Australian Industry Energy Transitions Initiative

Pathways to industrial decarbonisation

PHASE 3 TECHNICAL REPORT - FEBRUARY 2023

Analysis by Climateworks Centre and CSIRO

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The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

The Australian Industry ETI is convened by Climateworks Centre, operating within the Monash Sustainable Development Institute, and Climate-KIC Australia, in collaboration with the Energy Transitions Commission and delivery partners CSIRO, RMI (formerly Rocky Mountain Institute) and BloombergNEF.

The Australian Industry ETI's industry partners and supporters have contributed to the research, findings, conclusions and messages in this report. Industry partners have generally validated the model inputs and architecture and endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. While this report provides an evidence-based, independent analysis informed by consultation with industry, it does not necessarily reflect the position of each individual partner.

Partners: Australian Gas Infrastructure Group, APA Group, Aurecon, AustralianSuper, BHP, BlueScope Steel, bp Australia, Cbus, the Clean Energy Finance Corporation, Fortescue Metals Group, HSBC, Orica, National Australia Bank, Rio Tinto, Schneider Electric, Wesfarmers Chemicals, Energy & Fertilisers, Westpac and Woodside Energy. Supporters: Australian Industry Group and the Australian Industry Greenhouse Network.

This report is the result of three years of engagement with Australia's emissions-intensive industry and related businesses to coordinate learning and action, and develop pathways and projects towards achieving net zero emissions supply chains aligned to 1.5°C in Australia.

We acknowledge and pay our respect to the Traditional Owners and Elders – past and present – of the lands and waters on which program partners operate nationally.

Climateworks Centre and CSIRO 2023*, 'Pathways to industrial decarbonisation: Phase 3 technical report'*, Australian Industry Energy Transitions Initiative, Climateworks Centre.

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Contents

Table of Figures

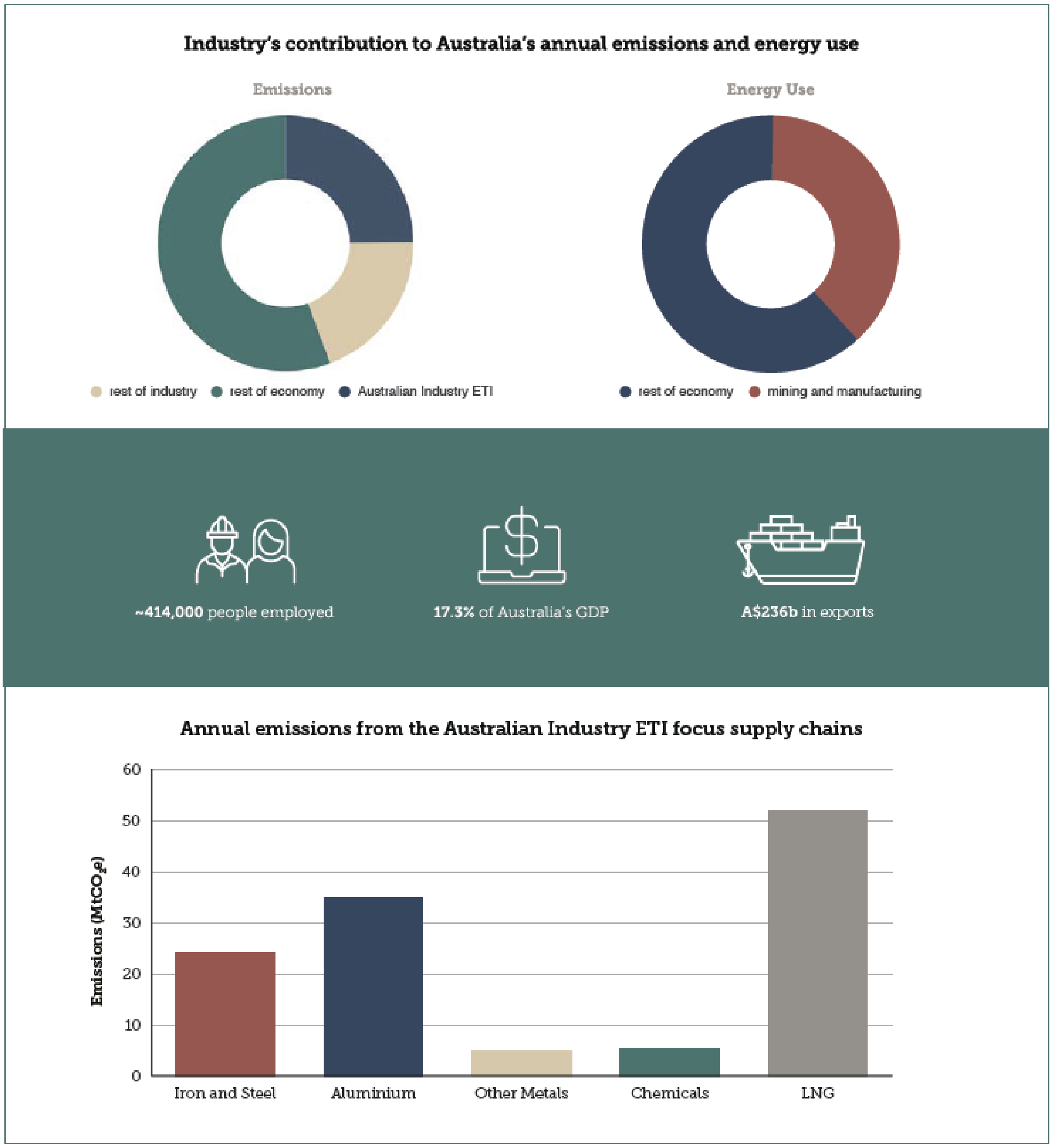
Introduction

The Australian Industry Energy Transitions Initiative (Australian Industry ETI) brings together some of Australia's largest companies to accelerate action towards achieving net zero emissions supply chains by 2050.

The Australian Industry ETI has worked collaboratively with heavy industry and business partners, focusing on five key industrial supply chains: iron and steel, aluminium, other metals (copper, nickel, zinc and lithium), chemicals (ammonia, fertilisers and commercial explosives) and liquified natural gas (LNG). Collectively, these supply chains are responsible for 17.3 per cent of Australia's GDP, generate exports worth over A$236 billion each year and directly employ an estimated 414,000 people (Australian Bureau of Statistics 2020; 2022a; 2022b).

Heavy industry comprises a significant proportion of Australia's annual energy use and emissions. Mining and manufacturing account for around 42 per cent of total emissions, while the five supply chains in focus for the Australian Industry ETI contribute an estimated 25 per cent (Figure 1). Most emissions result from the combustion of fossil fuels, either on-site to power boilers, turbines and haulage, or through electricity use. The remainder of emissions are from non-energy sources such as fugitive and process emissions. From the Australian Industry ETI supply chains, 85 $MtCO_2e$ of energy-related emissions and 39 $MtCO_2e$ of non-energy emissions are released each year.

Figure 1: The significance of the Australian Industry ETI supply chains



Given Australian Industry ETI supply chains contribute approximately 25 per cent of Australia's annual emissions, abating emissions from these sectors is critical to Australia achieving the Paris Agreement goals. Industrial processes are typically considered hard to abate, as addressing them poses more technological and commercial challenges than other sectors of the economy. The Australian Industry ETI aims to position Australian industry to maximise opportunities in the shift to net zero emissions supply chains by 2050 and help Australia build an economy that takes advantage of the transition.

Since 2020, the Australian Industry ETI has brought together industry and business partners, including Australia Gas Infrastructure Group; APA Group; Aurecon; AustralianSuper; BHP; BlueScope Steel; bp Australia; Cbus; the Clean Energy Finance Corporation; Fortescue Metals Group; Orica; National Australia Bank; Schneider Electric; Wesfarmers Chemicals, Energy & Fertilisers; Westpac; and Woodside Energy. The initiative's work has also benefited from the input of other participants, including HSBC Australia and Rio Tinto. It is supported by the Australian Industry Group, Energy

Transitions Commission and the Australian Industry Greenhouse Network, with research partners including CSIRO, BloombergNEF and RMI.

Purpose of this report

This technical report is a companion document to the Australian Industry ETI phase 3 report, *Pathways to industrial decarbonisation: Positioning Australian industry to prosper in a net zero global economy*, providing the technical details of the modelling that supports the report's findings. This includes detailed information on the models used, scenario development, modelling assumptions and model results for the overall economy, the energy system and each supply chain. The *Pathways to industrial decarbonisation* report is the culmination of a three-year work plan and outlines the pathways for heavy industry decarbonisation, identifying key barriers and enablers across five supply chains and the broader energy system.

These reports follow on from two previous reports. The Australian Industry ETI's first report, *Setting up industry for net zero*, identified the range of existing and emerging solutions that can address almost all emissions in heavy industry supply chains (Australian Industry Energy Transitions Initiative 2021). In the second report, *Setting up industrial regions for net zero*, the opportunities in five key industrial regions were identified, highlighting the need for scale, coordination, collaboration and urgent action to realise these opportunities (Australian Industry Energy Transitions Initiative 2022).

This technical report is split into five sections:

1. **Methodology**: This section details the overall approach taken by the Australian Industry ETI, including modelling tools used and their configuration.
2. **Scenario definition and key assumptions**: This section details the scenarios used in the modelling and the high-level assumptions for each scenario across carbon budgets, government policy and support, the energy system, road transport and technology development.
3. **Energy system**: key cost and performance assumptions: This section outlines the specific electricity system, hydrogen and bioenergy assumptions used in the modelling.
4. **Industrial supply chains:** key activity and technology development assumptions: This section outlines the specific industry sector modelling approach and assumptions for each of the key supply chains. This includes activity assumptions as well as technology development assumptions.
5. **Results:** This section provides results from the modelling at the economy-wide and supply chain level.

Methodology

Overall approach to developing the research

A scenario approach to manage uncertainty

Scenario modelling is a useful tool for exploring the uncertainty inherent in a net zero transition. Significant unknowns exist around global changes, global events and the scope and timing of technological developments and deployment. Complexity also comes from the multiple interacting systems involved (for example, environmental, economic and social).

Despite the uncertainty, scenario modelling can:

- Assess a range of outcomes and build a vision around a more positive future
- Identify, test and quantify the impact of key transition drivers
- Inform the prioritisation, sequencing and timing of key actions
- Illustrate different energy and emissions outcomes over time

- Highlight technology and renewable energy deployment targets aligned with a net zero transition
- Demonstrate the sensitivity of the analysis to uncertain and complex assumptions.

Key principles for decarbonisation pathways

A net zero aligned decarbonisation pathway requires credible scenario analysis. A credible net zero scenario aims to eliminate emissions within supply chains at a pace and scale consistent with limiting warming to a set climate target. The Taskforce on Climate-Related Financial Disclosures (TCFD) recommends that scenario analyses and narratives be plausible, distinctive (i.e. diverse scenarios focusing on different combinations of key factors), consistent (i.e. easy to follow with their own consistent internal logic), relevant and challenging (Task Force on Climate-Related Financial Disclosures 2017).

Using the TCFD recommendations as guidance, Australian Industry ETI has identified the following characteristics of a credible net zero transition pathway:

1. **Plausible**: The pathway should be the most likely of scenarios that limit warming to 1.5°C or well below 2°C.
2. **Consistent**: The pathway should have strong internal logic and not be built on incompatible assumptions or parameters.
3. **Responsible**: The pathway should minimise the risk of not achieving necessary emissions reductions in a sustainable and equitable manner.
4. **Objective**: The pathway and its goals should be established by science, irrespective of what is preferable to an organisation.
5. **Actionable**: The pathway should be backed by operating metrics and actions rather than commitments or pledges alone.

To arrive at a pathway aligned with these characteristics requires that the analysis include the most likely of the scenarios that limit warming to 1.5°C or well below 2°C. The scenarios should also minimise the risk of not achieving necessary emissions reductions in a sustainable and equitable manner, through reducing delays, avoiding dependency on a specific future development, and prioritising technology feasibility over economic competitiveness alone, where solutions exist. Scenarios should also account for risks and uncertainties regarding over-reliance on negative emissions (for example, permanence, additionality, double-counting, effectiveness and energy penalty of negative emissions technologies, and ability to deploy at scale), recognise increased capacity of advanced economies and particular geographies to decarbonise, and consider social and ecological impacts of different actions (for example, nature-based solutions and bioenergy).

Australian Industry ETI modelling approach

The Australian Industry ETI modelling developed three scenarios that explore potential emissions reductions pathways across the Australian economy, within a context of global action consistent with limiting global warming to 1.5°C. The three core scenarios are modelled alongside sensitivities that explore key sources of uncertainty such as future gas prices and the potential for Australia to develop new green export industries such as hydrogen and green iron.

Key principles were developed to ensure the credibility of the Australian Industry ETI modelling approach:

- Decarbonisation pathways for Australia's industrial supply chains should be developed with the goal of achieving emissions reductions in line with the Paris Agreement and limiting global warming to 1.5°C
- Effort should be made to reduce emissions within supply chains, with negative emissions used to complement, rather than substitute, direct abatement where possible
- Where negative emissions are required, these should be aligned to principles followed by the Energy Transitions Commission (2018) and Oxford (Allen et al. 2020), preferencing 'carbon removals' over 'emissions reductions'
- The International Energy Agency's (IEA) 'Net Zero Emissions' scenario (2021) should be considered a benchmark for global energy use and industrial decarbonisation in line with 1.5°C
- Modelled scenarios should target the IEA benchmark by applying plausible assumptions, targeting improvements in absolute and cumulative emissions.

