt and lithium) deemed critical, valued at approximately $1.5 billion[166]. The UK Government is drafting a UK Critical Minerals Strategy in 2022 as part of its Net Zero Strategy[249] and ministers have recently explored the creation of a national stockpile of so-called rare earth metals amid rising concerns over Chinese dominance of supplies [250].

3.6.2 Selected material risks

The selected materials have been assessed on their supply risk based upon the quantity of each required per year compared to 2020 annual imports (as presented in Figure 3.6), their criticality and their substitutability. See Table 3.1 for further details.

Material	Risk	Justification
Aluminium	Low	Small volume increases needed for low carbon energy infrastructure compared to current UK imports. Supply not critical. Domestic recycling capacity identified. Can be substituted for some applications.
Carbon	Medium	Large volume increases needed for low carbon energy infrastructure compared to current UK imports. Supply not critical.
Chromium	Medium	This assessment identified only small quantities of specific nickel use in the technologies considered and supply not critical[165]. However, large quantities are expected to be required for the manufacture of steel.
Concrete	Low	Small volume increases needed for low carbon energy infrastructure compared to current UK consumption. Domestic supply of materials.
Copper	Medium	Large volume increases needed for low carbon energy infrastructure compared to current UK imports. Supply not critical[165].
Iridium	High	PGMs listed by EU and UK as critical raw materials[165].
Iron & Steel	Low	Small volume increases needed for low carbon energy infrastructure compared to current UK imports. Supply not critical[165]. Domestic recycling capacity identified.
Lithium-Cobalt Oxide	High	Large volume increases needed for low carbon energy infrastructure compared to current UK imports. Cobalt & Lithium listed by EU and UK as critical raw materials[165].
Neodymium	High	Large volume increases needed for low carbon energy infrastructure compared to current UK imports. Light rare earth elements listed by EU and UK as critical raw materials[165].
Nickel	Medium	Whilst this assessment identified small quantities of specific nickel use in technologies, large quantities are expected to be required in embedded steel. Large quantities of high-quality nickel is needed in EVs and Hydrogen production, however it is not listed as a critical material despite concerns over its future supply[165].
Platinum	High	PGMs listed by EU and UK as critical raw materials[165].
Titanium	High	Titanium listed by EU as a critical raw material[165].

Table 3.1 **Risk of material supply based on this assessment**

The technologies most at risk of material supply have been assessed in Table 3.2 with a justification for their classification based on the outputs from Table 3.1.

Energy technology	Risk	Justification
Onshore wind	High	Large quantities of rare earth elements such as neodymium required to meet capacity demand up to 2050 compared with current consumption. There is opportunity to recover most materials from decommissioning and options to extend the lifetime of components.
Offshore wind	High	Large quantities of rare earth elements such as neodymium required to meet capacity demand up to 2050 as well as other materials such as nickel and chromium in corrosion resistant steels. There is opportunity to recover most materials from decommissioning and options to extend the lifetime of components.
EVs & refuelling infrastructure	High	Large quantities of scarce materials including lithium, cobalt, nickel, and graphite will be needed to meet demand up to 2050. As these materials are currently consumed in small quantities, there will need to be improvements in extraction, processing, and recycling capacity for these materials.
Heat pumps	Medium	There is expected to be a large increase in heatpump capacity up to 2050 though the materials required are not novel. However, large quantities of materials including copper will be required to meet demand.
Hydrogen	High	Large quantities of scarce materials including lithium, cobalt, nickel, and graphite will be needed to meet demand for green hydrogen up to 2050. As with EVs, there will need to be improvements in extraction, processing and recycling capacity for these materials and improvements in design to improve recoverability of materials. Blue hydrogen will also require large quantities of scarce materials in catalysts and adsorbing materials.
Hydropower	Medium	Although less scarce materials are needed for hydropower, very large quantities of concrete may be required to meet capacity demand up to 2050. This could result in a large increase in the current consumption of concrete. Although materials are mostly supplied domestically, capacity may need to be improved dramatically.
Solar	Medium	Solar PV panels require scarce materials in their construction. However, relatively low quantities of these resources are likely to be required in Scotland up to 2050. Furthermore, current recycling technology is able to recover →90% of materials.
Electricity T&D	Low	T&D infrastructure studied in this report will required a significant quantity of steel, aluminium, and concrete. However, extraction, processing and recycling of these materials are relatively well established so there is less of a risk of material supply in this sector than for other technologies.
Offshore O&G	Low	Few materials are required for O&G decommissioning. Nevertheless, large quantities of quarried rock may be required for decommissioning subsea assets. Decommissioning of assets result in the opportunity for material recovery for low carbon technologies. Furthermore, they could be repurposed for offshore low carbon technologies including hydrogen, CCS, and offshore wind.

Table 3.2 Risk of material supply for assessed technologies

3.6 Impacts

The impacts associated with the material extraction, upstream processing and downstream processing are varied and a detailed analysis was out of scope of this study. This section provides high-level insight into key economic, environmental, and social concerns only.

3.6.1 Economic impacts

Scotland's Energy (including renewables) sector was identified in Scotland's Economic Strategy (2015) as one of the growth sectors in which Scotland can build on existing comparative advantage and increase productivity and growth[251]. However, there is domestic competition within the Scottish economy across numerous sectors for all of the identified materials; sectors include construction, information technology, automotive and aerospace sectors[hh].

Scotland extracts aggregates domestically which are used to produce cement, glass, and the foundations for infrastructure, which makes them a key input to the construction sector. This sector accounts for around 6% of the UK's gross domestic product (~£116 billion annually) and employed 7.1% of Scottish workers in 2018[252]. The UK, and Scottish construction sector is a net importer of materials, with roughly 60% of imported materials used in UK construction projects imported from the EU[253]. The economic impact of the material consumption outlined in this report is felt beyond Scotland. In many of the countries and regions highlighted in the previous section, extractive industries are a basis for the primary sector of the economy and national governments of exporting countries often rely heavily on these industries for their economic development.

Many developing countries are dependent on the exploration and the exploitation of their natural resources. They are heavily reliant on the income generated by these sectors and the employment opportunities they provide[254].

Although very little is currently mined in the UK and Scotland, it is home to some of the mining sector's largest companies, investors, and markets. The London Metal Exchange is the largest global market for the trade of metals; thus, UK government policy can have considerable influence on corporate transparency, environmental performance, and corporate governance. In 2022, over 1300 UK-based companies will need to disclose climate-related financial information on a mandatory basis – in line with the Task Force on Climate-Related Financial Disclosures (TCFD)[255].

The transition to a more circular, low-carbon economy offers opportunities for growth in the renewable sector. As part of the move to a net zero emissions economy, the Scottish government announced a Green Investment Portfolio[256] with Scottish Enterprise in 2019 with the aim of supporting major infrastructure projects in the circular economy. This includes support for low carbon energy generation, heating and distribution, decarbonisation of transport and material repurposing, as well as other sectors including the built environment, nature restoration and industrial funding. As an example of the benefits a circular economy could bring to the Scottish renewable sector, the Offshore Wind Industry Council (OWIC) estimated that the offshore wind sector could employ over 97,000 people in the UK with an estimated average annual investment to be over £17 billion by 2030[257]. 30 percent of existing jobs are located in Scotland. ORE Catapult estimated that the circular economy around offshore wind could provide 20,000 jobs across the UK, on top of the 60,000 projected by the UK Government to be employed within the sector by 2030[258].

A quantitative economic analysis is beyond the scope of this study. It is recommended that a more detailed economic analysis of the materials used in the technologies investigated in this study be the focus of further study on the impact of materials on the Scottish economy.

3.6.2 Environmental impacts

Extraction

Mining often has a negative impact on the environment through deforestation, pollution, water use, and land scarring; mining is responsible for around 7% of annual forest loss in developing countries and over 8% of global energy is consumed for producing metals (extraction and processing); contributing to 10% of global emissions[259].

These impacts are caused both during the exploitation of a mine and after production has ended, when a mining site is improperly decommissioned. In some instances, responsibility for decommissioning falls on local governments rather than the obligated mine operators[166].

Nevertheless, it is thought that the mining industry can meet increasing demand up to 2050 using more sustainable and responsible practices[260]. The UK and Scotland have anti-corruption laws with overseas reach and, over the last 15 years, have developed voluntary corporate sustainability reporting and certification schemes for environmental, social and governance (ESG) to allow commercial mining sector to demonstrate their sustainability. Large companies must disclose climate-related financial information on a mandatory basis[259]. Despite this, gaps remain in the transparency of reporting and mines are ultimately governed and regulated by laws in the host countries[259].

Innovation can further mitigate some of the negative environmental impacts of mining and facilitate access to difficult to reach materials with lower impact[259]. For example, new "key-hole surgery" techniques use an electric field to selectively dissolve and recover the metal in-situ from ore deposits that were previously considered inaccessible[261]. Further investment is needed if innovations are to reach commercial scale as propagation of innovative technologies across the industry is slow due to high capital costs, and competitive rather than collaborative efforts[259].

Production

Conversion of the raw material to useful products also has significant environmental impacts. The supply chain can be long and complex and involve numerous processing stages, each with negative environmental impacts. Processing takes place in Scotland and further up the supply chain in countries where environmental restrictions can be less stringent. Most of the materials analysed in this study are metals; Metals production and processing can often contribute to[262]:

- Air emissions (furnace fumes, oil mists, dust, casting and cooling processes);
- Energy consumption (furnaces, air-handling units, motors and drives etc.);
- Chemical and oil spills;
- Noise pollution from materials handling (rolling mills, billet casting etc.);
- Hazardous waste disposal (refractories, slags, sludges, lubricating fluids etc.)
- Contaminated water discharges
- Processing of non-metal materials such as concrete takes place within Scotland and is highly heat and carbon intensive and generates dust emissions[178].

Transportation

Most of the materials identified in this report are extracted in continents outside of Europe and produced via complex and often interlinked supply networks. The raw materials are often transported long distances to be processed, often in other countries[263]. Transportation of raw materials typically takes place via sea, rail and/or road. Marine transportation causes significant negative impacts on the marine environment, including air pollution, greenhouse gas emissions, spread of invasive species, oil and chemical spills, underwater noise pollution, damage to marine megafauna, as well as further environmental damage during breaking activities[264].

Railways are also responsible for a large amount of emissions that cover a wide range of pollutants and toxic substances that affect the environment. Effects can include, noise and vibration, air pollution and emissions, soil pollution, water pollution, soil erosion and changes in hydrology[265].

Road transport results in high emissions of greenhouse gases and air pollutants. It is responsible for significant contributions to emissions of carbon dioxide, nitrogen oxides, particulate matter (PM)10 and PM2.5 from internal combustion engines and tyre wear[266]. It should be noted that as Scotland's grid decarbonises, the emissions associated with these material's life cycles, including downstream reprocessing will play a potentially increasing contributing factor to limiting Scotland's net zero ambitions.

3.6.3 Societal impacts

The environmental and social impacts of extraction and processing pose a risk to the renewable energy transition by influencing public and investor support. In Scotland, mining projects are subject to Environmental Impact Assessments (EIAs) and thus their social and environmental impacts should be relatively contained in comparison to projects in developing nations[267].

However, mining has a complex relationship with the communities, cultures and societies of the (often developing) countries it operates within. Examples include the high levels of water use for nickel production in which results in competition for resources with local communities[166]. Mining has historically been associated with child and forced labour, such as in cobalt mining in the Congo or the extraction and processing of rare earth elements in the interior of China[166]. However, mining can and, in some instances already has, made positive contributions to local economies. In some locations, a mining company is the largest local employer and can be better organised than the local government, playing a key role in emergency situations, enhancing services and infrastructure, and drawing foreign direct investment into the country[268].

The transition to a more circular, low-carbon economy offers opportunities for Scottish workers in the energy and materials sector. In order to adopt these circular principles, it is essential that there is a focus on embedding circular skills and the 'greening' of jobs. The Climate Emergency Skills Action Plan (CESAP)[269] provides 'a framework for the skills investment needed to meet the climate change challenge and successfully support Scotland's transition to a low carbon economy in a just and inclusive manner'. Key to this is the transfer and reframing of skills and work practices that contribute to the decarbonisation efforts of the energy sector. The CESAP highlights the need to better educate and communicate the wider opportunities that the energy transition can bring to the existing workforce.

3.7 Rebound effects

The analysis in this report concludes that there will be greater demand for all materials up to, and beyond, 2050. If demand outpacing supply leads to higher prices, extraction and processing activities are likely to increase to try and meet demand. As availability is limited further, firms would then need to reduce their demand for these materials through substitution and/or by improving the efficiency of their resource use[270]. Rebound effects can also impact energy consumption, resulting in increases in energy demand and ultimately materials use.

This analysis provides a scale of how far supply needs to adjust if no such substitution or efficiency improvements are implemented. Even with large increases in material retention and substitution, there is still likely to be strong demand for primary minerals as the secondary materials available for recovery will be insufficient to meet demand[270]. The material generated through decommissioning of infrastructure is not necessarily recoverable or directly reusable within the low-carbon energy sector; Further material imports, substitution, and efficiency improvements will therefore be needed to fill this deficit.

This study has identified much of the materials required by the energy sector are processed outside of Scotland, and that there would subsequently be benefits to implementing circular practices within each of the technologies to retain material within the UK or Scottish economy and reduce dependence on imports.

The aim of a circular economy is to decouple economic growth from the exploitation of natural resources. Activities that incorporate circular practices and improved resource efficiency encourage greater production and consumption which can partially (or fully) offset their benefits[271]. However, if a system becomes efficient to the point of closure, producers and users react to this change by increasing consumption and production (often as the product becomes cheaper or more readily available). There is evidence that circular economy strategies can trigger rebound effects which can be classified under the following four effects[271]:

- Direct rebound - immediate increase in consumer demand due to lower prices from increased efficiency;
- Secondary effects - increases in demand of other goods as consumers spend their savings elsewhere;
- Economy-wide effects – Macro-scale, largely unpredictable effects that increased efficiency has on prices and demand of other goods; and
- Transformational effects - the potential of energy efficiency increases to influence consumer preference, innovation, governance, or other large-scale effects.

Furthermore, rebound effects can be attributed to price effects; this occurs when increased secondary production activity impacts prices. To entice buyers to purchase lower-grade materials, they are offered at a discount relative to primary materials. Manufacturers that choose to use these materials are comparatively better-off so can purchase more material and use it to make more products than they could before.

As a result, they can be sold at a lower price to consumers which multiplies this effect. As a result, more goods are produced, sold and used. The result is that increasing the circular economy may prevent some primary production, but it may not prevent it on a one-to-one basis[271].

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusion

This study has provided high-level approximations of the materials required for, and generated by, seven low-carbon energy technologies, onshore T&D infrastructure and O&G decommissioning up to 2050 under Scotland's net zero targets.

This study has identified that up to 241 Mt of total materials, and up to 230 Mt of selected materials, are expected to be required in Scotland by 2050 (of which 22-32 Mt are potentially recoverable materials). This represents at least 12% more materials each year than Scotland directly consumed in 2018 across all sectors[272].

According to this analysis, between 190-210 Mt of selected materials could be required by 2030 of which 87% is concrete. This is primarily driven by the large capacity of hydropower that is due online by 2030; in this analysis, hydropower makes up 80-85% of overall materials and more than 90% of the concrete needed up to 2050[ii]. Whilst the confidence in the hydropower models is low due to design variants discussed in Section 2.7, this assessment supports literature elsewhere which suggests that "concrete stocks are about 20 times larger than metal stocks, primarily due to the large amounts of concrete in hydropower dams"; The findings of this study suggest up to 10 times using the same materials but assessing different technologies. The material composition of the example dam used in the model is supported by other examples identified in literature[273] and as advised by industry experts within Wood. Nevertheless, as this study provides a high-level assessment of all technologies, a detailed study should be undertaken to understand more accurate concrete estimates for current and planned hydropower assets in Scotland.

The decommissioning of renewable energy technologies at EoL is expected to generate up to 290 Mt of selected material in Scotland by 2050 (of which 11-18 Mt are potentially recoverable materials). However, it should be noted that these materials are not necessarily recoverable or directly reused within low-carbon technology infrastructure. The vast majority (94-96%) of these materials are concrete[jj] which cannot be directly recovered for reuse. Apart from concrete, the materials for the energy infrastructure under investigation in this report are mostly extracted outside of Europe and processed outside of the UK.

Scotland currently exports most of the decommissioning materials identified within this report, with few captured for recycling or reprocessing domestically[kk]. Consequently, there is a continued reliance on imports of materials to produce new assets and replace those which have been decommissioned. As the transition to net zero accelerates, Scotland's dependence on material imports is set to increase, even if generated materials can be recovered. Furthermore, rebound effects of circular strategies could promote the overall consumption of materials up to, and beyond, 2050 despite closure of material loops; further deepening the reliance on imported materials[274].

Offshore wind, heatpumps, hydrogen and EVs and their associated infrastructure are in early stages of expansion in Scotland; and their growth is expected to generate the greatest increase in material requirements on today's consumption over the coming decades as a result of Scottish Energy Strategy which has set out plans to dramatically increase the roll-out of these technologies[275]. Growth in these technologies is driving the extraction of minerals for materials such as neodymium and Li-Co at a much greater scale than previously seen. For example, this study predicts that by 2050, without intervention, Scotland will require around six times the current level of imports of Li-Co each year between now and 2050 to meet the anticipated increase in capacity of EVs which will require significant changes within the global supply chain of these materials. Even materials which have more established supply chains, such as steel and aluminium, will require significant increases in production from today's levels to meet demand from the renewable energy sector up to 2050. Within the renewables sector, there has been demonstration of technologies that reduce the dependence on imported materials, particularly critical materials, through substitution, material reduction, and better design for circularity. For example, the development of rare earth element-free generators is underway to reduce the dependence on rare-earth elements in wind turbines and there are efforts to reduce lithium requirements in EV batteries through the development of LFP batteries and high-manganese-content batteries[277]. The electricity T&D sector demonstrates better circular design by directly reusing or recycling more than 95% of materials generated from decommissioned assets within new T&D projects[146].

There is evidence of the reuse of materials in other technologies like onshore wind, blue hydrogen, and O&G, however, where this does take place, refurbished components are often exported for use in lower-income countries[278]. Reuse is a preferred EoL treatment in terms of material value retention, however, reuse activities related to this sector often take place outside of Scotland. As such valuable materials are being leaked from the Scottish economy and this activity is not yet fully supporting Scotland's ambitions for a circular economy. This is particularly pertinent for materials where there are significant supply risks, such as neodymium.

There will always be a proportion of material that cannot be directly substituted, refurbished or reused. Some materials such as PGMs, chromium and nickel cannot be directly substituted[279]. PGMs are generally traded in small quantities. As a result, any increase in demand could have significant impacts on the global supply chain although, it should be noted that most databases aggregate PGMs, making it difficult to determine quantities of specific metals within this group such as iridium and platinum[280]. The UK has the capacity to reprocess and recycle some of the materials generated from energy infrastructure at EoL; including a proportion of steel, iron and aluminium (and more recently neodymium). However, the bulk of these are currently exported for reprocessing[281, 282]. Extraction of materials from used equipment can yield far greater quantities than those extracted through mining of raw materials. For example, it is reported that 30 tonnes of recycled Li-ion batteries could provide the same quantity of usable materials as 250 tonnes of Lithium ore, or 900 tonnes of cobalt ore[75]. Despite Scotland being a major exporter of renewable (notably wind) energy, there is little, if any, infrastructure to support material recovery in the energy sector.

Other materials assessed in this report including chromium, iridium, lithium, cobalt and nickel are not easily recyclable due to their use as alloys, and there is currently no capacity to do so in the UK. Nevertheless, UK industry is recognising the importance of securing supply through the development of domestic material re-processing capacity and the recovery of materials such as lithium as demonstrated by the installation of the Fenix Battery Recycling facility in Kilwinning near Glasgow, Glencore-Britishvolt and Veolia's announcements to develop domestic Li-Co recycling capacity[283, 284], and Birmingham university's neodymium recycling plant[285].

A challenge to the development of more sustainable material flows for a growing renewable energy sector is around supply chain capacity. Whilst processing capacity can be expanded within a few years; extraction capacity can take 10+ years to develop. Furthermore, producers of some materials, particularly rare earth elements, are restricting their output, causing their value to soar and countries to begin stockpiling. Several metal supplies were identified as insecure in 2011 by the UK Government[286] and the this is expected to be considered within the UK Critical Minerals Strategy (currently in draft form)[287].

Whilst the Earth technically contains enough metal ore to meet the projected demand for most metals[288], extracting and processing poses environmental and social challenges [289]. Mining has a complex relationship with the communities, cultures and societies of the countries it operates within. Extractive industries are often the primary economic sector of exporting countries, causing national governments to rely heavily on these resources. Mining often has the negative impacts of deforestation, pollution and unsatisfactory decommissioning. It has also long been associated with child and forced labour but can make positive contributions to the local economy[290].

These negative impacts can reduce public and investor support for the renewable energy transition. As the IEA notes in a recent report[291], policy makers need to provide clear signals about their climate ambitions in order to boost investor confidence in new projects. Such efforts should be accompanied by a broad strategy that includes supply chain resilience and sustainability standards.

4.2 Limitations and recommendations

This study was intended to provide a high-level understanding of the material needs of the Scottish energy sector and the demands anticipated from future changes in the energy mix as Scotland advances its energy transition to meet net zero targets. It provides a broad overview and so more detailed analysis for each of the technologies should be undertaken to determine more accurate material requirements. The confidence in each of the models is presented in Appendix B.