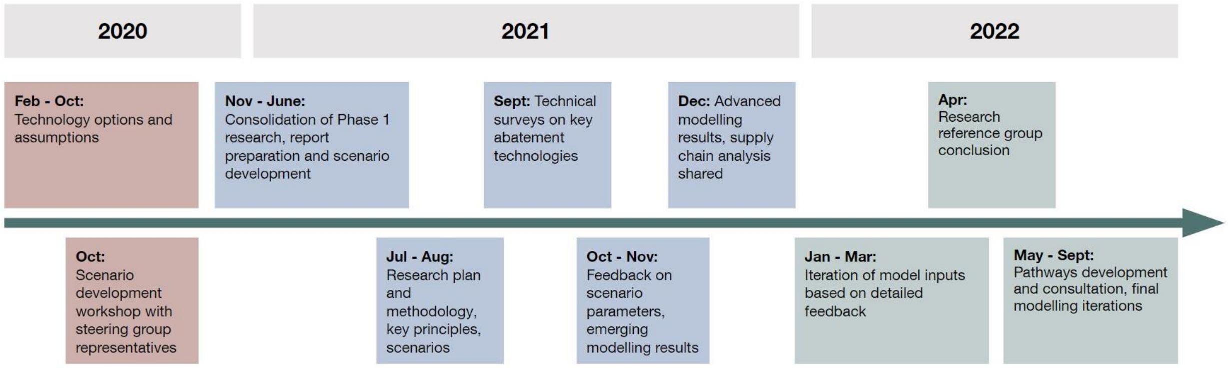
The scenarios developed for this study are discussed further in section 'Scenario definition and key assumptions', below.

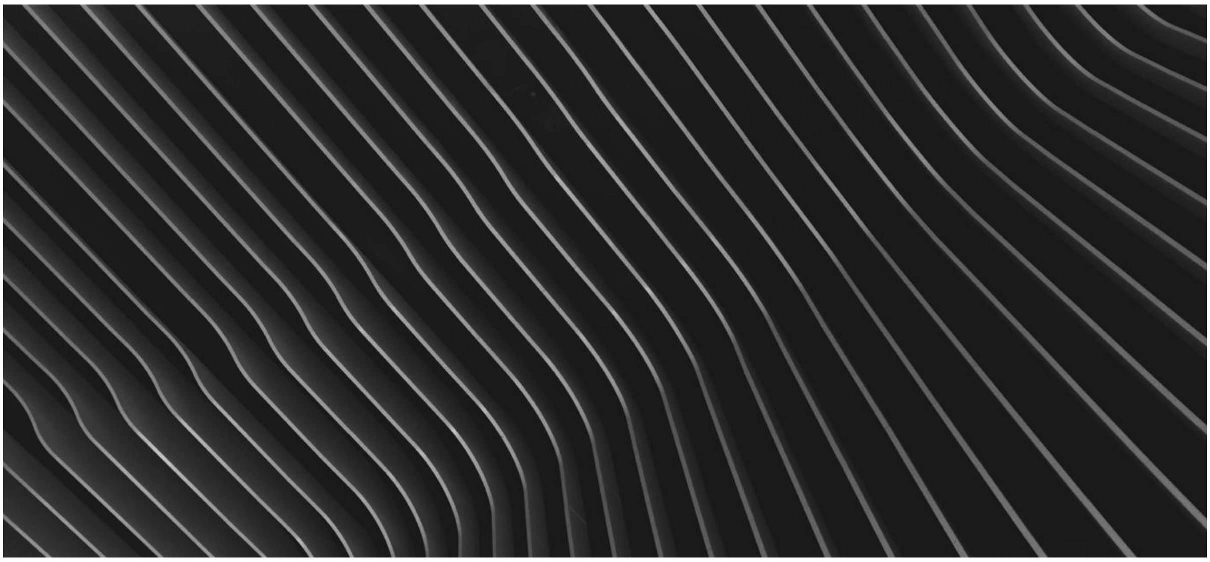
The modelling approach used by the Australian Industry ETI provides a comprehensive set of scenario outputs, including technology deployment timelines, emissions outcomes and investment costs, which provide detailed insights into least-cost decarbonisation for the heavy industry sector. These key insights were adapted into actionable decarbonisation pathways, which are discussed in the *Pathways to industrial decarbonisation* report.

To produce the modelling and analysis, the Australian Industry ETI engaged extensively with a diverse group of program partners who have contributed to the technology options considered and the model inputs and assumptions (see Figure 2).

The initial research and development of the underlying supply chain and technology assumptions for the work, included in the Phase 1 Technical Report (Australian Industry Energy Transitions Initiative 2021), is based on discussions and feedback from partners. The scenario definition process was initiated through a workshop with steering group representatives in October 2020. At the workshop a range of drivers of change were reviewed and compared, and participants discussed some of the key questions they would like to examine using the scenario approach. The subsequent development of the scenario approach and modelling inputs during 2021–2022 was guided through regular workshops and discussions with subject matter experts from the partner group.

Figure 2: Timeline of research activities





The scenario modelling for this project uses the AusTIMES model, an Australian adaptation of the TIMES (The Integrated MARKAL-EFOM System) model, an energy system modelling framework used in over 20 countries and developed and maintained under the IEA Energy Technology Systems Analysis Project (ETSAP) (International Energy Agency Energy Technology Systems Analysis Program n.d.).

AusTIMES was chosen due to:

- its ability to provide technology-explicit, least-cost pathways for a particular scenario that can readily be translated into actionable pathways for heavy industry
- its technology richness, which enables exploration of a wide range of specific abatement solutions, with detailed cost data
- its ability to capture key trade-offs between industry and other areas of the economy, under a national emissions abatement goal.

See the following 'AusTIMES model overview' section for more information about the AusTIMES model.

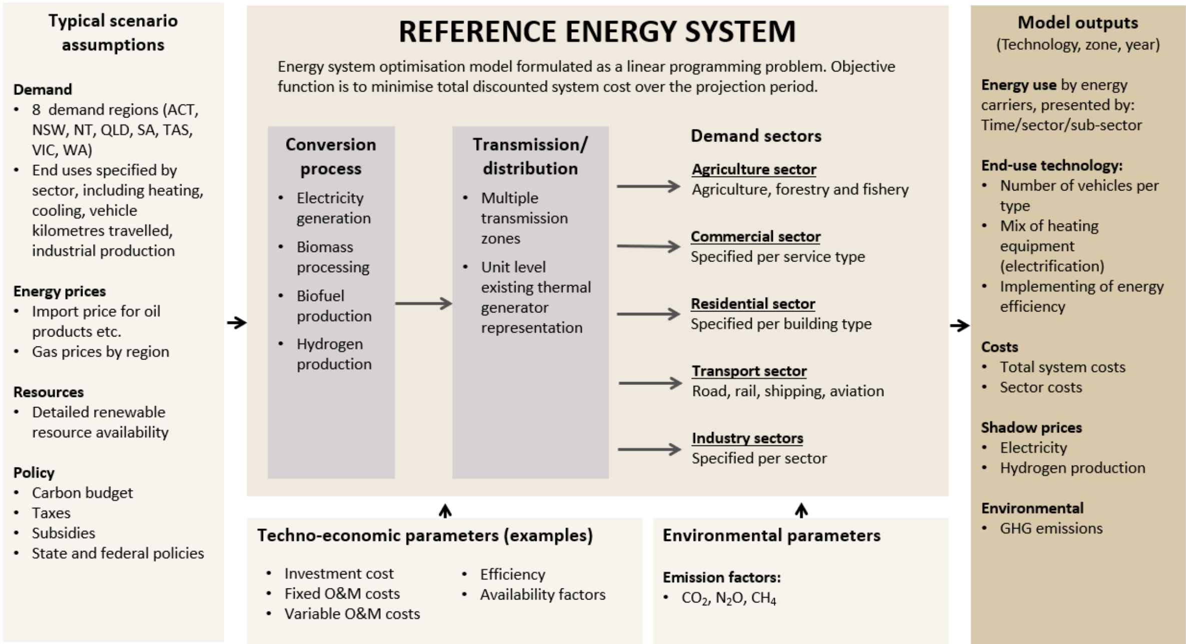
In addition to AusTIMES, the modelling also used STABLE, an energy system model developed by CSIRO, to support more granular energy system modelling. The STABLE model provides additional support to optimise energy system reliability under different decarbonisation pathways (see 'STABLE model overview') and uses the outputs of the AusTIMES model as inputs for modelling.

Although AusTIMES is able to track retirements and future investment needs, it does not have the temporal detail to check for reliability. CSIRO's STABLE model can search for reliable solutions and further refine storage investment choices with scenarios that can include demand time series, technology and resource availability, transmission constraints, distributed battery technology uptake, virtual power aggregation and hydrogen production. This allowed a deeper level of granularity in energy system results compared to using AusTIMES alone.

AusTIMES model overview

Climateworks Centre developed AusTIMES, the Australian version of the TIMES model, in collaboration with CSIRO, who are a contracting party to the IEA-ETSAP. The model satisfies energy services demand at the minimum total system cost subject to physical, technological and policy constraints (see Figure 3). Accordingly, the model makes simultaneous decisions regarding technology investment, primary energy supply and energy trade. Extensive documentation of the TIMES model generator is available from the ETSAP website (International Energy Agency Energy Technology Systems Analysis Program n.d.).

Figure 3: Visual representation of the AusTIMES model



The TIMES model generator is a partial equilibrium model of the energy sector. In the energy domain, partial equilibrium models, sometimes referred to as 'bottom-up' models, were initially developed in the 1970s and 1980s (for example, Manne 1976; Hoffman & Jorgenson 1977; Fishbone & Abilock 1981). Partial equilibrium models are used because the analysis of energy and environmental policy requires technological explicitness; the same end-use service (such as space heating or lighting) or end-use fuel (such as electricity or transport fuel) can often be provided by one of several different technologies that use different primary energy resources and entail different emission intensities, yet may be similar in cost (Greening & Bataille 2009). This means that in different scenarios, consumption of various primary energy sources may vary across sectors and technologies.

Partial equilibrium modelling enables the incorporation of various technologies associated with each supply option and allows a market equilibrium to be calculated. It also allows for competing technologies to be evaluated simultaneously without prior assumptions about which technology, or how much of each, will be used. Some technologies may not be taken up at all. This allows flexibility in the analysis: detailed demand characteristics, supply technologies and additional constraints can be included to capture the impact of resource availability, industry scale-up, saturation effects, cost reductions and policy constraints on market operation.

The advantage of using a system model approach rather than an individual fuel/technology/process modelling approach is that infrastructure constraints can be explicitly included, such as the life of existing asset stocks (for example, plants, buildings, vehicles, equipment and appliances) and consumer technology adoption curves for abatement options, which are subject to non-financial decision-making. By using a system approach, we can account for the different impact of abatement options when they are combined rather than implemented separately.

Model features

The AusTIMES model has the following structural features:

- Covers all states and mainland territories: ACT, NSW, NT, QLD, SA, TAS, VIC and WA
- Represents time in five-year increments for financial years 2015–2060, with results presented to 2050, the timeframe in scope for the *Pathways to industrial decarbonisation* report
- Covers end-use sectors, including agriculture (eight subsectors), industry (11 subsectors in mining, 26 subsectors in manufacturing and six subsectors in other industry), commercial and

services (11 building types), residential (three building types), road transport (10 vehicle segments) and non-road transport (three modes)

  - Each sector includes information on energy consumption and assumed efficiency gains as well as options regarding which primary energy sources can be consumed, additional costed fuel switching or efficiency improvements, options for avoiding non-energy emissions and potential for carbon capture and storage (CCS)
  - These sectors have been mapped to Australian and New Zealand Standard Industrial Classification (ANZSIC) 2006 divisions (see mapping in Table 1)
  - Additional detail about non-industry sectors of the model can be found in Appendix A of the CSIRO and Climateworks publication *Multi-sector energy modelling* (Reedman et al. 2021).

- Represents fuel types and energy feedstocks across end-use sectors:
  - Industry and agriculture: oil, black coal, brown coal, natural gas, hydrogen, electricity and bioenergy (representing bagasse in existing applications, ethanol, biodiesel and biogas)
  - Residential buildings: natural gas, liquid petroleum gas, hydrogen, wood and electricity
  - Commercial buildings: oil (as reported in Australian Energy Statistics), natural gas, hydrogen and electricity.
- Represents the annual operations of the supply-side of the electricity sector:
  - Electricity demand aggregated to 16 load blocks, reflecting seasonal and time of day variation across the year
  - 19 transmission zones: 16 zones in the National Electricity Market (NEM); South-West Interconnected System; North-West Interconnected System; and Darwin Katherine Interconnected System
  - Existing generators mapped to transmission zones at the unit-level (thermal and hydro) or farm-level (wind and solar)
  - Renewable resource availability at renewable energy zone spatial resolution for solar, onshore and offshore wind and tidal resources as well as sub-state spatial resolution for geothermal and wave resources in the NEM
  - Trade in electricity between NEM regions subject to interconnector limits
  - 31 electricity generation and storage technologies: black coal pulverised fuel; black coal with CCS; brown coal pulverised fuel; brown coal with CCS; combined cycle gas turbine (CCGT); open-cycle gas turbine; gas CCGT with CCS; gas reciprocating engine; biomass; biomass with CCS; pumped storage hydro (PSH) with four hours storage; PSH with eight hours of storage; PSH with 12 hours of storage; PSH with 24 hours of storage; PSH with 48 hours of storage; onshore wind; offshore wind; large-scale, single-axis tracking solar photovoltaic (PV); concentrating solar thermal with hours storage; residential rooftop solar PV; commercial rooftop solar PV; hot fractured rocks (enhanced geothermal); conventional geothermal; wave; tidal; hydrogen reciprocating engine; diesel reciprocating engine; small modular nuclear reactor; battery with two hours of storage; battery with four hours of storage; battery with eight hours of storage
  - Current policies: national Large-scale Renewable Energy Target; Queensland Renewable Energy Target; Tasmania Renewable Energy Target; Victoria Renewable Energy Target; Small-scale Renewable Energy Scheme; NSW Energy Security Target; and the NSW Electricity Infrastructure Roadmap
  - AusTIMES includes an explicit representation of grid electricity supply to end-use sectors in the economy. However, representation of off-grid electricity generation is limited.

- Includes five hydrogen production pathways:
    - Two electrolysis pathways: proton exchange membrane and alkaline electrolysis
    - Steam methane reforming (SMR)
    - SMR with CCS
    - Coal gasification with CCS – although coal gasification was not included as an option for the modelling used for the Australian Industry ETI.