This study has identified limitations and areas of future research noted below:

- This study presents the quantities of selected materials within each technology but does not disaggregate between those materials needed for producing infrastructure in Scotland and those which are embedded within imported infrastructure that has been produced elsewhere. Further study should be undertaken to differentiate between the quantities of raw materials needed for domestic production of infrastructure and those that are imported as products.
- It should also be noted that the generated materials reported in this study are not all currently recoverable. Alloys, for example, may not be 100% recoverable using current reprocessing technologies. Further analysis must be done to determine the proportion of this material that can be recovered.
- This study provides only limited high-level analysis of the impacts of materials on the Scottish economy. A more detailed, quantitative economic analysis of materials for Scotland should be included in any further studies to understand the impact these materials have on the Scottish economy up to and beyond 2050.
- The requirement for nickel and chromium in steel within each technology should be investigated further as data were insufficient to quantify this in this study. A more detailed study is also required to understand the requirements of future Scottish energy infrastructure for individual PGMs, and the supply chain risks associated with this.
- Given the early stage of development of the hydrogen economy in Scotland, confidence in the hydrogen assessment is low. A detailed study into the material demands for the wider hydrogen network including hydrogen hubs, transmission etc. should be investigated given the large quantities of rare materials that may be required in this sector.
- A more detailed study of T&D networks, particularly subsea cables, sub stations and battery storage infrastructure, is needed to better understand the materials usage in this sector up to 2050 as they will play a vital role in connecting offshore energy to Scotland, the wider UK and Europe.
- The materials requirement for hydropower should be more thoroughly investigated – particularly the concrete requirements for new large-scale pumped-storage facilities currently in planning phase. From this analysis, hydropower makes up 80-85% of overall materials and more than 90% of the concrete needed up to 2050[ll]. Whilst the confidence in the hydropower models is low due to design variants discussed in Section 2.7, this assessment supports literature elsewhere which suggests that materials consumption for hydropower dominates material requirements[292]. A detailed study should be undertaken to understand more accurate concrete estimates for current and planned hydropower assets in Scotland.
- Opportunities for cross-sector collaboration in the treatment of materials should be investigated. For example, the decommissioning of offshore assets requires large quantities of quarried rock. With appropriate pre-treatment, the aggregate generated from decommissioned hydropower assets could be considered as a direct replacement for the quarried rock that is currently used for rock-dumping decommissioned O&G pipelines. In further studies, the materials' impacts beyond 2050 should be considered. Most data identified in the literature review considered forecasts to 2030 and to 2050. Although targets are set for 2050, this should not be considered the limit for capacity forecasts. Little is currently known on the capacity demands beyond 2050 and what this could mean for materials.

APPENDIX A METHODOLOGY

This section outlines the methodology followed for capacity forecasting, materials selection, materials analysis and quality assurance.

The project was approached in the following four phases:

- Phase 1: Scoping – Identification of data requirements and key data sources, confirmation of approach.
- Phase 2: Data gathering – Collection and collation of data into suitable (and presentable) format.
- Phase 3: Data analysis – Analysis of collected data, forecast modelling & visualisations.
- Phase 4: Presentation & reporting – Summary of findings and further steps.

Phase 1: Scoping
The project scope was defined with Zero Waste Scotland at project kick-off[39] following review by Wood of the information provided by Zero Waste Scotland and initial research into data availability and identification of key experts.

This study focused on the following for each listed energy technology:

- Infrastructure and capacity requirements up to 2050.
- Infrastructure lifespan and decommissioning up to 2050; with projection to 2075.
- Typical material composition of installations and high-level inputs required.
- Material treatment at EoL (EoL) and opportunities for life extension.

Following agreement on a list of priority materials, the data were collated and analysed on the following:

- Total tonnage for all technologies to 2030 and 2050, with projection beyond 2050.
- Summarise the impacts and location of raw material extraction & preparation and current fate of waste materials.
- Geographical spread of material extraction, arisings and hotspots.
- Material flow, availability of resources and potential impacts on supply chains.
- Environmental, social and economic impacts of material extraction and processing.
- Rebound effects of increased circularity

Phase 2: Data collection and forecast model
This section introduces the methodology for data collection and construction of the forecast models. This was applied to each technology.

Literature review & data gathering
A literature review was carried out to determine:

- Projected energy demands for Scotland to 2050 (upper and lower band scenario).
- Projected Energy mix for Scotland to 2050.
- Number of installations. This could be based upon current installation rates, projected energy demand, projected energy mix and typical asset lifetimes if more accurate data were unavailable.
- Current locations and potential development areas for each technology and infrastructure.
- Typical material composition of installations and subsequent estimation of tonnages required for new installations and those coming to EoL.
- Qualitative scoping of the state of play in Scottish energy sector beyond 2050.

The following key sources were considered initially, and these were supplemented during the course of the study. All references are provided within this report:

- Zero Waste Scotland, 2021. Battery use in

Scotland now and in the future.
- Zero Waste Scotland, 2021. The future of onshore wind decommissioning in Scotland.
- Amec (now Wood), 2014. Circular Economy Evidence Building Programme Renewable Energy Sector Report.
- Amec (now Wood), 2014. IMT002-019 Wind Turbine Magnet Study Neodymium Magnet Study.
- Amec (now Wood), 2014. Circular Economy Evidence Building Programme Transmission and Distribution Sector.
- Amec (now Wood), 2014. Circular Economy Evidence Building Programme Oil and Gas Sector Report.

Technical experts within Wood, ORE catapult, Zero Waste Scotland and RHI group were consulted to sense check early findings and plug data gaps.

Capacity forecast modelling

For each technology, a high and low estimate of capacity was developed, based on data identified during the literature review.

An Excel-based model was developed to project:

- Current and future installations; and
- Current and future decommissioning. Only decommissioning was modelled for oil and gas.

The model was developed in two stages which allowed for higher accuracy in technologies where greater granularity of data were available (such as for onshore wind). A schematic of the model structure is shown in Figure A.1.

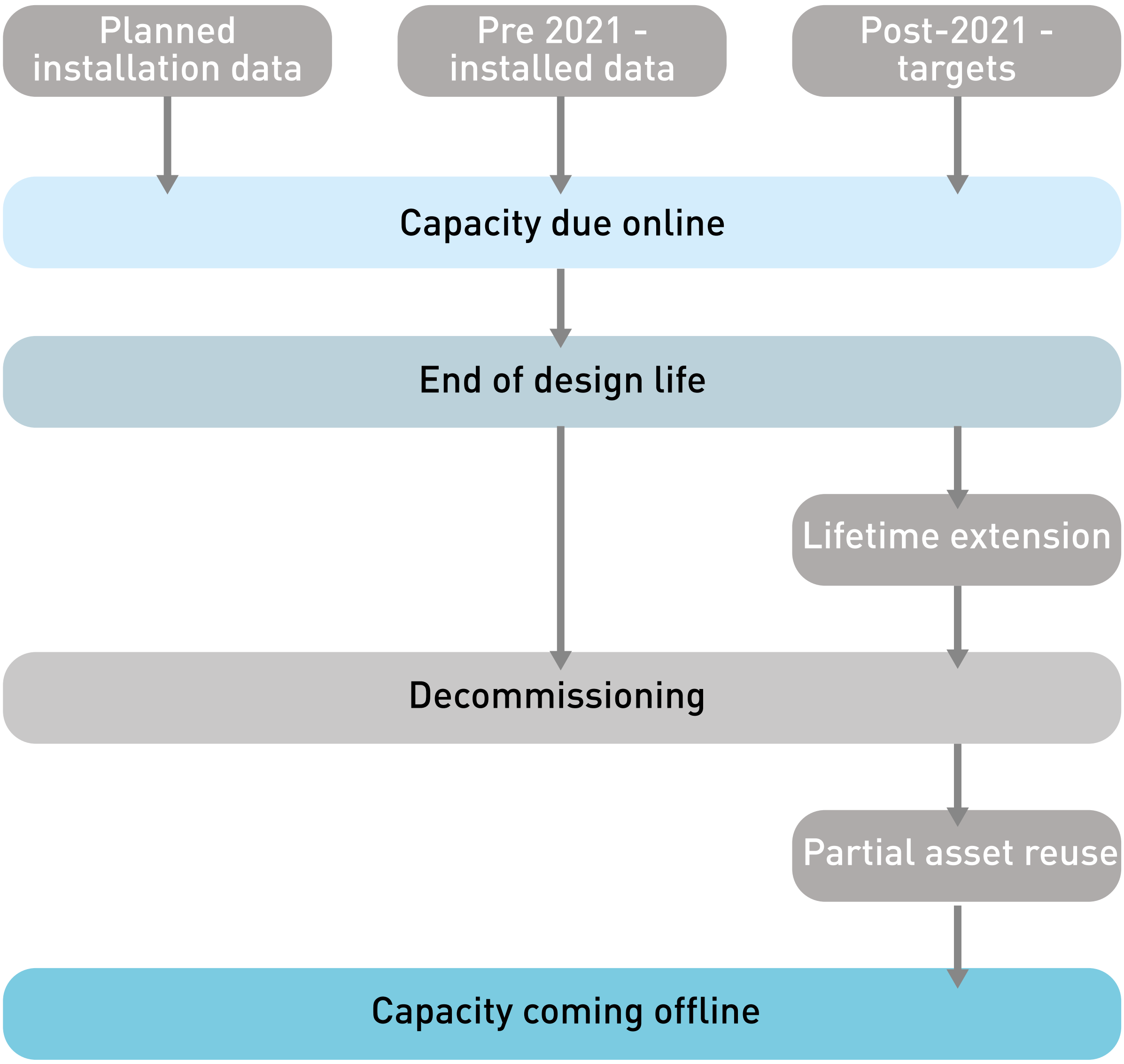


Figure A.1 Schematic of the model structure

Commissioned capacity
Depending on the available data, infrastructure needs were based on the number of current and planned installations (Part 1), the projected energy demand of each technology up until 2050 (Part 2) or a combination of both.

Part 1: Planned capacity and existing capacity (short-medium term)
The planned capacity and existing capacity (short-medium term) model was populated using publicly available planning data. Installations already online and due to come online in the short to medium term future were identified allowing for greater accuracy for the capacity due online in the short to medium term future (depending on the design lifetime of the technology). Note, this part of the model was only applied to technologies for which planning data were available.

Part 2: Targets up to 2050 (longer term)
Planned capacity is only sufficient in the short-medium term. Beyond these planning dates, where planned capacity fell short of targets or where planning data were unavailable, forecasts and/or recognised targets were used. These data were applied to bridge the gap between planned capacity and forecast capacity to ensure that longer-term projections were included up to 2050. Each model includes a high and low long-term capacity forecast assumption.

Capacity coming offline
As with all infrastructure, each energy technology asset has an estimated life expectancy. Installations are expected to reach their EoL (EoL) after a typical number of years (e.g., onshore wind 15-35 years, hydropower 40-80 years). At this stage, the asset might be decommissioned, or it might have its lifetime extended. Each model includes a high and low lifespan assumption and an assumption regarding the proportion of materials arising from decommissioning.

Life extension
Where relevant, a proportion of the assets reaching EoL will have their life extended, e.g., by replacement of parts. At this point, the materials are assumed to be replaced like-for like. Therefore, these materials are generated and consumed simultaneously at this stage whilst the remainder of the materials remain 'in-use'. At the end of this new design life (with life-extension), the entire installation is decommissioned (note that some technologies e.g., Hydropower may have two rounds of life extension before being decommissioned).

Decommissioning
Once the installation reaches EoL, the asset is expected to be decommissioned. At this point, a proportion of the materials that went into installation of the unit are assumed to be generated as waste.

There are exceptions when components which cannot be easily recovered (e.g., subsea components of onshore wind, foundations of onshore wind turbines). Partial asset reuse has been built into some of the models (e.g., onshore & offshore wind) at this stage, allowing for reuse of foundations for a new installation if this becomes viable.