Table 1: Mapping of AusTIMES to ANZSIC industry subsectors

AusTIMES subsector (industry)	ANZSIC (2006) codes	ANZSIC division
Industry – Coal mining	06	Division B
Industry – Oil mining	07 (part)	Division B
Industry – Gas extraction	07 (part)	Division B
Industry – Iron ore mining	0801	Division B
Industry – Bauxite mining	0802	Division B
Industry – Lithium mining	0809 (part)	Division B
Industry – Copper mining	0803	Division B
Industry – Nickel mining	0806	Division B
Industry – Zinc mining	0807	Division B
Industry – Other non-ferrous metal ores mining	0804, 0805, 0809 (part)	Division B
Industry – Other mining	09	Division B
Industry – Meat products	111	Division C
Industry – Other food and drink products	112, 113, 114, 115, 116, 117, 118, 119	Division C
Industry – Textiles, clothing and footwear	13	Division C

Industry – Wood products	14	Division C
Industry – Paper products	15	Division C
Industry – Printing and publishing	16	Division C
Industry – Petroleum refinery	17	Division C
Industry – Ammonia	181 (part)	Division C
Industry – Fertilisers	1831	Division C
Industry – Explosives	1892	Division C
Industry – Other chemicals	181 (part), 182, 183 (part), 185, 189 (part)	Division C
Industry – Rubber and plastic products	19	Division C
Industry – Non-metallic construction materials (not cement)	201, 202, 209	Division C
Industry – Cement	203	Division C
Industry – Iron and steel	211	Division C
Industry – Alumina	2131	Division C
Industry – Aluminium	2132	Division C
Industry – Other non-ferrous metals	2133, 2139	Division C
Industry – Other metal products	212, 214, 22	Division C
Industry – Motor vehicles and parts	231	Division C
Industry – Other manufacturing products	239, 24, 25	Division C

Industry – Gas supply	27	Division D
Industry – Gas export (LNG)	07 (part)	Division B
Industry – Water supply	28	Division D
Industry – Construction services	30, 31, 32	Division E

Model calibration and inputs

The AusTIMES model for this study was calibrated to a base year of 2020 for each state and territory (Department of Industry, Science, Energy and Resources [DISER] 2021c), national inventory of greenhouse gas emissions to 2019 (Paris Agreement inventory n.d.), stock estimates of vehicles in the transport sector to 2021 (Australian Bureau of Statistics 2021), data on the existing power generation fleet as of 2020 (Australian Energy Market Operator [AEMO] 2020) and installed capacity of distributed generation from work in 2015 (Connor et al. 2015).

Additional inputs were sourced from BloombergNEF, the Energy Transitions Commission and a range of literature and industry sources to develop assumptions for this work. These include the activity trajectories to 2050 for each of the key industrial sectors and the input assumptions about decarbonisation technology costs and timelines. For details, see 'Industrial supply chains: key activity and technology development assumptions' section.

While AusTIMES models all sectors of the Australian economy, detailed modelling of non-industry sectors has not been a focus of the Australian Industry ETI. Modelling assumptions in those sectors are based largely on the approach taken in the *Decarbonisation Futures* modelling work by Climateworks Centre (2020). However, the scenario narratives and settings are distinct from the scenarios used in the *Decarbonisation Futures* work.

Model details – Objective function

TIMES modelling is formulated as a linear programming problem. The objective function minimises total discounted system costs over the projection period (inter-temporal optimisation) while adhering to specific constraints. TIMES is simultaneously making decisions on investment and operation, primary energy supply, and energy trade between regions, according to the following equation:

$$\text{NPV} = \sum_{r=1.y=\text{REFYR}}^{R,2060} \frac{\text{ANNCOST}_{r,y}}{(1+d)^{(y-\text{REFYR})}}$$

NPV: net present value of the total costs

ANNCOST: total annual cost incorporating investment, operation and trade (where relevant)

d: general discount rate

REFYR: reference year for discounting

y: set of years for which there are costs

r, R: region

While minimising total discounted cost, the model must satisfy a large number of constraints (the equations of the model), which express the physical and logical relationships that must be satisfied in order to properly depict the energy system. Details on the constraints are available in Part I of the TIMES model documentation (International Energy Agency Energy Technology Systems Analysis Program n.d.).

Implementation of decarbonisation objectives in AusTIMES

There are a number of options for the implementation of decarbonisation objectives in AusTIMES, including:

1. Implementing an annual carbon price trajectory per scenario that results in sufficient emissions reduction to meet the scenario objective
2. Implementing an annual emissions reduction target that reaches the desired quantum of emissions in a particular future year
3. Specifying a carbon budget (a cumulative emissions target by a certain year).

A combination of the second and third options were used for the Australian Industry ETI modelling work. The specific budgets for each scenario are detailed in the 'Scenario definition and key assumptions' section of this report. The model also includes a carbon price, matched to approximate current offset prices in Australia: $20/t$CO_2$e in 2020, linearly increasing to $25/t$CO_2$e in 2050.

Although AusTIMES is populated with data on a number of technologies, the costs of emissions abatement across all sectors (especially agriculture) are not fully populated in the model. The total economy-wide cost of decarbonisation is therefore not provided as an output of this work.

AusTIMES optimises for least cost across all sectors and states of the Australian economy simultaneously. This means that the abatement effort is distributed across sectors and states on a least-cost basis, subject to any imposed constraints. As such, sectors will not necessarily deploy all the abatement potential available to them.

In this way, the modelling accounts for the fact that some sectors of the economy are relatively easier to abate than others. In addition, decarbonisation in these modelling results does not necessarily represent the technical potential for each state or sector. Therefore, it is likely possible to model more ambitious decarbonisation pathways by forcing deployment of all available technologies in the model, with the primary implication being increased total system costs.

AusTIMES includes all emissions that Australia is responsible for under its United Nations Framework Convention on Climate Change reporting obligations, captured at the point of combustion. This allows us to report emission outcomes as scope 1 or scope 1 and 2 emissions attributable to a sector.

Analysis of scope 3 emissions (indirect GHG emissions that are a consequence of a company's activities but from sources not owned or controlled by the company (World Resources Institute 2004)) was considered out of scope as it requires analysis beyond the standard outputs of AusTIMES, including international emissions. Though emissions associated with Australia's exports are not modelled in this study, demand has been aligned to scenarios such as BloombergNEF's *New Energy Outlook* (2021b) and the IEA's *Net Zero by 2050* (2021) to show changes in production and export demand over time as key trading partners attempt to reduce their emissions consistent with a 1.5°C trajectory.

Land-based emissions sequestration in AusTIMES

The model only considers sequestration in Australia, not international sequestration. The offsetting approach is based on the Oxford Offsetting Principles, which require transparency, verifiability and avoidance of negative unintended impacts on people or the environment. Calculating net emissions requires the consideration of both residual and sequestered emissions across the economy. AusTIMES models detailed emission abatement pathways for residual emissions in most sectors of the economy. It also includes some detail around negative emissions technologies, including CCS technologies for industry, electricity generation and hydrogen production. However, it does not provide a detailed framework for modelling land-based emissions sequestration. Therefore, a cost curve approach has been used to model land-based sequestration, based on data from *Australia's Long-Term Emission Reduction Plan: Modelling and Analysis* report (DISER 2021a), as shown in Table 2.

In *Australia's Long-Term Emission Reduction Plan: Modelling and Analysis*, the land sequestration supply is sourced from CSIRO's Land Use Trade-Offs (LUTO) model (Connor et al. 2015) and is modelled as a voluntary market-driven activity, only occurring where economic benefit is provided to landholders. Soil carbon, on-farm plantings and afforestation, and off-farm supply (including savannah and native forest management) have been accounted for in the modelling, but avoided land sector emissions from deforestation or other sources are not included (DISER 2021a). The costs used were from the 'Conservative, high-threshold' scenario. Full details of the assumptions used to develop the costs and availability can be found in the report.

Table 2: Cost and availability of land-based sequestration from *Australia's Long-Term Emission Reduction Plan: Modelling and Analysis* (DISER 2021a)

Conservative, high-threshold	Supply price (A$/t$CO_2$e)	$0	$10	$20	$30	$40	$50	$60	$70	$85	$100	$150	$200	$250	$300
Total supply	MtCO_2e	8.1	10	11.9	16.4	21.1	25.9	30.7	35.4	54	77.7	167.2	245	306.3	367.5
Soil carbon	MtCO_2e	3	3.3	3.7	4.1	4.4	4.8	5.2	5.6	6.3	7.2	10.3	13.5	16.8	20.2
On-farm plantings	MtCO_2e	1.4	2.1	2.8	5.3	8	10.7	13.4	16.1	32.3	54.6	139.1	209.8	262.2	314.7
Other supply	MtCO_2e	3.7	4.5	5.4	7	8.7	10.4	12	13.7	15.4	15.9	17.9	21.7	27.2	32.6
Area of on-farm plantings	Mha	0.1	0.2	0.2	0.4	0.6	0.8	1	1.2	2.2	3.5	6.6	10.9	13.6	16.3
Area removed from production	Mha	0	0	0	0	0	0	0	0	0	0	3.2	6.9	8.6	10.3

The same sequestration costs and potentials were applied to all scenarios. Regional sequestration levels are based on allocations determined in previous modelling work, based on the LUTO model (Climateworks Centre, ANU, CSIRO and CoPS 2014), and proportions do not vary between scenarios. Such outputs represent the carbon forestry sequestration expected from plantings in each state. Emissions requiring abatement are determined nationally, so state-level land use sequestration is not explicitly considered.

Engineered carbon removals in AusTIMES

Direct air capture was not included in this modelling, due to a lack of certainty around costs, timelines for deployment and operational requirements. A range of CCS technologies are available in the model, including for use in producing blue hydrogen as well as in the iron and steel, alumina, chemicals and LNG supply chains (more details are included in the 'Industrial supply chains: key activity and technology development assumptions' section).

STABLE model overview

Model features

The STABLE (Spatial Temporal Analysis of Balancing Levelised-Cost of Energy) model is in the class of 'intermediate horizon' models, which use both dispatch and generation expansion models.

In dispatch modelling, the focus is on the detailed operation of existing plants and capacities in a time resolution from minutes to subsets of an hour. In generation expansion modelling, the focus is on the optimisation of capacity investment (generation, storage or transmission) in annual timeframes over a 5 to 50-year range. An intermediate horizon model seeks to optimise investment in the presence of system reliability considerations, looking across a year in half-hourly or hourly time steps. This approach improves the modelling power by allowing the dynamics of operations to inform the requirements for investment, including addressing the needs of increasing penetration of variable renewables.

STABLE is formulated using a linear programming framework, and its solutions are found by solving a linear-cost optimisation problem subject to linear equalities and inequalities. The base mathematical problem formulation is derived from the open-source model DIETER (DIW Berlin n.d.).

A large number of constraints were formulated to ensure the solution satisfies operational requirements, including energy demand balance, capacity limits in the generation and transmission of power, ramping limits, operating reserves, minimum stable operations, hydroelectric storage inflows, inertia requirements, storage dynamics and renewable energy targets. Other constraints describe the feasible decisions around investment in new generation, storage, system strength and transmission technologies. Specific constraints impose known projects at the time of their expected commissioning. Certain scenarios model plant sizing and utilisation to meet yearly hydrogen targets in a least-cost manner.

Model calibration and inputs

For the modelling in this initiative, STABLE optimises over a full single year at hourly time resolution (that is, 8,760 hours), using an annualised amortisation of capacity expansion capital costs. Each reference to a year is the corresponding financial year ending that year (for example, a reference to 2023 means the year from 00:00 1 July 2022 to midnight 30 June 2023). Starting from the current state of the NEM in 2019–2020, the solving of any particular year starts by using the capacity determined in the solution of the previous year, which in turn serves as the starting capacity for the optimisation model in the next year.

Primary sources for data inputs into STABLE are:

- CSIRO GenCost outputs for plant capital cost inputs (Graham et al. 2022)
- AEMO Integrated System Plan inputs and assumptions workbooks (AEMO 2022a)
- AEMO renewable profiles
- AEMO load data and internal CSIRO models and tools for half-hourly demand profiles.

Scenario definition and key assumptions

The Australian Industry ETI modelling developed three scenarios to enable exploration of transition pathways for industry in Australia, each aligned to a common global scenario. Each scenario is designed to investigate different future possibilities for Australia, and relative differences between the scenarios can provide insights to support better decision-making in the future. Our work identified several key drivers of decarbonisation of heavy industry, including domestic policy support and leadership from industry. The chosen scenarios explore the implications of these drivers.

The first scenario modelled is the 'Incremental scenario', which reflects current trends in areas such as investment, technology development and policy. This scenario results in a lack of action on emissions reductions that fails to keep Australian emissions within a 2°C carbon budget.

The 'Industry-led scenario' sees strong leadership from industry, accelerating technology deployment and abatement. In this scenario, broader domestic action across other sectors of the economy is limited which means that, while Australia stays within a carbon budget aligned to an 83 per cent chance of staying within 2°C, emissions reductions are not enough to meet a 1.5°C budget.

The 'Coordinated action scenario' is designed to inform the action needed to limit temperature rise to below 1.5°C. This scenario represents a significant stretch beyond current efforts across investment, technology development, policy and industry leadership. While this scenario would indeed be challenging to realise, it does show what is needed to achieve a least-cost transition to net zero emissions within a 1.5°C carbon budget for Australia.

Global context

The purpose of the Australian Industry ETI modelling was to investigate different future possibilities for Australian industry within a decarbonising global economy. Therefore, a common global scenario was chosen to enable the focus to be on domestic implications of the transition, simplifying the comparison between the three scenarios.

The decarbonisation of Australian industry is assumed to occur within the overarching context of a global net zero transition aligned with limiting warming to 1.5°C. The general characteristics of global analyses used to inform Australian Industry ETI modelling include:

- Global cooperation on emissions reduction and ambition consistent with limiting global warming to well below 2°C, including an equitable approach that reflects countries' different stages of economic development
- Strong action on emissions reduction in Australia's major trading partners throughout Asia
- High levels of materials and energy efficiency, electrification and behaviour change
- Strong government action including efficiency standards; market reforms; research, development and demonstration; elimination of fossil fuel subsidies; renewable fuel mandates; and direct emissions reduction regulations
- Rapid and sustained cost reductions in renewable energy technologies
- Massive growth in electric vehicle uptake, representing up to 60 per cent of new car sales globally by 2030
- Strong consumer preference for low-emissions products and implementation of emissions-based trade measures.

These characteristics help form a picture of the world within which Australian industry transitions for the purposes of Australian Industry ETI modelling. This is particularly relevant for the demand outlook for export-oriented industrial processes and global assumptions on technology cost and performance.

Core scenarios

Table 3 provides a high-level description of each modelled scenario. Further detail about the assumptions supporting these scenarios can be found below, in the 'Parameterising key features of the core scenarios' section of the report.