Selection of materials for further analysis
A material profile was established for each technology based on material compositions identified through the literature review, and/or on input from technical experts. A longlist of the materials identified in the technologies were shortlisted, as agreed with Zero Waste Scotland based on the quantity produced across all technologies, on whether they were cross-cutting (needed cross a range of low-carbon technologies), concentrated (needed in large volumes for one specific technology) or whether it was associated with criticality in supply. Further data were gathered to gain a high-level understanding of the materials analysed, focusing in particular on:

- The value chain and flow of these materials, with identification of which raw materials reside in Scotland.
- The current environmental, economic and social impacts of raw material extraction, preparation and where this typically takes place.
- The locations of current infrastructure and potential future sites in Scotland and material recovery hotspots.

- The landscape beyond 2050; to include future energy demands, improvements to construction methods, adoption of circular principles, development of new technologies and associated infrastructure and materials etc.

Phase 3: Data analysis & visualisation
This section introduces the methodology for analysing the forecast material tonnages and analysis of the selected materials.

Forecasting analysis
Projected material tonnages required and due to arise to 2030, and 2050 were calculated using the forecasting model developed in Phase 2. Tonnages of the selected materials were applied on a 'per-MW' basis where these data were available. For other technologies such as EVs and T&D, it was based on a 'per unit' or 'per-km' basis.

A qualitative analysis of the energy distribution beyond 2050 to 2075 was undertaken to develop a narrative of future energy generation might look like. This analysis investigated how advances in technology, construction methods and material requirements could evolve up to 2075.

Material impacts analysis
Initial analysis of the materials requirement allowed Wood to propose the key materials to be carried forward for further analysis and mapping.

Each material was assessed based on projected requirements compared with the quantity that is currently used as well as the proportion of material that is generated and could be recovered. A qualitative analysis of the impacts of materials included:

- A high-level description of supply chain including production quantities, upstream and downstream processing methods.
- Typical locations of extraction, preparation and downstream processing.
- Environmental impacts.
- Economic impacts.
- Societal impacts.

- Consideration of longer-term influences over availability and value of materials including global supply risks and rebound effects of increased circularity.

The average annual materials required and generated were presented by comparing the material outputs from the model against UK imports for 2020 (figures for Scotland unavailable). Annual material requirements were calculated by dividing the quantity of materials needed (by each year) by the number of years between 2020 and that year, therefore presenting an average quantity for that time period.

EoL analysis
A brief qualitative analysis of the EOL options currently available to the selected materials and where this typically takes place including:

- High-level assessment of resource availability by identifying the global production quantities, current UK imports and availability of domestic treatment facilities.
- Methods of extending installation lifetime through identifying life-limiting components within technologies and methods to extend their lifetime or prepare them for reuse.
- Investigating the rebound effects of decoupling of primary resource demand as circularity is integrated into the sector and provide a summary of our findings.

Phase 4: Presentation and reporting
The findings from this study are presented in this report alongside a final presentation to Zero Waste Scotland to provide recommendations for next steps.

Quality assurance
Model review
The forecasting model for onshore wind was developed based on an existing model provided by Zero Waste Scotland for onshore wind decommissioning. Following calibration of the onshore wind model, it was technically reviewed by Wood renewable energy experts and Zero Waste Scotland.

Following approval, individual models were developed for each technology. The models for the subsequent technologies were developed with input from technical experts within Wood to ensure that the assumptions made were justified. Once the models had been finalised, they were reviewed by technical experts to ensure that the outputs were robust. Due to time constraints, the preliminary models were issued to Zero Waste Scotland for preliminary review alongside internal review.

A confidence rating was applied to each model output based on confidence of the capacity forecast and materials forecast and shown in Appendix B.

APPENDIX B CONFIDENCE RATING

This appendix presents the confidence applied to each of the models based upon the confidence in the capacity forecast estimates and the materials confidence rating

Technology	Capacity confidence	Materials confidence
01 - Onshore	High	High
02 - Offshore	High	High
03a - EV refuelling	Low	Medium
03b - EVs	High	High
04a - Heat pumps (domestic)	Medium	High
04b - Heat pumps (utility)	Medium	High
05a - Hydrogen (green)	Low	Low
05b - Hydrogen (blue/grey)	Low	Low
06a - Hydro (large)	Medium	Low
06b - Hydro (small)	Medium	Low
07 - Solar	Medium	Medium
08 - T&D	Medium	High
09 - Oil & Gas	Medium	Medium

Figure B.1 Confidence rating for each model

APPENDIX C MATERIAL DATA SHEETS

Datasheets for each selected material are presented in this appendix. It includes the technologies that they are used in, the main global producers, annual global production, UK annual consumption (where known) and UK annual imports. It also includes upstream and downstream processing description as well as economic impacts, environmental impacts and social impacts of material extraction and processing.

Aluminium		
Aluminium is a widely used metal with valuable characteristics including malleability, high strength, low density, high thermal and electrical conductivity, corrosion resistance, great recyclability, and non-toxicity.	**Application**	Onshore, Transmission and Distribution, EVs and Charging, Solar PV and Hydrogen
	Main Producer	Australia (55%), Indonesia (28%), Brazil (7%)[293]
	Global Annual production	68,000,000 tonnes (2020)[293]
	UK Annual Consumption	310,200 tonnes (2020)[294]
	UK Annual Imports	302,229 tonnes (2020)[294]

Supply chain	
Upstream	**Downstream**
There are several minerals available in the world from which aluminium can be obtained, the most common being bauxite. Bauxites are extracted from the ground and processed into alumina (aluminium oxide). Pure aluminium is produced using electrolytic reduction, an energy-intensive process in which aluminium oxide is broken down into its components using an electric current[323]. Most of the bauxite used to make aluminium in UK originates from areas such as Jamaica, West Africa, Australia and South America. Bauxite is also considered a critical raw material[324].	The UK has a well-established aluminium recycling industry and although a total figure for scrap aluminium is not available, approximately 56% of aluminium packaging is recycled[297]. Despite having the capacity for recycling 100% of the UK's aluminium packaging waste at the Novellis Recycling Plant in Warrington, nearly half of UK waste is exported[298]. India, China and EU countries such as Germany, Belgium and the Netherlands are among the top importers of aluminium scrap from the UK. In 2018 it was estimated that export volume of scrap aluminium was 423,943 tonnes[299]. However, despite the endless recyclability potential of aluminium, there is a high discrepancy between the percentage of the material that is recycled and that amount that is subsequently found as recycled content. This is a global issue whereby despite rates of 42% and 70% of aluminium recycled at EOL, with rates as high as 90% in some countries, the recycled content of new aluminium products is estimated to be between 34% and 36%[300]. The availability of scrap aluminium is not enough to meet its growing demand.

Economic impacts

Aluminium is required for a range of low-carbon technologies and will therefore be a critical element for realizing a low-carbon future. As a result, in the coming decades, demand for aluminium is expected to increase by a further 50% by 2050, reaching over 9 Mt of scrap demand in the EU[301]. Aluminium scrap from recycling will continue to grow as a valued commodity, contributing significantly to total aluminium production.

In some uses aluminium is likely to be substitutable. For example, aluminium is currently used for the frames in solar PV and, according to the World Bank, the vast majority of growth in demand for aluminium is tied to this technology[300]. However, in future, these frames could be made from synthetic or composite materials.

Environmental impacts

Aluminium production consumes a significant amount of energy and has a huge emissions potential [302]. In addition, the melting steps and processes associated with primary production (including mining, purifying, and anode production for refining) contribute to significant volumes of contaminants in local communities[303]. By using aluminium scrap, CO2 emissions can be reduced by 92% compared to raw aluminium and energy consumption by 95%[301]. It should be noted that as Scotland's grid decarbonises, the emissions associated with these material's life cycles will play a potentially increasing contributing factor to limiting Scotland's net zero ambitions.

Societal impacts

Countries with the largest bauxite reserves worldwide include Guinea and Vietnam, followed by Australia[304]. The mining safety in Guinea and Vietnam, is a cause for concern. It should be noted that during the aluminium production process, hazardous compounds such as fluorine, sulphur dioxide, hydrogen sulphide, and polycyclic aromatic hydrocarbons are released into the air, leading to potentially many chronic and acute epidemiological effects on human health[305].

Carbon		
Carbon is an abundant element that can be found in a range different compounds and allotropes, from activated carbon to single layer graphene sheets. The different forms have a wide range of physical and chemical characteristics, making it a highly versatile material. The forms of carbon assessed in this report are activated carbon and graphite.	**Application**	Carbon used as activated carbon in Steam methane reforming (Hydrogen production). It is used as graphite in a range of applications including in EVs.
	Main Producer Graphite	China (75%) (2020)[293]
	Activated Carbon	China, United States, India (2020)[293]
	Graphite	1,000,000 tonnes (2020) [293]
	Activated Carbon	3,300,000 (2021) [306]
	Graphite	Data unavailable
	Activated Carbon	Data unavailable
	UK Annual Imports Graphite	16,777 tonnes (2020) [294]
	Activated Carbon	16,000 tonnes (2020)[294]

Supply chain

Graphite

Upstream	Downstream
China accounted for about 65% of global graphite mining in 2016, and 35% of consumption. The country with the second highest production level was India. Natural graphite is considered a critical material[307]. Graphite is extracted by two techniques: the open pit method, where the ore is lying close to the earth and the layer of surface material covering the ore is thin, and the underground method, which is done to reach the deepest ores. For the extraction of the ore using the underground method, several methods like drift mining, hard rock mining, shaft mining and slope mining are employed. There is no longer mining of graphite in the UK. The Scottish Highlands only appear to have historically produced a few tonnes of graphite annually.	On the condition that used graphite can be segregated from other materials, without contamination, it can be successfully recycled.

Activated Carbon	
Upstream	**Downstream**
In 2019, China was the leading exporter of activated carbon, exporting c. 260,000 tonnes. India and the Philippines were also leading exporters. Both Europe (particularly the Netherlands) and the USA, are also leading producers. Activated carbon is usually derived from waste products such as cola, coconut shells and wood. These sources are converted into charcoal before being 'activated'. It can be activated either through physical activation or chemical activation. In physical activation, activated carbon is created using hot gases. The introduction of air, through either carbonisation or activation/oxidation, burns off the gases. What results is a graded, screened, and de-dusted form of activated carbon. In chemical activation chemicals, typically and acid or a salt, are added to the carbon material, which is then then subjected to temperatures between 250–600 °C. The temperature activates the carbon at this stage.	Activated carbon can be reused if the adsorptive capacity is restored. This process, called reactivation or regeneration, involves desorbing adsorbed contaminants on the activated carbon surface. The most common technique is Thermal Reactivation. There are a number of companies in the UK which specialise in recycling graphite and carbon reactivation, although details on the quantity recycled of each material has not been identified.

Economic Impacts

Graphite:
Both synthetic graphite and natural graphite, are used in the anodes of EV batteries. As sales of EVs grow, demand for the metal is likely to increase rapidly.

Around 75,000 tonnes of graphite are required to create 1 million EVs, meaning 900,000 tonnes of graphite will be needed to produce 12 million EVs by 2025.

The Scotland is a small net importer of natural graphite and there has been no systematic or modern exploration for graphite in the UK. There is currently no mine production of graphite in the UK and there are no deposits in which graphite reserves or resources have been reported.
Compared with other materials, such as aluminium, graphite is needed for fewer technologies. As a result, there is a higher demand uncertainty. This is because technological disruption and deployment could significantly impact their demand[300].