Table 3: Narrative description of core scenarios

Scenario	Details
Incremental	**A lack of domestic policy, other incentives and industry action leads to slow decarbonisation throughout the economy.** As a result, Australian industry is subject to carbon border adjustments and less preferential supplier status due to higher-carbon products, thus losing market share over time relative to other modelled scenarios. This scenario allows us to explore a technology-led, cost-driven transition, with limited action on climate.
Industry-led	**Domestic action on climate is in line with a very high chance of limiting global warming to 2°C, reaching net zero in 2050, but this is insufficient to meet the Paris Agreement goals. Despite this, leadership of existing heavy industry accelerates technology deployment and abatement, but significant negative emissions are needed to remain within a 1.5°C budget.** Australian industry is better able to maintain market share by supplying lower-carbon products in key export sectors, but has limited capacity to build new markets. This scenario explores opportunities for industry to demonstrate leadership and ambition on climate in a relatively unsupportive domestic context. It is primarily useful for comparison against the 'Coordinated action scenario'.
Coordinated action	**Australian industry decarbonises rapidly with substantial government incentives complementing industry leadership, driving strong abatement in all sectors in line with 1.5°C. Zero emissions technologies are widespread, with far lower negative emissions needed for a 1.5°C-compatible budget compared to other scenarios.** This scenario includes ambitious efforts to bring on new decarbonisation technologies such as green steelmaking and green hydrogen and requires substantial investment in energy systems and green industrial production. The speed and scale of the transition helps Australia establish a competitive advantage in green industries, leading to new export markets and sustained shares in existing markets. This scenario allows us to explore the impact of strong action across the entire economy, including the benefits of effective energy system integration.

Parameterising key features of the core scenarios

Scenario parameters vary in their ease of quantification and representation in the AusTIMES model architecture. For example, a numerical value for Australia's carbon budget has been developed by Climateworks Centre and is relatively straightforward to implement in the model as an additional constraint (see the 'Climate ambition - carbon budgets' section for further discussion). Other parameters are more subjective and difficult to quantify as representations of scenario issues. For example, themes such as 'government support' require the use of proxy assumptions. These could include delaying the year that a technology is available for deployment in the model in less ambitious scenarios or increasing the amount of technology that can be deployed in a given year.

Table 4 provides an overview of key drivers of the core scenarios, with a more detailed discussion on specific parameters given in the following subsections.

Table 4: Key drivers of the core scenarios

Parameter	Incremental	Industry-led	Coordinated action
Domestic climate objective – overall economy	None	2°C (83% probability)	1.5°C (67% probability)
Domestic climate objective – industry	None	1.5°C (50% probability)	Aligned with overall economy
Net zero by 2050 target	No	Yes	Yes
Technological innovation, testing, accelerated deployment	Low	Moderate	High
Government climate and energy policy	Low	Moderate	High
Government support for new industries	Low	Moderate	High
Global community's response to Australian industry's product offering	Negative	Moderate	Positive
Supporting transport sector developments, for example, vehicle-to-grid battery availability	Low	Moderate	High

Climate ambition – carbon budgets

In applying the decarbonisation implementation approach outlined earlier in 'Implementation of decarbonisation objectives in AusTIMES', carbon budgets were set for the 'Industry-led' and 'Coordinated action' scenarios. These budgets represent the total cumulative emissions allowed between 2021 and 2050 for the scenarios to remain consistent with a particular temperature outcome. The 'Incremental scenario' did not have a carbon budget.

The budgets chosen (shown in Table 5) are based on global carbon budgets in the Intergovernmental Panel on Climate Change's (IPCC) *Sixth Assessment Report* (Arias et al. 2021) and downscaled to Australia based on Australia's share of cumulative emissions in the IPCC's 1.5°C 'Sustainable Development' Illustrative Mitigation Pathway (Byers et al. 2022; Soergel et al. 2021). This share was found to be 0.78 per cent. In 'Industry-led', an Australian budget aligned to an 83 per cent chance of 2°C was chosen. In 'Coordinated action', two 1.5°C budgets were chosen. A budget aligned to a 67 per cent chance of 1.5°C was applied, with an allowance for overshoot. This means that cumulative emissions may peak above the budget but are eventually drawn back down below the budget through the use of negative emissions. While the IPCC recognises that a limited level of overshoot is likely to form part of a 1.5°C trajectory, there are risks associated with over-reliance on overshoot pathways (Rogelj et al. 2018). Therefore, alignment of the final emissions trajectory was also ensured against a budget aligned to a 50 per cent chance of 1.5°C, with no allowance for overshoot. The definition of a pre-industrial baseline was aligned to the IPCC's definition, which is the average of the period 1850–1900 (Arias et al. 2021).

Table 5: Carbon budgets for scenarios (based on Climateworks Centre analysis)

Temperature outcome	Probability	Budget ($GtCO_2e$)	Scenario mapping
1.5°C	67%	2.935	'Coordinated action' (allowing for overshoot)
1.5°C	50%	3.784	'Coordinated action' (not allowing for overshoot)
2°C	83%	7.184	'Industry-led'

An additional assumption of a specific emissions constraint for industry sectors was included in the 'Industry-led scenario' to ensure that these sectors take action beyond the rest of the economy as per the scenario narrative. This is aligned to a calculated budget for industry sectors, based on the industry energy use emissions trajectory from the IEA's *Net Zero by 2050* scenario (2021), which is aligned to a 50 per cent probability of limiting warming to 1.5°C with low or limited overshoot. The budget for the industry sector (excluding agriculture) was calculated to be 2.65 $GtCO_2e$.

Energy system assumptions

Table 6 provides an overview of energy system assumptions for each of the three scenarios modelled.

Table 6: Energy system assumption summary

<table>
<tr><th>Assumption</th><th>Incremental</th><th>Industry-led</th><th>Coordinated action</th><th>Comments</th></tr>
<tr><td>Residential and commercial small-scale solar</td><td>31 GW by 2050</td><td>42 GW by 2050</td><td>56 GW by 2050</td><td rowspan="2">Reflects customer-driven investment and system demand for renewable energy and storage. The values are designed to be broadly consistent with the medium to high ranges included in AEMO's NEM scenarios.</td></tr>
<tr><td>Residential and commercial small-scale batteries</td><td>20 GWh by 2050</td><td>26 GWh by 2030</td><td>30 GWh by 2050</td></tr>
<tr><td>Availability of advanced inverters to support system strength</td><td>2030</td><td>2026</td><td>2026</td><td>Advanced inverters reduce the need for synchronous devices and Australia's ability to deploy them will be stronger with industry and government support.</td></tr>
<tr><td>Fuel price assumptions</td><td colspan="4">Fuel price assumptions were developed by CSIRO, based on the 2022 AEMO Integrated System Plan. Details of this work are available in the Integrated System Plan – Inputs, assumptions and scenarios workbook (AEMO 2022a). The same assumptions were used across the three scenarios.</td></tr>
</table>

Road transport

Table 7 provides an overview of road transport assumptions for each of the three scenarios modelled.

Table 7: Road transport assumption summary

<table>
<tr><th>Assumption</th><th>Incremental</th><th>Industry-led</th><th>Coordinated action</th><th>Comments</th></tr>
<tr><td>Vehicle-to-grid (V2G) battery availability</td><td>5% of EVs by 2050</td><td>20% of EVs by 2050</td><td>25% of EVs by 2050</td><td>V2G reduces the need for large-scale batteries. The values are designed to be broadly consistent with the medium to high ranges included in AEMO's NEM scenarios.</td></tr>
<tr><td>Short-range electric vehicle upfront cost parity</td><td>2030</td><td>2025</td><td>2025</td><td>Assumptions are indicative of a combination of global changes in vehicle costs and manufacturing priorities and varying levels of Australian Government support or incentives to accelerate the transition to a predominantly battery-electric road transport fleet. The values are designed to be broadly consistent with the medium to high ranges included in AEMO's NEM scenarios.</td></tr>
<tr><td>New internal combustion engine (ICE) vehicles unavailable for sale</td><td>2045</td><td>2040</td><td>2035</td><td rowspan="2">Advanced inverters reduce the need for synchronous devices and Australia’s ability to deploy them will be stronger with industry and government support</td></tr>
<tr><td>ICE vehicles removed from fleet</td><td>2055</td><td>2050</td><td>2045</td></tr>
</table>

Cross-cutting technology assumptions

There are a range of assumptions relating to technology availability and uptake that are applied model-wide. Table 8 provides an overview of these technology assumptions for each of the three scenarios modelled. The general energy efficiency and electrification assumptions applied in the modelling are detailed in the following subsections.

Table 8: Cross cutting technology assumption summary

Assumption	Incremental	Industry-led	Coordinated action	Comments
Abatement technology annual build rates	Baseline	10% faster than baseline	15% faster than baseline	Assumptions are intended to represent growing ability for accelerated deployment due to enhanced coordination and investment in technology R&D. Baseline assumptions were developed following an assessment of current industrial activity and estimates of plausible technology uptake.
General discount rate	5.9%	5.9%	5.9%	Adjusted model discount rates can be a suitable proxy for various aspects of scenario narratives. In the Australian Industry ETI modelling, specific discount rates are primarily used as an additional 'hurdle' rate to represent non-cost barriers to technology deployment (e.g. access to finance, imperfect information and split incentives). This approach was informed by recent modelling undertaken by Climateworks Centre and CSIRO (Reedman et al. 2021).
Hurdle rates for energy efficiency, electrification and low carbon technologies	20%	20% (7% for industry)	7%	
Abatement technology availability	Delayed 5 years	Delayed 2 years	Aligned with estimated timelines for commercial availability	Slower initial deployment reflects more limited incentives/ambition to decarbonise in the 'Incremental scenario' and to a lesser extent in the 'Industry-led scenario'.

Model-wide energy efficiency assumptions

Energy efficiency assumptions are included in two ways in the modelling – through both autonomous and endogenous energy efficiency – with no variation between scenarios.

All sectors experience a business-as-usual energy efficiency improvement at no cost which is known as autonomous energy efficiency. The rates of efficiency gain range from 0.45–1.41 per cent per annum in residential buildings, 0.11–0.95 per cent per annum in commercial buildings, and -0.09 per cent (efficiency reduction) to 0.54 per cent per annum in industry. These are informed by long-term energy efficiency trends (CSIRO 2019; BloombergNEF 2021b; De Vita et al. 2018).

Endogenous energy efficiency refers to costed options which are implemented if they are economically attractive based on a combination of capital costs, equipment lifetime and fuel costs. The final uptake of endogenous efficiency is determined by the model and is not an input. This category largely represents technologies that are commercially available today. Examples for the buildings sector include technologies such as LED lighting, heat pump hot water systems, and improved heating, ventilation and air conditioning (HVAC) systems. In industry, this captures a range of technologies under the broad categories of process improvements, small equipment upgrades and large equipment upgrades. Detailed information on specific industry technologies investigated through the Australian Industry ETI work can be found in the 'Industrial supply chains: key activity and technology development assumptions' section of the report.

Model-wide electrification assumptions

Model-wide electrification assumptions are consistent across the three scenarios in the modelling and are included as an annual maximum share of energy use that can be switched to electricity, with an associated cost. The maximum amount of electrification varies by sector, with some sectors able to be fully electrified by 2030 and some not reaching 100 per cent by 2050.

A wide range of specific electrification technologies were investigated through the Australian Industry ETI work, detailed in the following 'Industrial supply chains: key activity and technology development assumptions' section. For end uses where specific technologies were not considered, electrification is possible through a generic set of technologies, including options for electrifying boilers, haulage, compressors and furnaces.

Activity assumptions

General activity assumptions

Activity growth rates of most industrial subsectors are based on forecasts of sectoral activity developed for the *Australian National Outlook 2019* (CSIRO 2019), drawing on results of computable general equilibrium analysis by the Centre of Policy Studies at Victoria University. Some sectors such as coal mining and gas extraction are based on assumed exports (derived from the IEA's *Net Zero by 2050* scenario (2021) and aligned with a decarbonising global economy) plus modelled domestic demand across all sectors: buildings, industry, transport, power generation and hydrogen production. Separate assumptions have been developed for the key sectors in the Australian Industry ETI work.

Output for key supply chains in Australian Industry ETI sectors

Specific activity assumptions were developed for each key sector of the Australian Industry ETI, informed by a range of sources, including BloombergNEF's *New Energy Outlook 2021* (2021b) and additional internal calculations.

Specific assumptions for each key industry sector are available in the subsections of 'Industrial supply chains: key activity and technology development assumptions'. The scenario narrative that drives these assumptions are:

- **'Incremental'** – represents declining competitiveness of Australian industry due to higher emissions
- **'Industry-led'** – represents maintained levels of industrial competitiveness
- **'Coordinated action'** – represents improved competitiveness of Australian industry due to lower emissions.

Sensitivity analyses

Table 9 provides an overview of the sensitivity analyses conducted to complement the modelling results from the three scenarios.

Table 9: Sensitivity analyses summary

Core scenario	Name	Sensitivity
'Coordinated action'	'Coordinated action with exports'	Additional green iron and electrolysis hydrogen demand
'Coordinated action'	Gas prices	Maximum (variable) ($32.00/GJ in 2022, $30.90/GJ in 2050)
		Maximum (flat) ($31.40/GJ from 2023)
		High (flat) ($20.80/GJ from 2023)
		Medium (variable) ($14.70/GJ, $14.20/GJ in 2050)
		Medium (flat) ($14.40/GJ from 2023)

'Coordinated action with exports' sensitivity analysis

The modelling includes a sensitivity analysis for 'Coordinated action' that imposes an additional 58.5 Mt of exported green iron (aligned to 50 Mt green steel in AEMO's 'Hydrogen superpower' scenario (2021), using a conversion of 1.17 Mt iron per 1 Mt steel), in addition to 18.1 Mt of hydrogen exports, in line with the 'National Hydrogen Strategy – Energy of the Future' scenario (DISER 2019). The modelling includes a requirement for 100 per cent of hydrogen exports to be produced via electrolysis post-2040, consistent with scenario narratives and limited available carbon budget. For simplicity, this sensitivity analysis does not investigate any additional energy requirements for hydrogen exports, such as for liquefaction or transformation to ammonia for shipping.