The global activated carbon market is projected to grow from $3.12 billion in 2021 to $4.50 billion in 2028 at a CAGR of 5.4% in forecast period, 2021-2028. By 2026, the global activated carbon market is expected to reach 3.9 Mt[308]. There is limited data available for Scotland and the rest of the UK.

Environmental Impacts

Graphite:
Research has shown that natural graphite mining can cause dust emissions. Furthermore, the production of anode grade graphite, used in lithium-ion batteries is energy-intensive. Currently, energy-demanding process stages within graphite supply chains are commonly located in regions with low-cost energy. In these areas it is common that the grid is dominated by coal and as a result has a high climate change impact per kWh.
Activated Carbon:
While not all activated carbons are regenerated or reactivated, this process offers considerable environmental benefits, when compared to the production and use of virgin activated carbon[309].

Societal Impacts
The purification of battery-grade anode products (graphite) requires high quantities of sodium hydroxide and hydrofluoric acid, which may be harmful to both human health and the environment.

Chromium

Chromium is a main additive in high-performance stainless steel due to its anti-corrosive properties. Amongst many other applications it is also used in industry to reduce friction and minimize seizing of parts.		
	Application	Heat pumps, EVs and Charging and Hydrogen
	Main Producer	South Africa (82%), Turkey (6%) and Pakistan (2%) (2020)[293]
	Global Annual production	16,400,000 tonnes (2020)[293]
	UK Annual Consumption	24,700 tonnes (2020)[294]
	UK Annual Imports	54,351 tonnes (2020)[294]

Supply chain

Upstream	Downstream
Chromium is found mainly in chromite. This ore is found in many places including South Africa, India, Kazakhstan and Turkey. Chromium metal is usually produced by reducing chromite with carbon in an electric-arc furnace or reducing chromium (III) oxide with aluminium or silicon. Depending on the grade of the ore deposit, the extraction of chromium may only require hand sorting and screening. Processing (crushing, separating, smelting, refining, etc.), is required for lower grade ores.	Chromium chemicals are generally consumed in dissipative end uses and thus are not recycled. However, there may be some recycling of chromium from waste materials in the future because of increasingly strict environmental standards and increasing disposal costs for wastes[310].

Economic Impacts

Chromium has no substitute in stainless steel, the leading end use, or in superalloys, the major strategic end use. World resources of chromium are considered ample for the foreseeable future[310]. However, past political and economic events have raised concern about the uninterrupted availability and reliability of supplies of these commodities due to supplier regions. Increased costs for electricity, an unreliable supply of electricity, and challenges related to deep level mining, together with the decreasing cost of chromite ore, could affect production in South Africa in particular- the leading exporter of chromium.

Environmental Impacts

The effluents and solid wastes from the mining process and during chrome-plating, are identified as a major source of environmental pollution[312]. Among the air pollutants created are nitrogen oxides, carbon oxides and sulphur oxides (NOx, COx, SOx) and particulate dusts that contain heavy metals such as chromium, zinc, lead, nickel and cadmium[313].

Societal Impacts

Worker conditions are a cause of concern in South Africa and other countries that hold reserves, particularly to artisanal miners as chromium has long been recognized as a toxic, mutagenic and carcinogenic metal[312].

Concrete

Concrete is versatile construction material, used in large quantities for a wide range of groundworks. It is essential to meet future infrastructure demand.	**Application**	Onshore, Offshore, Hydroelectricity, Transmission and distribution, Heat pumps, and Hydrogen
	Main Producer	95% of UK concrete is produced in the UK
	Global Annual production	32 billion tonnes (average)[314]
	UK Annual Consumption	90,000,000 tonnes (2020)[315]
	UK Annual Imports	1,730,000 tonnes (2019)[316]

Supply chain

Upstream

Concrete is made by mixing cement with supplementary cementitious materials, water, fine aggregate (sand/crushed rock fines), coarse aggregate (gravel or crushed rock) with or without admixtures, reinforcement, fibres and pigments[317]. Aggregates, which make up to 75% of concrete, are extracted from natural sand or sand-and-gravel pits, hard-rock quarries, dredging submerged deposits, or mining underground sediments[318].

In the extraction of aggregates from rock quarries explosives are often used to shift the rock from the working face. The rock is then crushed and passed through a series of screens. In sand and gravel quarries, gravel is usually no deeper than the groundwater table. When the gravel is deeper than this it is extracted through pumping.

Marine aggregate is extracted through dredging either by pumping from the seabed either an anchored or moving vessel. UK concrete, both ready-mixed and precast, is produced from around 1,000 sites across the UK[319].

Downstream

Concrete is 100% recyclable and recycled aggregates, arising from sources such as demolition or construction of buildings and structures, or from civil engineering works, are an important source of aggregates in the UK. To recycle these aggregates, materials, such as fines, wood, plastic or metal are removed, and the aggregates are processed by crushing and screening. In the UK, 90% of hard construction and demolition waste is recycled as aggregates[319].

Economic Impacts

Concrete is a local material with an established, national supply chain. As an industry it contributes around £18 bn to the UK's GDP and directly employs 74,000 people, supporting a further 3.5m jobs[319]. Concerns over the sourcing of sand (required to make cement and subsequently concrete), with some regions around the world already in significantly short supply, have been raised[319]. In recent months, UK builders have experienced difficulties in sourcing cement due to issues related to Brexit [320]. However, due to an established recycling industry, the UK's Mineral Products Association (MPA) - the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries - regards the UK specifically as having potential to be self-sufficient in the manufacturing of concrete and cement, with all key raw geological materials domestically available[319].

Environmental Impacts
The production of concrete is a highly energy intensive process which results in high levels of CO2 output. This is largely due to the steps involved in producing cement. Globally, cement production is the third ranking producer of man-made CO2 (after transport and energy generation) and is responsible for ~5% of CO2 emissions. In the raw material extraction, there are further environmental impacts, which include Landscape degradation and the generation of dust and noise. The processing of aggregates involves the use of potable water, used to wash aggregates, suppress dust and in the manufacturing process.
Societal Impacts
Concrete is a local material with an established, national supply chain that creates jobs. As an industry it contributes around £18bn to the UK's GDP and directly employs 74,000 people, supporting a further 3.5m jobs[321].

Copper		
Copper is the second most electrically conductive material after silver and is the third most used metal in manufacturing301.	**Application**	Onshore, Offshore, Hydroelectricity, Heatpumps, EVs & Charging, Hydrogen
	Main Producer	Peru (25%), Chile (13%)[322]
	Global Annual production	24,800,000 tonnes (2020)[293]
	UK Annual Consumption	14,400 tonnes (2020)[294]
	UK Annual Imports	45,012 tonnes (2020)[294]

Supply chain

Upstream	Downstream
Concrete is made by mixing cement with supplementary cementitious materials, water, Approximately 40% of copper mining takes place in South America. Although only 8% of mining occurs in China, it accounts for 39% of refining globally. Copper mines can be found in various countries in the EU, most notably Poland and Scandinavia. EU, mines represent ~4.4% of global production. Copper extraction in the first instance, involves the mining of the ore, common types of which are copper oxide and copper sulphide. Copper oxide undergoes hydrometallurgy and copper sulphide undergoes pyrometallurgy. However, the first extraction phase does not differ between these ores. Extraction is usually through open-pit mining. This requires the use of boring machinery which drill holes into the hard rock, into which explosives are inserted to break	Copper is recyclable without loss of quality. It is the 3rd most recycled metal, after iron and aluminium and around 40% of the demand for copper within Europe is supplied from recycled copper. Preventing the mixing of copper with other metals is vital. This is in order to both maintain the conductive properties of the copper and, because the contamination of the copper has a negative effect on the quality of steel. Currently, almost half of copper use in the EU comes from recycling[323].

Economic impacts
The market size, measured by revenue, of the UK copper production industry in 2022 is £489.3m, representing a decline of 3.8% per year on average between 2017 and 2022[324]. However, an increase in renewable technologies and infrastructure, including increased EV production, has contributed to an increase in demand for copper in recent years. With many countries now focusing on reducing crude scrap copper production following environmental concerns, the demand for scrap metal, and scrap copper in particular, is expected to stay strong. Copper offers high-cost performance for applications where high electrical conductivity, corrosion, or friction resistance is required, and as a result substitution of the material remains low. In China, the world leading market for copper, the push for superior energy efficiency in electric motors, electrical mobility, and more stringent environmental regulations has been advantageous for copper. As a result, copper still has the lowest relative net substitution across the world at 0.6% of China's total copper use. Recently, Cornwall Resources have announced they are moving forward with the development of their Redmoor project where they anticipate significant copper deposits[341]. A mining scoping study has been completed.
Environmental Impacts
Concrete is a local material with an established, national supply chain that creates jobs. As an industry iLarge volumes of low concentration sulphur dioxide are often produced by the smelting process. Due to the low concentration further processing to remove the sulphur is often not undertaken. Acid rain resulting from the combination of rain and SO_2 can cause damage to crops, trees and buildings. Leaching solutions are typically regenerated and reused continuously for extended periods. On occasion, such as during temporary or permanent closure, the solutions are disposed of as wastes via land application or other means. When copper is extracted through open pit mining, adverse environmental effects include intensive water consumption, erosion, sinkhole formation, biodiversity loss and chemical contamination of groundwater[326].
Societal Impacts
There are various risks associated with the mining of copper which can affect the health and wellbeing of those working in and living around the mines. Respiratory illnesses, such as asthma and tuberculosis can be caused by the inhalation of silica dust particles resulting from the mining and processing of copper. Miners have been reported to suffer from silicosis or pneumoconiosis. Adequate control of operations can mitigate these risks[327].

Iridium

Iridium, along with the likes of platinum, is considered a precious metal. It is one of the hardest and most corrosion resistant metals known and is the second most dense metal.	**Application**	Green hydrogen production
	Main Producer	South Africa, Russia, Zimbabwe
	Global Annual production	Data unavailable
	UK Annual Consumption	Data unavailable
	UK Annual Imports	8 tonnes (2020)[394, 40]

Supply chain

Upstream	Downstream
Iridium is extracted from PGM-rich ores and as a by-product during the electrorefining of nickel, where platinum group metals settle to the bottom of the cell as anode mud, forming the starting point for their extraction[329]. The metal extracted related to iridium is often presented with other PGMs due to their respectively small amounts; global resources of PGMs are estimated to total more than 100 million kilograms with the largest reserves in the Bushveld Complex in South Africa[329].	Iridium is largely unrecycled due it often being used in small quantities that are subsequently deemed to too expensive to recover and recycle.

Economic impacts

The top 3 producers and reserve holders are South Africa, Russia and the USA. Iridium prices have fluctuated over a considerable range. Indeed, with such a relatively small share in the world market compared to other industrial metals, iridium prices react strongly to instabilities in production, demand, speculation, hoarding, and politics in the producing countries[330].

Environmental Impacts

There are several processes associated with the extraction of iridium including melting, dissolving and evaporation. Very little is known about the toxicity of iridium compounds, primarily because it is used so rarely[331].

Societal Impacts

Iridium in bulk metallic form is not biologically important or hazardous to health due to its lack of reactivity with tissues However, poor treatment of mine workers in South Africa and Russia have been widely documented[332].