Gas price sensitivity analyses

A number of sensitivity analyses for 'Coordinated action' were tested with different NEM gas prices at a varying and a flat rate. These sensitivities allow comparisons in technology selection at different gas prices and are particularly useful to test what gas prices leads to the model phasing out CCS for supply chains such as alumina and LNG.

The prices used for 2022 were as follows:

- $32.00/GJ – highest reported gas contract tariffs for a year's supply, according to the Australian Industry Group (Fowler & Macdonald-Smith 2022)
- $21.20/GJ – highest gas price offered in April and May to C&I customers, according to the Australian Competition and Consumer Commission (2022)

- $14.70/GJ – mid-point of $21.20 and Q2 2021 average wholesale gas price, according to AEMO (2022b).

These were applied as a flat price out to 2050, and a varying price that changes in line with selected international gas price projections from Deloitte (2022). The gas prices for Western Australia and the Northern Territory were the same as the core scenario across all sensitivities.

Energy system: key cost and performance assumptions

Electricity

Electricity models are highly sensitive to technology cost assumptions. For that reason, the electricity modelling community has a strong tradition of sharing cost assumptions and, where possible, using common sources. A very detailed common source of electricity modelling data is AEMO's inputs and assumptions workbook, published around every six months. The workbook that informed our data assumptions was published in June 2022 and can be downloaded as an Excel file (see reference AEMO 2022a). An accompanying report is also available (AEMO 2021).

The AEMO workbook includes capital and operating costs for all relevant generation and storage technologies, and includes fuel costs. It also includes transmission costs for connecting renewable generation to NEM renewable energy zones and the costs of major projects to provide connections between states and between transmission zones within a state. The workbook also provides other details about the technical performance of technologies such as ramping rates, round-trip efficiency of storage, hydro power inflows, the capacity and expected retirement date of existing generation and storage and maximum renewable resources available in each renewable energy zone.

AEMO's workbook has its own scenario set specific to AEMO's needs. Given the focus of the Australian Industry ETI scenarios, in most cases we drew from AEMO's 'Step change' and 'Hydrogen superpower' scenarios, both of which represent strong climate policy action.

Besides the input and assumptions workbook, AEMO also provides historical half-hourly load information by state and half-hourly production profiles for variable renewable generation technologies in each NEM renewable energy zone.

The data available for Western Australia is less detailed. Renewable energy zones have not been defined and no production profile data is provided. Half-hourly loads and existing generation and storage capacity is available for the South West Interconnected System (SWIS), which operates in the state's south-western region. The key public document is Western Australia's *Whole of System Plan*, from which some data files have been made publicly available (Government of Western Australia 2022).

For other regions in Western Australia, we define the existing capacity and generation from other sources such as Australian Energy Council's yearbook *Electricity Gas Australia* (Australian Energy Council n.d.) and the Australian Government's *Australian Energy Statistics* (Department of Climate Change, Energy, the Environment and Water 2022). We construct a synthetic load for these areas by combining a known residential and commercial load shape (based on data from the SWIS) with a much larger flat load to reflect the higher balance of industrial load in this region.

Hydrogen

There are two key sources for hydrogen cost and technology performance information: the *GenCost 2021–22* report (Graham et al. 2022) and the *National Hydrogen Roadmap* (Bruce et al. 2018). The *National Hydrogen Roadmap* was published in 2018, and many of its assumptions have been superseded by more recent GenCost publications, which updates hydrogen technology costs each year. However, there are some assumptions for which the *Roadmap* data remains current, such as current hydrogen tank storage and compression technology costs, water consumption and cost.

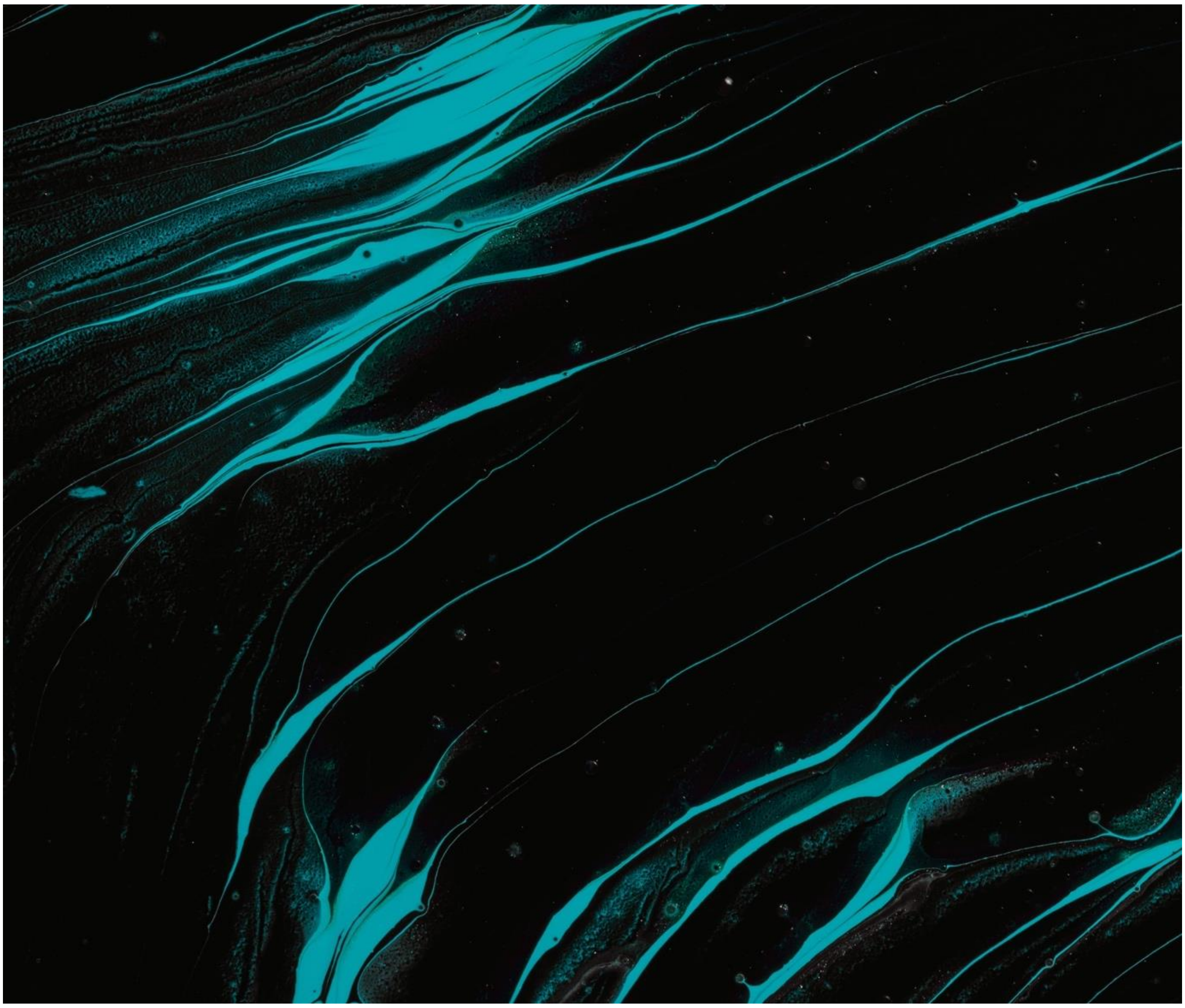
The GenCost project is a joint project of CSIRO and AEMO. Each year as part of the GenCost project, AEMO commissions an engineering firm to update the current costs of generation, storage and hydrogen technologies. This helps identify the rate of cost reductions and features of recently deployed technologies. CSIRO uses this information as an input to project future costs. Projections are provided for three scenarios, which have different levels of global climate change policy ambition. For the future cost of hydrogen electrolysers, we use the most ambitious GenCost scenario, 'Global NZE by 2050', as this is most consistent with the global settings assumed in our project. Data tables for electrolyser costs are provided in the appendix of *GenCost 2012–22* and can also be downloaded as an Excel file from CSIRO's Data Access Portal.

Bioenergy

Our model includes limits on biofuel availability due to technical constraints on biofuel production and maximum availability of feedstocks (Reedman et al. 2021). Industry sectors in the model have a bioenergy uptake limit (see Table 10) aligned with the industrial bioenergy fuel shares in the IEA's 'Net Zero Emissions' scenario (2021). However, in most industry sectors, uptake is limited and this maximum is not reached. The limited amount of bioenergy available to the model ensures that the model chooses to use it only where other options for abatement are limited.

Table 10: Maximum bioenergy uptake limits for industry sectors

	2020	2030	2050
Maximum uptake	12.5%	13.75%	15%



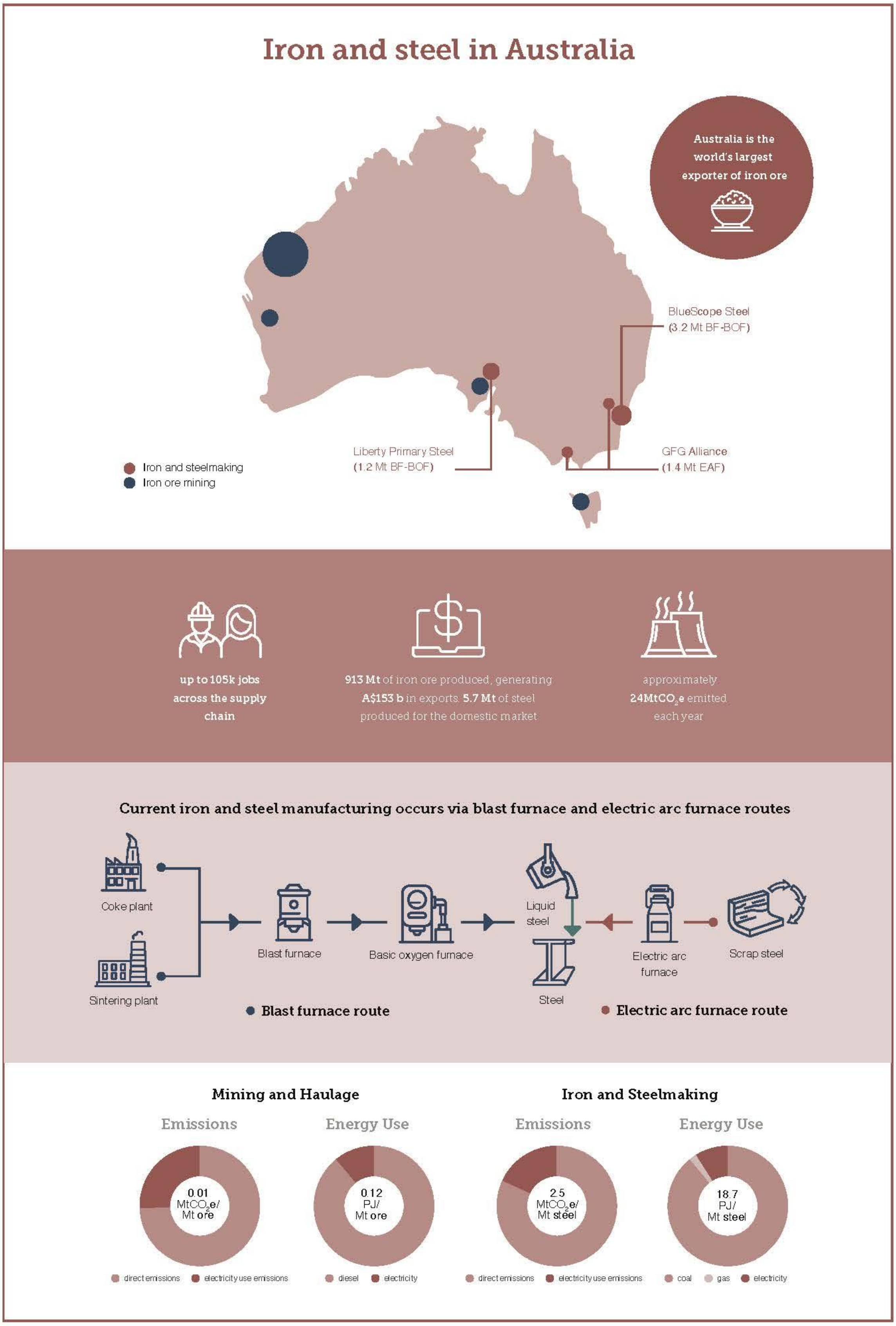
Industrial supply chains: key activity and technology development assumptions

Iron and steel

Sector overview

The iron and steel supply chain (see Figure 4) is represented in the model as two sectors: iron ore mining and haulage, and iron and steelmaking. Iron ore mining includes all mine site processes such as drilling, blasting and haulage, and any other processing of extracted ore. Steel production can be either primary or secondary, and there are a range of processes included in the model.

Figure 4: Iron and steel overview



Scenario activity assumptions

Iron ore

Production inputs draw on BloombergNEF *New Energy Outlook 2021* projections for global iron ore demand and additional assumptions regarding Australia's share of the global market (BloombergNEF 2021b).

Reduced iron ore production in the 'Incremental scenario' is driven by declining demand for primary steel in Australia's three existing major export markets: China, Japan and South Korea. This assumes that Australia is unable to seek out new export markets to offset these demand reductions (particularly significant in China's assumed outlook). Production in the 'Coordinated action scenario' is mapped to global demand for primary steel, which increases through to 2050 despite reductions in many countries. Production in 'Industry-led' is the mid-point of these two scenarios. See Figure 5 for production trajectories.

The rationale for differences between the scenarios is that greater abatement in the 'Industry-led' and 'Coordinated action' scenarios is a competitive advantage in a decarbonising world, allowing Australian industry to access other export markets in the face of other macroeconomic impacts such as peaking steel output in China.

Iron and steel

Production model inputs from 2020 to 2050 draw on BloombergNEF *New Energy Outlook 2021* projections for global steel demand and additional assumptions regarding Australia's share of the global market in line with scenario narratives.

Higher 2050 steel production in the 'Coordinated action scenario' is due to large projected growth in global demand. For the 'Incremental scenario', production is sourced directly from *New Energy Outlook 2021* which is relatively lower, representing diminished competitiveness for Australian steelmakers. Production in 'Industry-led' is the mid-point of these two scenarios. See Figure 6 for production trajectories.