Steel and Iron

Steel is mainly composed of iron; it is the most widely used metal in the world.	**Application**	All investigated technologies
	Main Producer	Australia (81%), Canada (4%), South Africa (4%) (2020)[333]
	Global Annual production	1,070,000,000 tonnes (2020)[293]
	UK Annual Consumption	15,583,100 (2020)[294]
	UK Annual Imports	887,279 tonnes (2020)[294]

Supply chain

Upstream	Downstream
Iron is extracted from iron ore at high temperatures in a blast furnace. The top three iron ore-producing countries - Australia (37.6%), Brazil (16.7%) and China (14.2%) - accounted for 69% of global production in 2020[334]. However, Brazil and China largely consume reserves in their domestic economies. Steel is an iron alloy containing less than 2% of carbon. In 2020, the UK consumed 8,172 900 tonnes of iron of which 86% was imported[335]. A large portion of this contributed to steel manufacturing for the domestic economy - 7,410,000 tonnes[335].	Steel is the world's most recycled construction material. In the UK, the steel recycling industry is well established; 87% of constructional steel is recycled; 10% is reused and only 3% goes to landfill[336]. However, very little is recycled in the UK (around 25%), despite in principle the volumes of scrap steel being sufficient to meet domestic demand[337]. In 2020, slightly over half of UK steel exports were to the EU, whilst almost two thirds of steel imports were from the EU[338].

Economic impacts

Although steel is widely recycled both in the UK and in the world - approximately 40%[366]. There is doubt as to whether this will meet projected infrastructure demands. With the energy intensive nature of production, the industry is already subject to emission quotas - effectively taxes - within the UK and in Europe. Technological innovation in steel manufacturing hope to use hydrogen as an energy source[337].

Environmental Impacts

The making of steel is a highly energy intensive process, contributing to 15% of the UK's total industrial emissions[335]. Although recycling presents significant energy savings (up to 72% of the energy needed for primary production), there is debate about the extent to which recycled steel can meet demand[335].

Societal Impacts

Poor treatment of mine workers in South Africa is widely documented.

Lithium-Cobalt Oxide

Lithium-Cobalt Oxide is an oxide primarily used in Lithium-ion batteries. It is expected to play a key role in the transition to zero carbon mobility. It requires extraction of Lithium & Cobalt.	**Application**	EV batteries
	Main Producer **Lithium** **Cobalt**	Australia (55%), Chile, Argentina Democratic Republic of the Congo (DCR)[166]
	Global Annual production **Lithium** **Cobalt**	82,000 tonnes (2020)[166] 140,000 tonnes (2020)[166]
	UK Annual Consumption **Lithium** **Cobalt**	1,919 tonnes (2017)[339] 3,000 tonnes (2020)[294]
	UK Annual Imports **Lithium** **Cobalt**	467 tonnes (2020) 6,160 tonnes (2020)[294]

Supply chain

Upstream	Downstream
Lithium is a naturally occurring metal found on almost every continent but is mined in South America and Australia. Despite its relative abundance, capacity for extraction is currently limited. Approximately half of global lithium production is from Australia, based on the mining of the mineral spodumene. Most of the remaining production comes from salt lakes in Chile and Argentina. The lithium concentrates (about half) are then exported to China where it is used to make battery-grade lithium chemicals[166]. Due to an extended period of low prices, the lithium industry has faced difficulties in scaling-up processes. In 90% of cases, cobalt mining is a by-product of copper and nickel production[166]. This presents supply chain risks as the upscaling of cobalt is therefore dependent on the upscaling of the production of these other metals. Lithium-cobalt oxide is produced under high heat using lithium carbonate and cobalt oxide in an oxygen atmosphere.	Constraints in recycling of both lithium and cobalt are largely due to the current lack of financial viability. The recycling rates of lithium have been influenced by rapid changes in battery chemistry and design, and competition from relatively cheap primary production of lithium, resulting in highly variable historical recycling rates of between 5-50%[166]. Likewise, though cobalt is easily recyclable this is still rarely done as it not yet economically attractive.

Economic impacts

raw materials

Investment in cobalt production outside of the Congo, an area of weak governance and historically high political instability, is difficult due to the competition presented by African cobalt in terms of production costs. However, whilst cobalt reserves are likely to remain exclusive to Congo, UK lithium carbonate reserves are being investigated. The Li4UK project has recently, for the first time, produced lithium carbonate from rocks found in Cornwall and Scotland[340]. The UK is exploring domestic reserves, Cornish Lithium recently reported it has found "globally significant" lithium grades in geothermal waters and is preparing for work on its pilot plant[341].

Environmental Impacts
The process of lithium extraction in South America, involving salt lakes, is a highly water intensive process that often takes place in regions of already high water-stress such as Chile. Additionally, the evaporation baths in which the lithium is then extracted, cause significant damage to the landscape. Mining in Australia also consumes large volumes of water; however, this is often better managed. Additionally, the environmental cost of the extensive shipping routes- from South America/Australia to China for processing and then to Europe for manufacturing- as well as the mining process, have often been raised in conversations around the industry's sustainability credentials. A more localised production of lithium-carbonate, as is currently being investigated by Li4UK, would reduce the environmental burdens associated with lithium extraction.
Societal Impacts
In South America, water extraction for lithium production has led to conflict between local communities and water companies. The DRC is notorious for poor working conditions, child labour and corruption. Even companies determined to source conflict and child labour free cobalt, are finding the process difficult.

Neodymium

Neodymium is a rare earth element. The most important use for neodymium is in an alloy with iron and boron to make very strong permanent magnets. This discovery, in 1983, made it possible to miniaturise many electronic devices, including mobile phones, microphones, loudspeakers and electronic musical instruments .	Application	Onshore wind, Offshore wind & EV
	Main Producer	China (58%) (2020)[293]
	Global Annual production	240,000 tonnes (2020)[293]
	UK Annual Consumption	Data unavailable
	UK Annual Imports	469 tonnes (2020)[294, 41]

Supply chain

Upstream	Downstream
China is largely responsible for the mining of rare earth metals, which includes neodymium, dysprosium and praseodymium. China also controls most of the refining processes (approximately 70%), and increasingly the production of parts containing rare earth metals[166]. The largest Western producer of rare earth metals, the Australian Lynas Corporation, is financed by Japan with the condition that Japanese industry is given priority of supply in case of scarcity[166]. Neodymium is considered a critical raw material[307].	Increasing amounts of research is being conducted into the recycling of rare earth metals. However, despite the geopolitical dependencies, it is still cheaper to extract these metals rather than to source them through recycling. Additionally, when recycling rare earth metals, product design is important as the magnets can very quickly become contaminated making recycling difficult. Recently the University of Birmingham built the UK's first recycling plant for high-performance rare earth magnets for use in EVs, aerospace, renewable energy and low carbon technologies[343].

Economic Impacts

Substitutes of rare earth metals are in most cases either inferior or still undiscovered[344]. These metals are essential in low-carbon technologies but have an almost exclusive geographic supply.

Environmental Impacts

Environmental pollution during the extraction of rare earth metals have been widely documented[300]. However, in recent years this pollution seems to have improved under pressure from the Chinese Government[300].

Societal impacts
There are reports of Chinese forced labour in the production of these metals. In addition, there are concerns of impacts to local communities due to the polluted soil and water around former mining sites[300].

Nickle		
Neodymium is a rare earth element. The most important use for neodymium is in an alloy with iron and boron to make very strong permanent magnets. This discovery, in 1983, made it possible to miniaturise many electronic devices, including mobile phones, microphones, loudspeakers and electronic musical instruments[389].	Application	EV, Hydrogen
	Main Producer	Philippines (94%) (2020)[346]
	Global Annual production	42,100,000 tonnes (2020)[293]
	UK Annual Consumption	16,386 tonnes (2020)[294]
	UK Annual Imports	21,722 tonnes (2020)[294]

Supply chain	
Upstream	**Downstream**
The bulk of the mined nickel comes from two types of ore deposits: laterites and magmatic sulphide deposits[347]. Nickel sulphide deposits are generally associated with iron and magnesium rich rocks and can be found in both volcanic and plutonic settings. Sulphide deposits often occur at great depth. Laterites are formed by the weathering of ultramafic rocks and are a near-surface occurrence.	Recycling of nickel is made difficult by its often alloy composition and wide application then rendering the alloy difficult to separate and recycle. Globally, around 17% of nickel is recycled[166].

Economic Impacts
Batteries require high-quality nickel (called class 1), which is expected to be in short supply[166]. Additionally, Indonesia, the world's largest nickel producer, recently imposed export restrictions as part of efforts to bring refineries to Indonesia and preserve more of the value chain within the domestic economy[348]. Manganese is a compelling alternative to Nickel in EV batteries, as its global production is four to five times greater than nickel production and 140 times greater than cobalt production[349].
Environmental Impacts
There are several environmental issues associated with nickel production and refining. In 2017, 23 predominantly nickel mines in the Philippines- then accounting for around 10% of global supplies- were closed due to environmental damage[350]. The Russian city of Norilsk, home to one of the world's largest nickel producers (Norilsk Nickel), is considered one of the most polluted cities in the world and was the scene of a major natural disaster after a spill of waste material in 2020[351].
Societal impacts
Health and livelihood impact concerns for local communities due to the environmental consequences of nickel mining have been widely raised[350, 351].

Platinum		
Platinum has excellent high-temperature characteristics, stable electrical properties and is highly unreactive. It is often used in catalytic converters.	**Application**	Solar, wind, electric cars, electricity storage, and hydrogen.
	Main Producer	South Africa (70%), Russia (12%) (2020)[293]
	Global Annual production	170,000 tonnes (2020)[293]
	UK Annual Consumption	Data unavailable
	UK Annual Imports	45 tonnes (2020)[294, 42]

Supply chain	
Upstream	**Downstream**
Platinum is one of the PGMs, which are mined collectively in platinum-containing ores. PGMs also include osmium, iridium, ruthenium, rhodium and palladium. Platinum is mainly mined in South Africa (70%), and Russia (12%), the ratios being slightly different for some other elements[166]. Platinum is considered a critical raw material[307].	Although specific recycling rates for platinum were not identified within the UK, the recycling rate of precious metals such as platinum are generally high due to the high prices and relatively easy recycling process of catalytic converters. High quality recycling of PGMs is necessary as they are difficult to replace with other metals, although can often be exchanged between themselves.

Economic Impacts

The supply chain of PGMs has had to manage regular disruptions due to strike action in South Africa. The demand for platinum is expected to rise following the growth of particularly the electric vehicle market. Although current platinum reserves are considered sufficient to satisfy increased demand, decreasing platinum ore grade and continued geographic concentration of platinum ores present availability risk factors of platinum[352].

Environmental impacts

Average platinum grades are low, about 4.4 g/t thus there are high volumes of waste rock and tailings generated from platinum mining[300]. Additional environmental impacts include high electricity consumption, water usage and CO2 emissions[353].

Societal Impact

PGMs are heavily associated with prolonged, violent strikes in South African mines. Resource demands for the extraction process can also contribute to tensions within the local community.

Titanium		
Titanium is a low density, high strength, and high corrosion resistant transition metal. Titanium is often used in steel as an alloying element.	**Application**	Heat pumps
	Main Producer	Mozambique (28%), Senegal (13%), Madagascar (13%)[354]
	Global Annual production	4,020,000 tonnes (2020)[43]
	UK Annual Consumption	29,000 tonnes (2020)[294]
	UK Annual Imports	19,890 tonnes (2020)[294]

Supply chain	
Upstream	Downstream
Titanium is not rare, but it is costly material as it is difficult to refine. The metal is usually made using the Kroll process, which involves significant labour and extreme heat[355]. Titanium is considered a critical raw material[307].	It is largely uneconomical to recycle titanium in the UK or Europe. However, recently a new titanium recycling factory was opened in Europe [356]. This is expected to contribute to the recycling of titanium metals from the machining process for making aeroplanes which create large amounts of scrap titanium that are often sent outside of Europe for reuse[356].

Economic Impacts
Titanium is not rare but, as mentioned, it is a costly material due to it being difficult to refine - titanium is six times more expensive to produce than steel[356]. Additionally, the largest exporters, of which in most years South Africa is one due to extensive reserves[357], have unreliable and poor energy infrastructure.

Environmental impacts
The production of titanium is a highly energy intensive process. Concerns over use of toxic chemicals used in certain mining activities have also been raised[358].

Societal Impact
The poor treatment of miners and widespread practice of unregulated artisanal small-scale mining within the locations where titanium is mostly sourced (in sub-Saharan Africa), are well documented[357].

APPENDIX D
MODELLING ASSUMPTIONS

This appendix lists the assumptions made during modelling. Full workings, further assumptions and calculations are found within the individual models

Assumptions
Onshore wind
1 Any small-scale developments less than 100 kW are not included within the BEIS data[359] and are therefore not considered within the estimates.
2 Projects consented, but not operational, assumed to come online 5 years after consent
3 Repowered assumes replacement of unit but not replacement of foundations & cabling. This has currently been set at 0% as this has not yet been undertaken at commercial scale.
4 From discussions with internal stakeholder, life extension is likely to consist of a partial replacement of the gearbox and full replacement of turbine blades. As a worst-case scenario, it was assumed that 100% of the gearbox is removed based on ZWS decommissioning model
5 Existing turbines on a repowered project will be decommissioned using the low and high repowering forecasts in assumptions 7 and 8.
6 Low decommissioning forecast will assume a low energy forecast and the following assumptions (Note, these assumptions have been combined as an average figure. See Workings tab):
a. 30% of operational turbines are life-extended after 20 years
b. 20% of operational turbines are life-extended after 25 years
c. 20% decommissioned after 25 years
d. 30% decommissioned after 35 years
7 High decommissioning forecast will assume a high energy forecast and the following assumptions (Note, these assumptions have been combined as an average figure. See Workings tab):
a. 25% of operational turbines are life-extended after 15 years
b. 25% of operational turbines are life-extended after 20 years
c. 25% of operational turbines are life-extended after 25 years
d. 15% decommissioned after 25 years
e. 10% decommissioned after 35 years
8 An average weight per MW has been assume as a basis for calculations based on data from ZWS Onshore decommissioning model. See rough workings for calculations
Offshore (fixed)
1 An average weight per MW has been assumed as a basis for calculations based on data from ZWS offshore commissioning model. See rough workings for calculations.
2 Turbine types have been aggregated into split into two categories: Fixed and floating.
3 The proportion of fixed: floating is expected to reduce to 46% by 2040.
4 By 2040, split between concrete-based floating and steel-based floating will be 50:50 based on discussions with ORE Catapult.
5 Repowered assumes replacement of unit but not replacement of foundations & cabling. This has currently been set at 0% as per the onshore wind model.
6 From discussions with internal stakeholder, life extension is likely to consist of a partial replacement of the gearbox and full replacement of turbine blades. As a worst-case scenario, it was assumed that 100% of the gearbox is removed based on ZWS onshore decommissioning model. This accounts for 50% of Nacelle Iron & Steel and 100% of blade components.

7 As targets for 2030 and 2050 are less than the 24.8 GW of additional planned capacity leased by the Crown estate, this model is entirely based upon planned installations.
8 Low forecast assumes an average asset lifetime of 30 years with a maximum life (with life-extension) of 50 years based upon discussions with ORE Catapult. An arbitrary figure of 10% life extension has been used. It was assumed that 0% of structures would be repowered as no such projects have been repowered to date.
9 Low energy forecast assumes a forecast based on government figures (2030). A Scottish target for 2050 has not yet been set. The UK target for 2050 has been used with the assumption that the ratio between Scottish and UK targets is the same as for 2030 (See Workings tab). Nevertheless, planned installation capacity data exceeds that of this forecast. The forecast has been built into the model in the event that Scottish offshore wind targets are raised above the planned installation figure.
10 High forecast assumes an average asset lifetime of 25 years (minimum) based upon discussions with ORE Catapult. It was assumed that life-extension would add an additional 10 years to the asset life. An arbitrary figure of 10% life extension has been used. It was assumed that 0% of structures would be repowered as no such projects have been repowered to date.
11 High energy forecast assumes a forecast based on government figures (2030). A Scottish target for 2050 has not yet been set. The UK target for 2050 has been used with the assumption that the ratio between Scottish and UK targets is the same as for 2030 (See Workings tab). Nevertheless, planned installation capacity data exceeds that of this forecast. The forecast has been built into the model in the event that Scottish offshore wind targets are raised above the planned installation figure.
12 The following assumptions were used by ORE Catapult in their model which has formed the basis for calculations in this model:
a) The jacket structures were assumed to use pin piles if anchoring method was unknown
b) Anchors and mooring lines have not been included in this study
c) All turbine values have been based on a 15 MW design and scaled outwards to calculate other MW sizes
d) For many of the fixed regions, if the water depth was only given as a range, we have taken the higher end of the range as this was more commonly publicly available
e) Followed the assumptions made from Deepwind slides regarding the foundations used and the turbine output size
f) For the fixed farms which it didn't specify the type of foundation and the water depth was <60m. Assumed it to be a monopile
g) For the floating farms which it didn't specify a foundation I have assumed a steel semi-sub as this is the most common floating design in the market
Offshore (floating)
1 An average weight per MW has been assumed as a basis for calculations based on data from ZWS offshore commissioning model. See rough workings for calculations.
2 Turbine types have been aggregated into split into two categories: Fixed and floating.
3 The proportion of fixed: floating is expected to reduce to 46% by 2040.
4 By 2040, split between concrete-based floating and steel-based floating will be 50:50 based on discussions with ORE Catapult.
5 Repowered assumes replacement of unit but not replacement of foundations & cabling. This has currently been set at 0% as per the onshore wind model.
6 From discussions with internal stakeholder, life extension is likely to consist of a partial replacement of the gearbox and full replacement of turbine blades. As a worst-case scenario, it was assumed that 100% of the gearbox is removed based on ZWS onshore decommissioning model. This accounts for 50% of Nacelle Iron & Steel and 100% of blade components.

7 As targets for 2030 and 2050 are less than the 24.8 GW of additional planned capacity leased by the Crown estate, this model is entirely based upon planned installations.
8 Low forecast assumes an average asset lifetime of 30 years with a maximum life (with life-extension) of 50 years based upon discussions with ORE Catapult. An arbitrary figure of 10% life extension has been used. It was assumed that 0% of structures would be repowered as no such projects have been repowered to date.
9 Low energy forecast assumes a forecast based on government figures (2030). A Scottish target for 2050 has not yet been set. The UK target for 2050 has been used with the assumption that the ratio between Scottish and UK targets is the same as for 2030 (See Workings tab). Nevertheless, planned installation capacity data exceeds that of this forecast. The forecast has been built into the model in the event that Scottish offshore wind targets are raised above the planned installation figure.
10 High forecast assumes an average asset lifetime of 25 years (minimum) based upon discussions with ORE Catapult. It was assumed that life-extension would add an additional 10 years to the asset life. An arbitrary figure of 10% life extension has been used. It was assumed that 0% of structures would be repowered as no such projects have been repowered to date.
11 High energy forecast assumes a forecast based on government figures (2030). A Scottish target for 2050 has not yet been set. The UK target for 2050 has been used with the assumption that the ratio between Scottish and UK targets is the same as for 2030 (See Workings tab). Nevertheless, planned installation capacity data exceeds that of this forecast. The forecast has been built into the model in the event that Scottish offshore wind targets are raised above the planned installation figure.
12 The following assumptions were used by ORE Catapult in their model which has formed the basis for calculations in this model:
a) The jacket structures were assumed to use pin piles if anchoring method was unknown
b) Anchors and mooring lines have not been included in this study
c) All turbine values have been based on a 15 MW design and scaled outwards to calculate other MW sizes
d) For many of the fixed regions, if the water depth was only given as a range, we have taken the higher end of the range as this was more commonly publicly available
e) Followed the assumptions made from Deepwind slides regarding the foundations used and the turbine output size
f) For the fixed farms which it didn’t specify the type of foundation and the water depth was <60m I have assumed it to be a monopile
g) For the floating farms which it didn't specify a foundation I have assumed a steel semi-sub as this is the most common floating design in the market
EV Refuelling
1 2030 and 2050 projections assume (i) demand per charging point/yr at 2020 levels (ChargePlace Scotland Network) 10,470,000 kWh from 1800 charge points (5.816 mWh/charger p year) (ii) projected required charging points to meet net zero (30,000 by 2030; 60,000 by 2050 - extrapolated from UK-wide projections) [23].
2 It was assumed that the ratio of public chargers to home chargers remained constant between 2022-2050.
3 It was assumed that the 2021 proportion of chargers UK and Scotland remained the same from 2020 to 2050.
4 Due to limited data available, it was assumed that the material composition of a public charger was the same as for a home charger.
5 For the high estimate, an average lifetime of 8 years was assumed [61]. The forecast number of chargers was estimated with an uncertainty factor of +10%.

7 It was assumed that after design life, 100% of chargers would be replaced. Therefore, no life extension was applied to this model.
8 It was assumed that the 2015 ratio of home chargers to public chargers would remain constant up to 2050.
EVs
1 A forecast for the UK was used as the basis for forecasting. Scotland's proportion of the UK's EVs in 2021 was assumed to remain constant up until 2050. This can be adjusted in the model in the workings tab.
2 EVs include Battery-powered EVs (BEVs) and Plug-in hybrid EVs (PHEVs).
3 The proportion of PHEVs to BEVs was assumed to increase to 75% by 2030 and 100% by 2050 assuming that manufacturers are ultimately transitioning to BEVs [85]. This can be adjusted to account for changes up to 2050 in the Workings tab.
4 Currently, EVs reach their EoL once the battery has reached its EoL [70]. Therefore, life extension has been set to 0% and the entire vehicle would be decommissioned. This can be adjusted in future as recycling capacity improves. Life extension assumes that the battery is replaced at the EoL.
5 For the high estimate, an average lifetime of 8 years was assumed [61]. The forecast number of EVs was estimated with an uncertainty factor of +10%.
6 For the low estimate, an average lifetime of 12 years was assumed [61]. The forecast number of EVs was estimated with an uncertainty factor of -10%.
Heatpumps (domestic)
1 Water source heat pumps made up <1% of global heat pumps so were excluded from this model [75]
2 Air source heat pumps are predicted to account for 95% of the global market between 2019 and 2030 [75]. This assumption was taken for Scotland and extended to the 2006–2050-year range.
3 Residential heat pumps are predicted to account for 83% of the global market between 2019 and 2030 [75]. This assumption was taken for Scotland and extended to the 2006–2050-year range.
4 Model excludes maintenance and peripheral infrastructure such as underfloor heating systems. Includes boreholes
5 Model assumes that heat pumps fitted from 2006 onwards
6 Length of life extension was not obtained. Additional years based upon typical design lifespan up until 50 years maximum [4]. Life extension currently set to 0%
7 Model assumes that life extension involves replacement of oil and refrigerant
8 High and Low-capacity estimates based on UK high and low-capacity scenarios for 2035 [1]. The proportion for Scotland was based upon population. Forecasts for other years are based on expected annual rates of installation. See workings tab for details
9 High capacity assumes design life of 14 years [4]
10 Low capacity assumes design life of 15 years [4]
Heatpumps (utility)
1 Water source heat pumps made up <1% of global heat pumps so were excluded from this model [75]
2 Air source heat pumps are predicted to account for 95% of the global market between 2019 and 2030 [75]. This assumption was taken for Scotland and extended to the 2006–2050-year range.
3 Residential heat pumps are predicted to account for 83% of the global market between 2019 and 2030 [75]. This assumption was taken for Scotland and extended to the 2006–2050-year range.