The model's export sensitivity – 'Coordinated action with exports' – imposes an additional 58.5 Mt of exported green iron (aligned to 50 Mt green steel in AEMO's 'Hydrogen superpower' scenario (2021), using a conversion of 1.17 Mt iron per 1 Mt steel).

Figure 5: Iron ore production trajectory

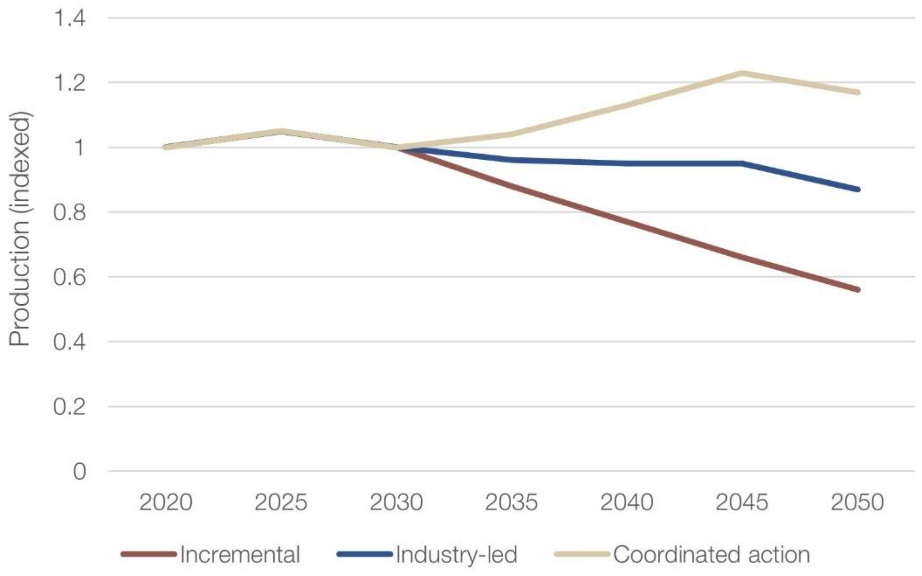
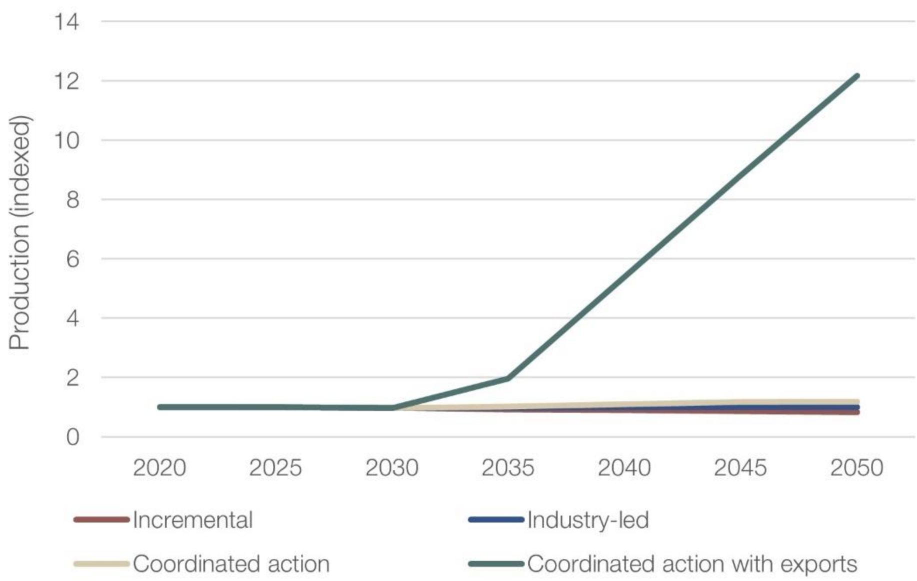
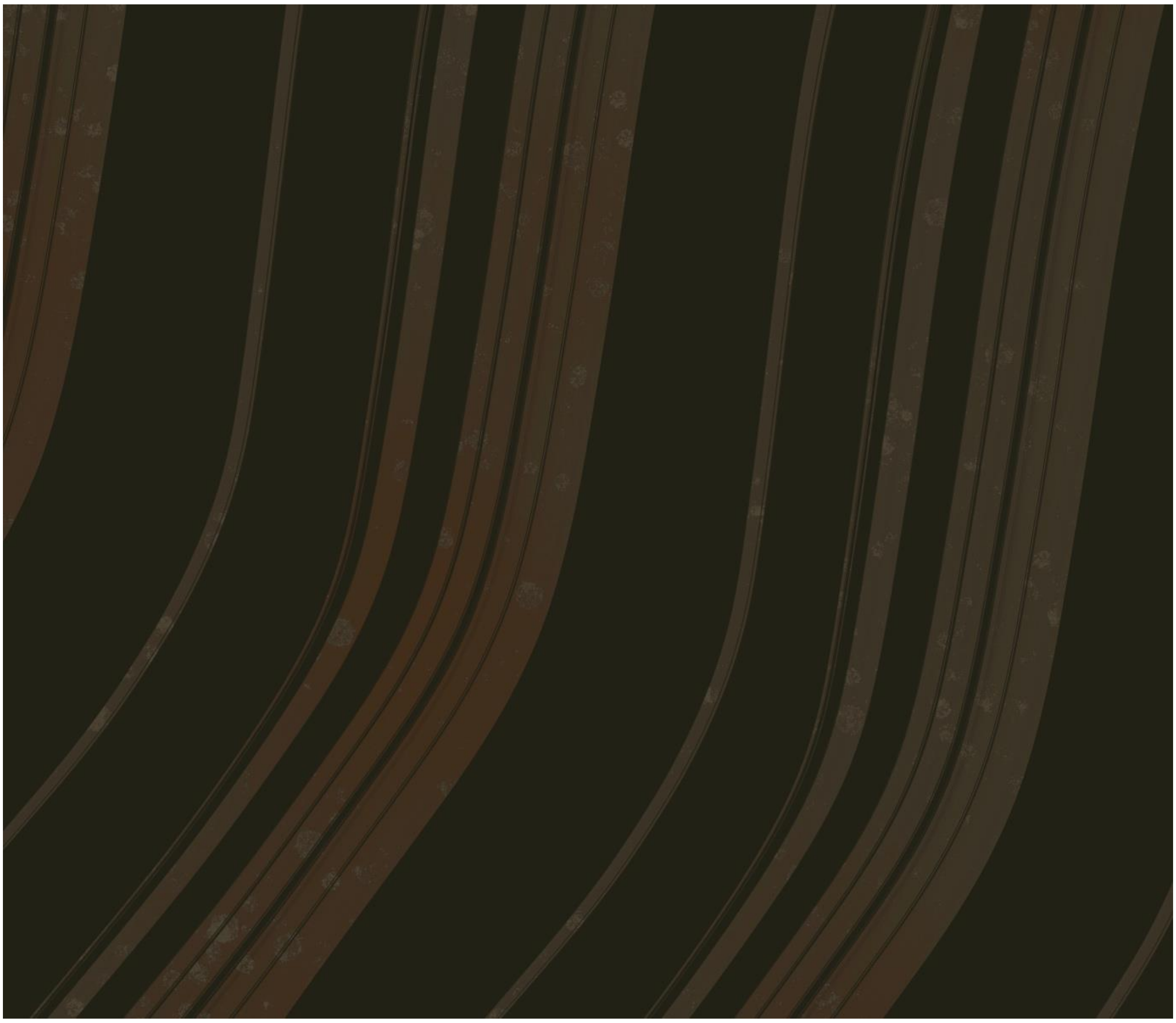


Figure 6: Iron and steel production trajectory


14
12
10
8
6
4
2
0
Production (indexed)
2020
2025
2030
2035
2040
2045
2050
Incremental
Industry-led
Coordinated action
Coordinated action with exports



Technology options and assumptions

Iron ore

Table 11 provides the technology assumptions for the supply chain. The start year listed is for the ‘Coordinated action’ scenario; ‘Industry-led’ and ‘Incremental’ have two and five-year delays applied respectively. Shaded cells show the incumbent technologies used in Australia.

Table 11: Iron ore technology assumptions

Process	Technology details	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Mine site haulage	Diesel haulage	-	7	Cost of ownership	119	118	116	$/hr	Incumbent technology	(Advisian 2021)
				Energy intensity	0.003	0.003	0.003	GJ/tonne-km		(Department of Resources, Energy and Tourism n.d.)
	Biodiesel haulage	2020	12.5	CAPEX	0.0	0.0	0.0	$M/PJ	Applicable to 67% of diesel use	
				Cost of ownership	119	118	116	$/hr		(Advisian 2021)
				Energy intensity	0.003	0.003	0.003	GJ/tonne-km		(Department of Resources, Energy and Tourism n.d.)
	Battery-electric trucks + trolley assist	2028	12.5	CAPEX	4.6	4.5	4.4	$M/vehicle	Applicable to 67% of diesel use	(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				Operations and maintenance (O&M) (not including energy use)	0.5	0.5	0.5	% CAPEX		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				Energy intensity	0.0013	0.0013	0.0012	GJ/tonne-km		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)

	Fuel cell electric trucks	2028	12.5	CAPEX	5.1	4.8	4.3	$/vehicle	Applicable to 67% of diesel use	(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				O&M (not including energy use)	0.4	0.4	0.3	% CAPEX		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				Energy intensity	0.0035	0.0033	0.0029	GJ/tonne-km		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
Other mine site equipment	Electrification			Maximum potential	-	100	100	% of fuel demand	Applicable to 33% of diesel use	(Madeddu et al. 2020)
	Energy efficiency			Energy efficiency potential	-	3	7	% of each type of fuel use		Based on previous Climateworks Centre industry analysis

Iron and steel production

Table 12 provides the technology assumptions for the supply chain. The start year listed is for the 'Coordinated action' scenario; 'Industry-led' and 'Incremental' have two and five-year delays applied respectively. These steel production technologies were selected to provide a range of options for the model. Technology selection was based on availability of information (there was insufficient information available to allow inclusion of some emerging technologies in the modelling) and discussions with industry partners. Shaded cells show the incumbent technologies used in Australia.

Table 12: Iron and steel technology assumptions

Process	Technology	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Primary steelmaking	Blast furnace - basic oxygen furnace (BF-BOF)	-	25	CAPEX	775	775	775	$/t steel	Incumbent technology	(International Energy Agency 2020a)
				OPEX	178	178	178	$/t steel		(International Energy Agency 2020a)
				Energy intensity	24.1	23.2	21.4	GJ/t steel		Partner feedback and (GFG Alliance 2018)

	BF-BOF with carbon capture and storage (CCS)	2030	25	Additional cost	150	140	100	$/tCO_2$	Premium of $80/$tCO_2$ applied to states with limited access to storage (NSW, SA)	Assumptions based on research from (BloombergNEF 2021c) and (International Energy Agency 2020b)
				Additional energy intensity	3.0	2.8	2.6	GJ/t steel		Assumptions based on research from (BloombergNEF 2021c)
				Emissions reduction potential	-47%	-47%	-47%	% reduction in BF-BOF emissions		(Fan & Friedmann 2021)
	BF-BOF with biochar or hydrogen injection	2025	-	Additional CAPEX	23	23	23	$/t steel	Applicable to 20% of sector energy use	(De Santis et al. 2021)
				Assume no additional OPEX or energy required vs BF-BOF (excluding fuel input costs).						
	BF-BOF with best available technologies and optimisation	2020	25	Additional CAPEX	293	293	293	$/t steel	Applicable to 25% of sector energy use	(Dialogue on European Decarbonisation Strategies 2020)
				OPEX	0	0	0	$/t steel		(Ghenda & Lüngen 2013)
				Energy efficiency potential	-25%	-25%	-25%	% change in energy use vs BF-BOF		(Dialogue on European Decarbonisation Strategies 2020)
	Gas direct reduced iron and electric arc furnace (Gas-DRI-EAF)	2022	25	CAPEX	1103	1103	1103	$/t steel	Four-year lead time included for new build. Applicable to 100% of sector energy use	(Mission Possible Partnership 2022a)
				OPEX	190	190	190	$/t steel		(International Energy Agency 2020a)
				Energy intensity	16.4	16.4	16.4	GJ/t steel		(Mission Possible Partnership 2022a)

	Gas-DRI-EAF with CCS	2030	25	Additional cost	200	130	80	$/tCO_2$	Premium of $80/tCO_2$ applied to states with limited access to storage (NSW, SA)	Assumptions based on research from (BloombergNEF 2021c) and (International Energy Agency 2020b)
				Additional energy intensity	1.9	1.8	1.7	GJ/t steel		Assumptions based on research from (BloombergNEF 2021c)
				Emissions reduction potential	-27%	-27%	-27%	% reduction in gas-DRI-EAF emissions		(Fan & Friedmann 2021)
	Hydrogen direct reduced iron and electric arc furnace (H_2-DRI-EAF)	2030	25	CAPEX	1103	1103	1103	$/t steel	Applicable to 100% of sector energy use, fuel cost not included here	(Mission Possible Partnership 2022a)
				OPEX	190	190	190	$/t steel		(International Energy Agency 2020a)
				Energy intensity	15.2	15.2	15.2	GJ/t steel		(Mission Possible Partnership 2022a)
	Biomethane-DRI-EAF	2030	25	Assume same inputs as NG-DRI-EAF. No additional CAPEX, OPEX or energy required (excluding input fuel costs).					Applicable to 100% of sector energy use	
	DRI-Melter-BOF	2028	25	CAPEX	953	953	953	$/tCO_2$	Applicable to 100% of sector energy use, can be fuelled using either gas or hydrogen, fuel costs not included here	(Mission Possible Partnership 2022a)
				OPEX	190	190	190	$/t steel		(International Energy Agency 2020a)
				Energy intensity	14.3	14.3	14.3	GJ/t steel		(Mission Possible Partnership 2022a)
	Electrolytic steel production	2040	25	CAPEX	1121	1100	1046	$/t steel	Applicable to 100% of sector energy use	(Mission Possible Partnership 2022a)
				OPEX	184	184	184	$/t steel		(International Energy Agency 2020a)
				Energy intensity	11.2	11.2	11.2	GJ/t steel		(Mission Possible Partnership 2022a)