4 Model excludes maintenance and peripheral infrastructure such as underfloor heating systems. Includes boreholes
5 Model assumes that heat pumps fitted from 2006 onwards
6 Length of life extension was not obtained. Additional years based upon typical design lifespan up until 50 years maximum [4]. It was assumed that 50% of heat pumps would have their life extended 50%
7 Model assumes that life extension involves replacement of oil and refrigerant, plastics, silica aerogel, Helium, Water and lubrication oil
8 High and Low-capacity estimates based on UK high and low-capacity scenarios for 2035 [1]. The proportion for Scotland was based upon population. Forecasts for other years are based on expected annual rates of installation. See workings tab for details
9 High capacity assumes design life of 20 years
10 Low capacity assumes design life of 25 years
Hydrogen (green)
1 Hydrogen capacity models have been based on the highest and lowest capacity scenarios for respective technologies according to [10]
2 This model accounts for hydrogen production. It excludes end user facilities, multi-vector facilities (e.g., hydrogen hubs), hydrogen storage and T&D
3 For green hydrogen, 100% PEM technology for green technology has been assumed based on discussions with internal stakeholders. A proportional split between PEM and other technologies has been incorporated into the model if this were to change
4 For PEM, a typical lifetime of between 5-10 years has been assumed. For both high and low-capacity scenarios, an average lifetime of 7 years was assumed with stack replacement every 2.3 years [12]
5 Based upon discussions with internal stakeholders, blue/grey hydrogen was assumed to be generated by steam methane reforming (SMR). A material breakdown for a large-scale SMR plant has been used and normalised to a per MW basis - see workings tab. This excludes peripheral units such as air separation units, natural gas storage, carbon capture storage etc.
6 The average lifetime of the large-scale SMR facility has been estimated at 30 years with replacement of activated carbon PSA Adsorbent and moving equipment (e.g., Pumps) every 10 years
7 The model assumes that prior to 2020, 100% of hydrogen production is through blue/grey means. It was assumed that hydrogen production has doubled from 1990 to 2020
8 Life extension assumes replacement of the Stack which is assumed to consist of 100% of the Nafion, Activated carbon, Iridium and Platinum
Hydrogen (blue grey)
1 Hydrogen capacity models have been based on the highest and lowest capacity scenarios for respective technologies according to [10]
2 This model accounts for hydrogen production. It excludes end user facilities, multi-vector facilities (e.g., hydrogen hubs), hydrogen storage and T&D
3 Based upon discussions with internal stakeholders, blue/grey hydrogen was assumed to be generated by steam methane reforming (SMR). A material breakdown for a large-scale SMR plant has been used and normalised to a per MW basis - see workings tab. This excludes peripheral units such as air separation units, natural gas storage, carbon capture storage etc.
4 The average lifetime of the large-scale SMR facility has been estimated at 30 years with replacement of activated carbon PSA Adsorbent and moving equipment (e.g., Pumps) every 10 years
5 The model assumes that prior to 2020, 100% of hydrogen production is through blue/grey means. It was assumed that hydrogen production has doubled from 1990 to 2020

6 Life extension assumes replacement of 100% of Activated carbon, Nickel, Iron and Chromium catalyst materials
Hydro (large)
1 For both high and low forecast estimates, it was assumed that only planned large-scale would be generated up to 2050 (i.e., no additional capacity based on forecast).
2 Using BEIS data, it was assumed that projects consented, but not operational, would come online 5 years after consent.
3 Large-scale hydroelectric installations are considered as installations above 4MW (according to BEIS database). This includes pumped-storage systems.
4 Large-scale hydroelectric power has a typical maximum lifetime of 80 years with refurbishment 'at least once' in its lifetime [38].
5 Low-capacity scenario assumes a typical starting lifetime of 40 years with one replacement of parts (life extension) after 40 years to give a maximum total lifespan of 80 years [38].
6 High-capacity scenario assumes a typical starting lifetime of 30 years with one replacement of parts (life extension) after 25 years and a second replacement of parts after another 250 years to give a maximum total lifespan of 80 years [38].
7 An average weight per MW has been assumed as a basis for calculations. See Workings tab for calculations.
8 A typical material composition for a large-scale (2,000 MW) hydro power unit was used as a basis for all large-scale facilities. From discussions with an internal stakeholder, this material composition was deemed to be a sensible estimate for smaller large-scale facilities.
9 It was assumed that at life extension, 50% of iron, 100% of plastic, and 50% of 'other' would be replaced.
Hydro (small)
1 Based on assumption that forecast future hydro includes small-scale only [73].
2 Using BEIS data, it was assumed that projects consented, but not operational, would come online 5 years after consent.
3 Small scale hydroelectric installations are considered as installations below 4 MW (according to BEIS data).
4 Small scale hydroelectric power has a typical maximum lifetime of 40 years with parts replacement 'at least once' in its lifetime [38].
5 Low-capacity scenario assumes a typical starting lifetime of 20 years with one replacement of parts (life extension) after 20 years to give a maximum total lifespan of 40 years [38].
6 High-capacity scenario assumes a typical starting lifetime of 20 years with one replacement of parts (life extension) after 10 years and a second replacement of parts after another 10 years to give a maximum total lifespan of 40 years [38].
7 An average weight per MW has been assumed as a basis for calculations. See Workings tab for calculations.
8 A typical material composition for a small-scale hydro power unit could not be identified. Furthermore, there are numerous small-scale hydropower generation types and scales so the material composition can vary significantly between projects [72]. From discussions with an internal stakeholder, the material composition included in this model was estimated based on their experience.
9 It was assumed that at life extension, 50% of iron, 100% of plastic, and 50% of 'other' would be replaced
Solar
1 Only utility and rooftop applications have been included in this study. Niche applications have been excluded

2 Utility and rooftop installations are included under the same targets
3 From BEIS data, projects consented, but not operational, are assumed to come online 5 years after consent
4 Repowered assumes replacement of unit but not replacement of foundations & cabling. This has currently been set at 0%
5 From discussions with internal stakeholder, life extension is likely to consist of a replacement of the inverter every 12 years. Inverters are electronic devices which make up a small proportion of the weight of an array. The inverter weight has been assumed to be 1% of panel weight
6 From discussions with internal stakeholder, utility solar in Scotland is unlikely to keep expanding due to lack of subsidies over last 4-5 years. It is unlikely that subsidies will return for Solar due to Scotland's wind assets. Therefore, it has been assumed that no more Utility farms will be built beyond those in operation/planning phase (i.e., beyond 2026). This can be adjusted easily in the model were subsidies to be reintroduced
7 It has been assumed that material composition of rooftop and utility panels are the same. The difference in overall composition relates to the frame. A holding value of 10 kg per frame (per panel) has been assumed due to lack of data
8 A high and low energy scenario has been applied using the CCC highest and lowest scenarios for UK solar capacity by 2050. Using the respective linear average build rates to achieve a forecast for 2030 and a linear trend to achieve today's rates. UK to Scotland ratio based upon today's proportion. See workings tab.
9 Silicon-type PV panels have been assumed for this model. Emerging PV materials beyond silicon and CdTe-based PV can be used for utility scale and rooftop PV, as well as for niche applications. Nevertheless, silicon will remain the main deployed PV technology in the UK towards 2050. [31]
10 For the low-capacity estimate, it was assumed that 50% would be decommissioned after its maximum expected lifetime of 25 years and 50% of projects would have their life extended once. 0% would have their life extended twice as this took the total lifetime beyond the 40 years provided by an internal stakeholder
11 For the high-capacity estimate, it was assumed that 65% of installations would be decommissioned after its expected lifetime of 16 years and 25% of projects would have their life extended once. 10% would have their life extended twice to take the total maximum of 40 years provided by an internal stakeholder
12 Due to lack of available data, it was assumed that the weight of a panel frame (for utility Solar) was 10 kg of steel. The weight of an inverter was estimated to be 5 kg with one inverter assumed for every 10 panels. Due to levels of uncertainty, these values have been highlighted yellow in the workings tab.
T&D
1 Most T&D infrastructure was constructed in the 1950s post war.
2 The typical lifetime of a pylon is 80 years [76]
3 Life extension involves replacement of the conductors, insulators and fittings which normally last for about 40 years [76]
4 For both low and high scenarios, a linear growth was assumed between 1950 and 2020 using the average growth rate between 2014 and 2020
5 For the low-capacity scenario, the same linear forecast was assumed up to 2050
6 For the high-capacity scenario, a growth rate of 1.5% was assumed based on input from technical expert

7 An average weight per km was taken based on the length of T&D lines in Scotland (2014) and material composition for a typical pylon was calculated in the Workings tab
Oil & Gas
1 Assumptions have been made based on data held by the UK Oil & Gas authority and includes upstream extraction activities. It excludes downstream facilities such as onshore refineries and processing
2 Assumption that only existing assets will be decommissioned as per the Oil & Gas Authority 2019 decommissioning report [55]. No additional infrastructure will be installed.
3 The proportion of assets that will be removed is based on the projected cost of decommissioning up to 2065 [99]
4 No. of installations in 'Scottish waters' is based on the assumption that 55 degrees latitude as the demarcation between Scottish Territorial Waters and rest of the UK waters. Under this method 44% of all installations in the North Sea are in Scottish Waters; for the purpose of this report this assumption has been applied equally to all installation types, though it should be noted that those in the northern sector are predominantly larger oil platforms, whilst those in the southern sector are predominantly smaller gas platforms (ZWS, O&G report) [54]
5 As this assessment covers decommissioning only, a full capacity model has not been generated as it has for the other technologies. Proportion of assets to be decommissioned is displayed in the capacity tab.
6 An average material composition across offshore assets was taken based on the proportion of assets and material composition from the Miller decommissioning programme [95]
7 Based on stakeholder engagement, it was assumed that 10% of pipelines would be removed from the seabed. The remainder would be isolated and left at the seabed with 'Rock dumping' at the ends and midpoint.
8 Based on stakeholder engagement, it was assumed that 10% of the pipelines would require rock dumping to ensure pipelines remain on the seabed. It was assumed that 860 tonnes of rock per km would be required.

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