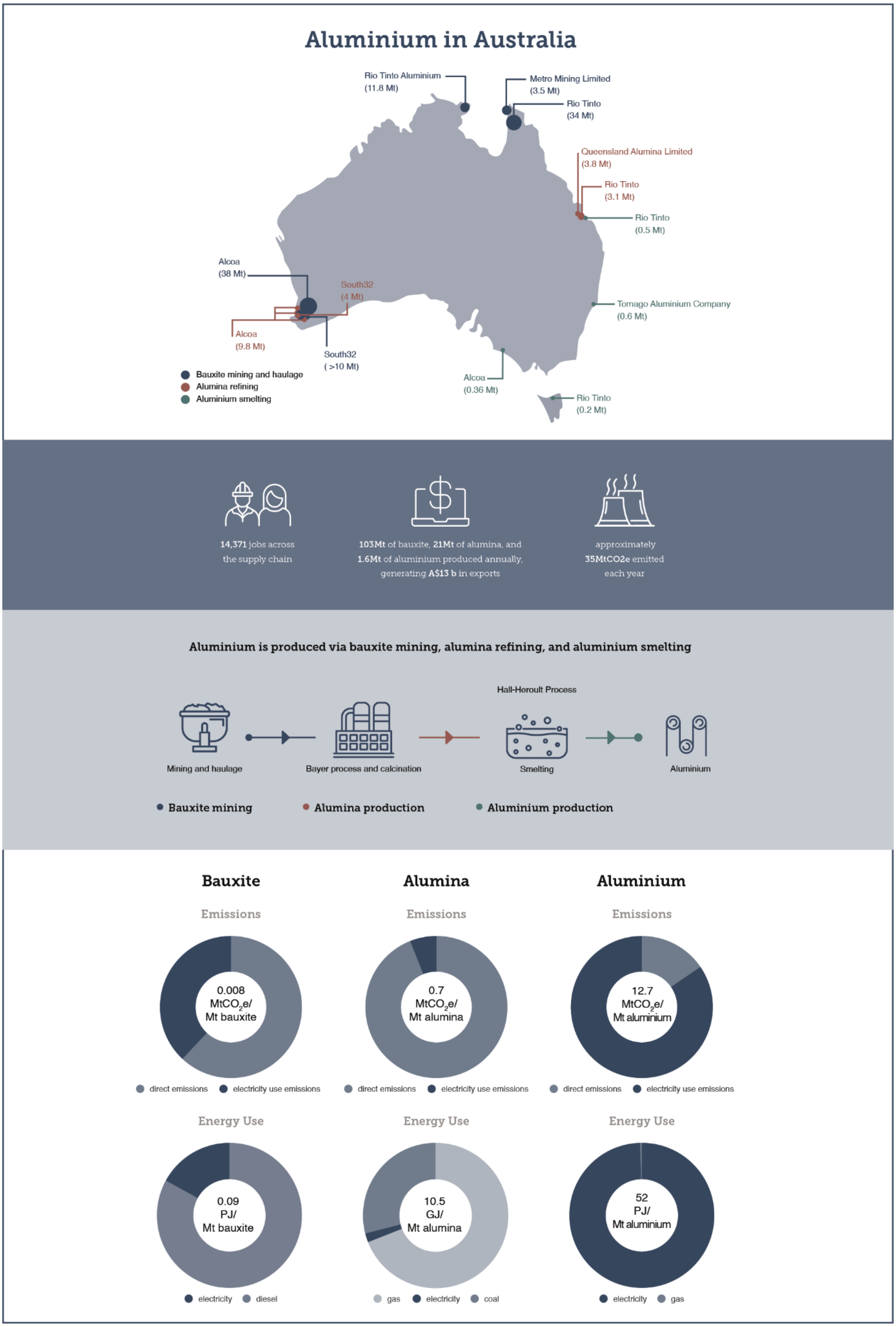
Secondary steelmaking	Scrap-based EAF	2020	25	CAPEX	378	378	378	$/t steel	Limited to 35% of national steel production. Also contributes 100% of production in Vic, scaled to follow BloombergNEF secondary steel production trajectory in NSW	(Mission Possible Partnership 2022a)
				OPEX	848	848	848	$/t steel		(Dialogue on European Decarbonisation Strategies 2020)
				Energy intensity	2.1	2.0	1.9	GJ/t steel		Assumptions based on research from (BloombergNEF 2021c)

Aluminium

Sector overview

The aluminium supply chain is represented in the modelling through three sectors: bauxite mining, alumina refining and aluminium smelting (see Figure 7). Bauxite is mined and processed to produce alumina, with approximately 65 per cent of Australia's bauxite processed domestically (Office of the Chief Economist 2022). Alumina is used to produce aluminium, with most Australian alumina being exported. Aluminium is produced in smelters (primary production) or by recycling (secondary production). Most of Australia's aluminium is exported, with a small amount used to supply domestic manufacturing needs (Office of the Chief Economist 2022; BloombergNEF 2021b).

Figure 7: Aluminium overview



Scenario activity assumptions

Bauxite

Production trajectories across the scenarios are based on both domestic demand and export demand. For all scenarios, the domestic bauxite trajectory is based on Australia's domestic primary aluminium demand from BloombergNEF *New Energy Outlook 2021* projections (2021b). The export demand in the 'Incremental scenario' is based on *New Energy Outlook 2021* projections of primary aluminium demand for China, whereas the 'Coordinated action scenario' trajectory uses the global growth in primary aluminium demand to represent increased market share due to decarbonisation of the industry. Production in 'Industry-led' is the mid-point of these two scenarios. See Figure 8 for production trajectories.

Alumina

Production model inputs from 2020 to 2050 draw on BloombergNEF *New Energy Outlook 2021* projections for global aluminium demand and additional assumptions regarding Australia's share of the global market in line with scenario narratives.

Greater increases in alumina production in 'Coordinated action' are due to large projected growth in primary aluminium demand specifically in Australia's current alumina export markets (e.g. United Arab Emirates, South Africa, China, India). For 'Incremental', growth is the same as 'Coordinated action' until 2030, and then is based on the outlook for global primary aluminium demand which is comparatively lower due to significant shifts towards secondary production, which is intended to represent diminished competitiveness. Production in 'Industry-led' is the mid-point of these two scenarios. See Figure 9 for production trajectories.

Aluminium

Production inputs from 2020 to 2050 draw on BloombergNEF *New Energy Outlook 2021* projections for global aluminium demand and additional assumptions regarding Australia's share of the global market.

All scenarios follow a common growth forecast to 2030, informed by the Australian forecast in *New Energy Outlook 2021*. This business-as-usual forecast continues to 2050 in 'Incremental', and Australian production grows slightly but loses global market share. Production accelerates in 'Coordinated action' due to Australia retaining its current market share of aluminium, which is higher than the *New Energy Outlook 2021* forecast. 'Industry-led' is the mid-point of the business-as-usual trajectory and the accelerated production trajectory. See Figure 10 for production trajectories.

Figure 8: Bauxite production trajectory

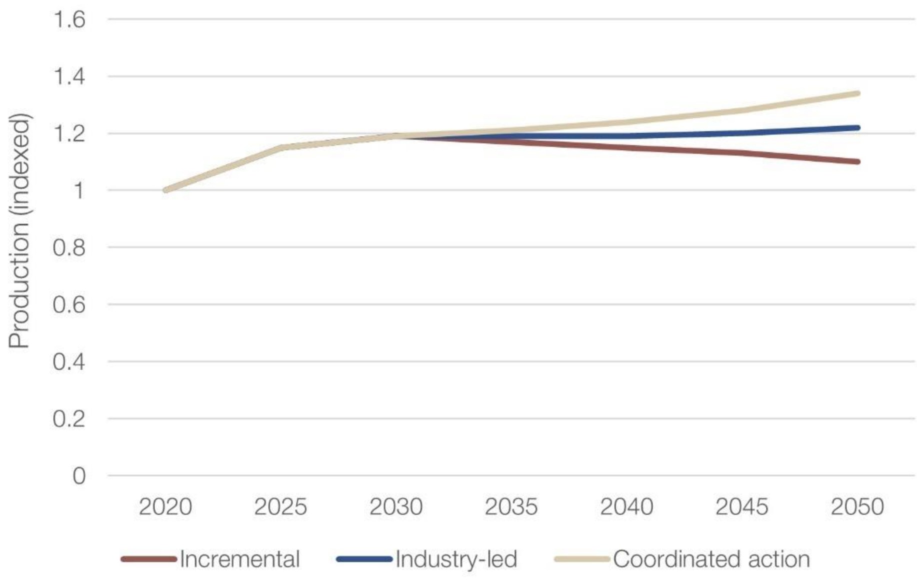


Figure 9: Alumina production trajectory

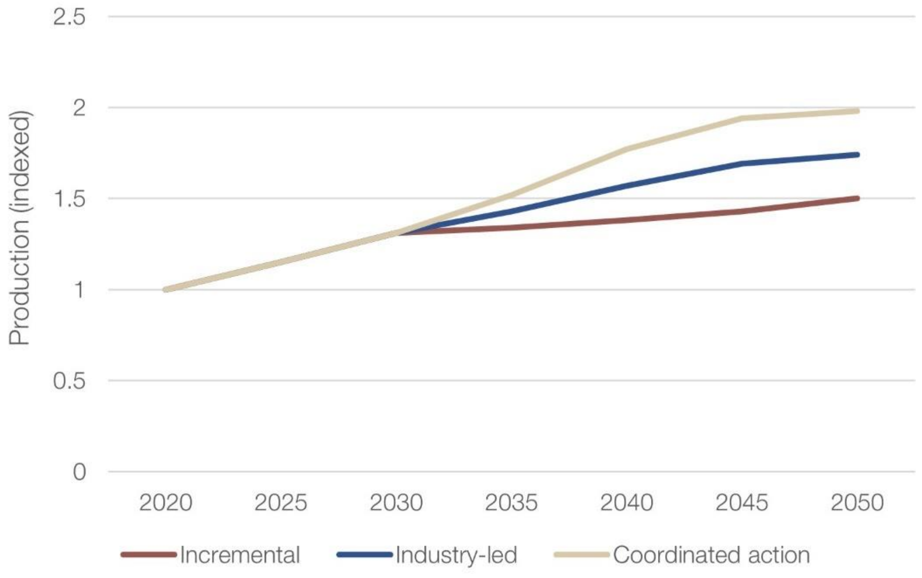
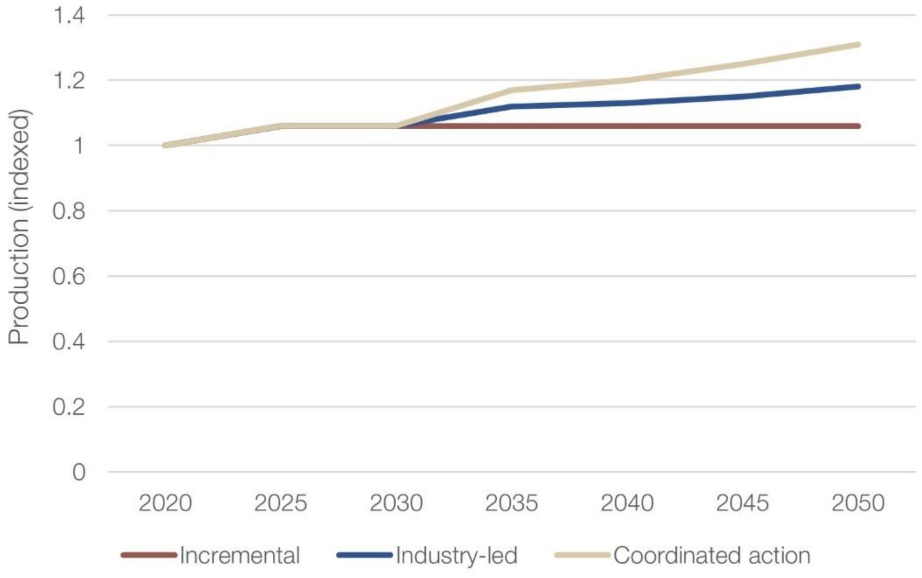


Figure 10: Aluminium production trajectory



Technology options and assumptions

Bauxite

Technology options for bauxite match those used for iron ore (see 'Iron ore').

Alumina

Table 13 provides the technology assumptions for the supply chain. The start year listed is for the 'Coordinated action' scenario; 'Industry-led' and 'Incremental' have two and five-year delays applied respectively. Shaded cells show the incumbent technologies used in Australia.

Recent publications such as the *Roadmap for Decarbonising Australian Alumina Refining* (ARENA 2022) and *MVR Retrofit and Commercialisation Report* (Chatfield 2022) also investigate options for decarbonising alumina refining. Some of the conclusions from these reports vary from what was found in this work, as differing methodologies and assumptions have been used for each. These differences highlight the uncertainty in the future technology pathway for this sector and make it clear that further pilots and demonstrations are vital to understand the optimum decarbonisation pathway.

One of the key differences between the *MVR Retrofit and Commercialisation Report* capital costs and the costs quoted in the *Pathways to industrial decarbonisation* report is the capacity being upgraded – Alcoa estimates the cost to upgrade current capacity ($4.5B), whereas the Australian Industry ETI work covers a cumulative cost for double the current capacity ($16.4B out to 2050).

In addition, the upgrade cost estimate (per tonne of alumina) for the Australian Industry ETI work is 34 per cent higher than the Alcoa work, another reason for the differences between the overall calculated costs. The ETI cost estimate was for a general application of MVR, which has led to a more conservative estimate.

Table 13: Alumina technology assumptions

Process	Technology	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Steam input for digestion	Gas driven boilers	-	25	CAPEX	0.085	0.069	0.069	$M/MWth	Incumbent technology	(The Danish Energy Agency 2021)
				OPEX	0.013	0.010	0.010	$M/MWth		(Nieuwlaar et al. 2016)
				Energy intensity	1.1	1.1	1.0	PJ input/PJ steam		(van Dam et al. 2021)

	Mechanical vapour recompression	2025	25	Additional CAPEX	0.540	0.509	0.478	$M/MWth	Applicable to 63.65% of sector energy use	(The Danish Energy Agency 2021)
				OPEX	0.013	0.013	0.012	$M/MWth		(Marsidi 2018)
				Energy intensity	0.2-0.5	0.2-0.5	0.2-0.5	PJ input/ PJ steam		(Marsidi 2018)
	Electric boilers	2020	25	CAPEX	0.12	0.11	0.11	$M/MWth	Applicable to 67% of sector energy use	(The Danish Energy Agency 2021)
				OPEX	0.02	0.02	0.02	$M/MWth		(Australian Renewable Energy Agency 2019) and (Kerttu 2019)
				Energy intensity	1.0	1.0	0.9	PJ input/ PJ steam		(van Dam et al. 2021)
	Biomass boilers	2020	25	CAPEX	0.96	0.91	0.83	$M/MWth	Applicable to 67% of sector energy use	(The Danish Energy Agency 2021)
				OPEX	0.143	0.14	0.12	$M/MWth		(van Dam et al. 2021)
				Energy intensity	1.1	1.1	1.0	PJ input/ PJ steam		(van Dam et al. 2021)
	Hydrogen boilers	2030	25	CAPEX	0.17	0.17	0.17	$M/MWth	Applicable to 67% of sector energy use	(van Dam et al. 2021)
				OPEX	0.03	0.03	0.03	$M/MWth		(van Dam et al. 2021)
				Energy intensity	1.2	1.1	1.0	PJ input/ PJ steam		(van Dam et al. 2021)
Digestion	Conventional digestion	-	25	CAPEX	861	861	861	$/t alumina	Incumbent technology	(ter Weer 2016)
				OPEX	21	21	21	$/t alumina		(ter Weer 2016)
				Energy intensity	8.1	7.8	7.2	GJ/t alumina		(Chan et al. 2019) and (Department of the Environment and Energy 2017)
	Tube digestion	2020	25	CAPEX	1781	1781	1781	$/t alumina		(Scarsella et al. 2016)

				OPEX	36	36	36	$/t alumina	Applicable to 67% of sector energy use	
				Energy intensity	6.9	6.6	6.1	GJ/t alumina		(Chan et al. 2019) and (Department of the Environment and Energy 2017)
Calcination	Conventional calcination (fluidised bed)	-	25	CAPEX	95	95	95	$/t alumina	Incumbent technology	(Perander et al. 2018)
				OPEX	96	96	96	$/t alumina		(Perander et al. 2018)
				Energy intensity	3.4	3.3	3.0	GJ/t alumina		(Australian Aluminium Council 2021)
	Electric calcination	2030	25	Cost	87	87	87	$/t alumina	Applicable to 33% of sector energy use	(Mission Possible Partnership 2022b)
				Energy intensity	3.4	3.3	3.0	GJ/t alumina		Assumed same as conventional calcination
	Hydrogen calcination	2025	25	Retrofit cost	17	17	17	$/t alumina	Applicable to 33% of sector energy use	Assumptions based on research from (BloombergNEF 2021a)
				Energy intensity	3.4	3.3	3.0	GJ/t alumina		Assumed same as conventional calcination
CCS	Post combustion CCS	2030	25	Additional cost	156.0	135.8	95.4	$/t$CO_2$e	Can capture up to 90% of all fossil fuel emissions in alumina	Assumptions based on research from (BloombergNEF 2021a) and (BloombergNEF 2020), (Allinson et al. 2009)
				Energy intensity	1.4	1.4	1.4	GJ/t alumina		Assumptions based on research from (BloombergNEF 2021a) and (BloombergNEF 2020)

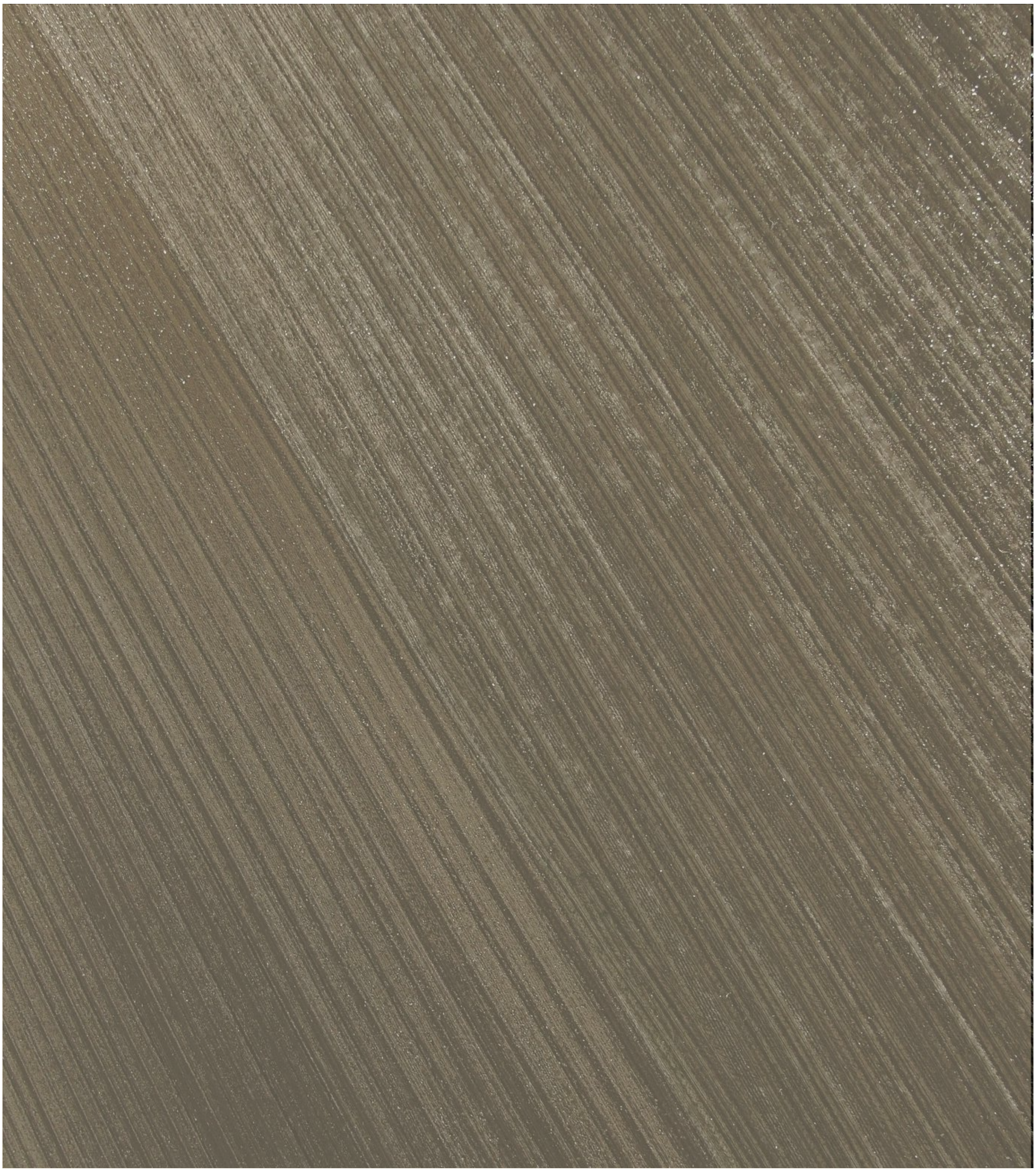
Aluminium

Table 14 provides the technology assumptions for the supply chain. The start year listed is for the 'Coordinated action' scenario; 'Industry-led' and 'Incremental' have two and five-year delays applied respectively. Shaded cells show the incumbent technologies used in Australia.

Table 14: Aluminium technology assumptions

Process	Technology	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Aluminium	Smelting	-	25	CAPEX	5486	5486	5486	\$/t aluminium	(incumbent technology)	Assumptions based on research from (BloombergNEF 2021a)
				OPEX	1226	1226	1226	\$/t aluminium		Assumptions based on research from (BloombergNEF 2021a)
				Energy intensity	52	50	46	GJ/t aluminium		(Australian Aluminium Council 2021)
				Emission intensity	12.69	12.69	12.69	tCO_2e/t aluminium		(Australian Aluminium Council 2021)
	Carbon anodes	-	25	CAPEX	0	0	0	\$/t aluminium	(incumbent technology) Assumption that anodes are purchased, not manufactured on site	
				OPEX	258	258	258	\$/t aluminium		Assumptions based on research from (BloombergNEF 2021a)
				Non-energy emissions intensity	1.8	1.8	1.6	tCO_2e/t aluminium		(Australian Aluminium Council 2021)
	Inert anodes	2030	25	CAPEX	3017	3017	3017	\$/t aluminium		Assumptions based on research from (BloombergNEF 2021a)

				OPEX	-184	-184	-184	$/t aluminium	Note: Assumed same energy intensity as current primary production	Assumptions based on research from (BloombergNEF 2021a)
				Energy intensity	52	50	46	GJ/t aluminium		Assumptions based on research from (BloombergNEF 2021a)
				Process emissions reduction potential	-100%	-100%	-100%	% reduction in aluminium process emissions		
	Secondary production	2025	25	Cost (LCOA)	1967	1966	1963	$/t aluminium	Applicable to up to 100% of sector energy use, reduces energy use by ~95%. Limited to 7% of total aluminium production	Assumptions based on research from (BloombergNEF 2021a)
				Energy intensity	4.8	4.6	4.3	GJ/t aluminium		Assumptions based on research from (BloombergNEF 2021a)

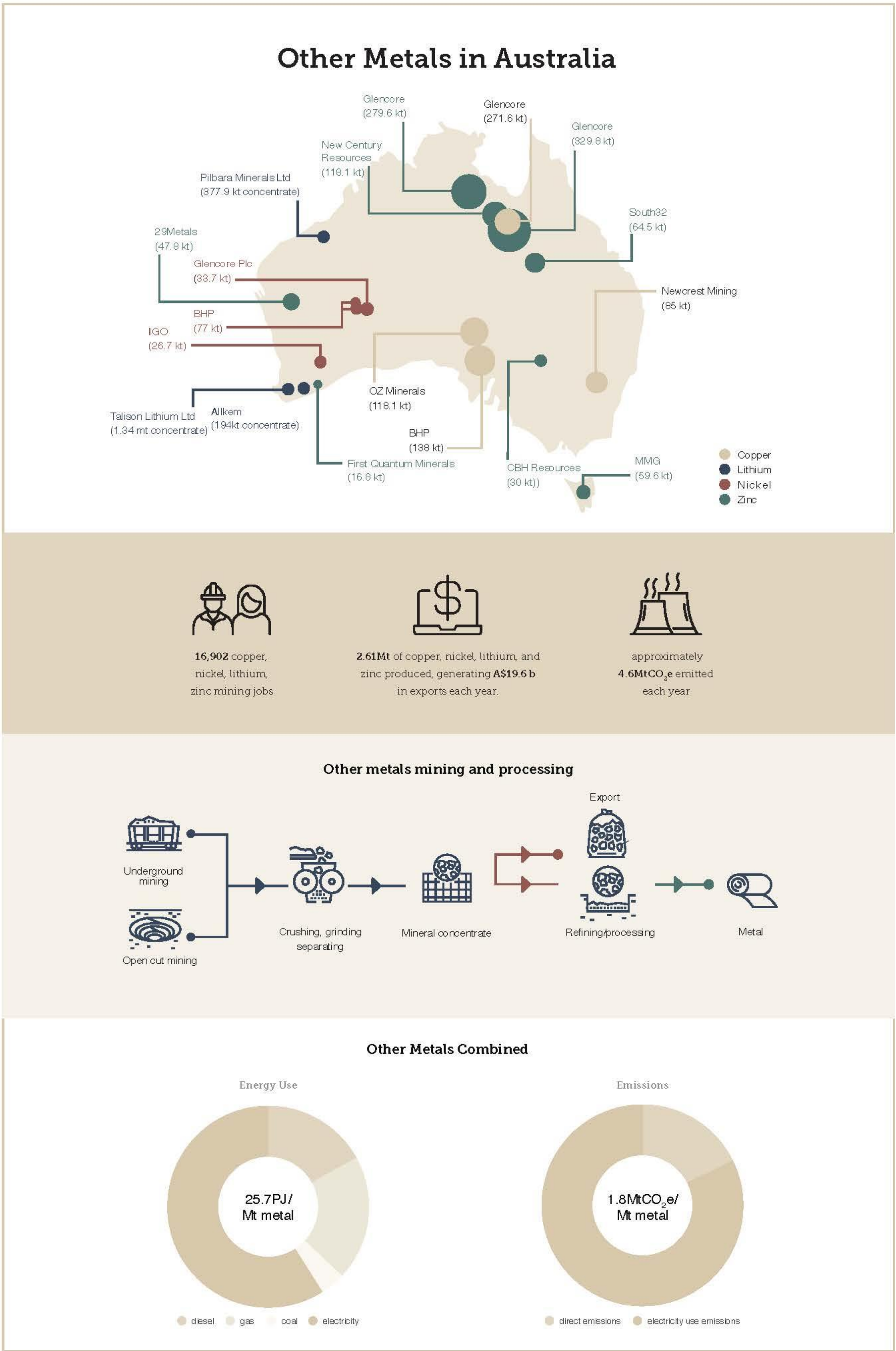


Other metals

Sector overview

The other metals supply chain is represented in the modelling as copper, lithium, nickel and zinc sectors (see Figure 11). Due to the relative size of these sectors, the mining and processing activities have been grouped in the model. The specific processes used include open-cut and underground mining, beneficiation and comminution as well as further processing and refining. The significant variance in processing requirements between mine sites, deposit types and ore grades have required some simplification in the model representation, and average assumptions have been used.

Figure 11: Other metals overview



Scenario activity assumptions

Production inputs draw on BloombergNEF *New Energy Outlook 2021* projections (2021b) for global metals demand and additional assumptions regarding Australia's share of the global market.

Activity in 'Coordinated action' assumes that the demand for Australian copper, lithium, nickel and zinc grows in line with the global market. The upper bounds of estimated production for copper, lithium, nickel and zinc are broadly aligned to the International Monetary Fund's *World Economic Outlook 2021* (2021).

Activity is equal in all scenarios until 2030, after which the 'Incremental' trajectory is aligned to scenario variations calculated for the aluminium supply chain (i.e. differences between 'Incremental' and 'Coordinated action' in that supply chain). Activity for 'Industry-led' is the mid-point of these two scenarios.

The rationale for the differing approach is that greater abatement in the 'Coordinated action' and 'Industry-led' scenarios is a competitive advantage in a decarbonising world. For example, 'clean nickel' could be highly desirable for electric vehicle batteries (Azevedo et al. 2020). This adjusted methodology was followed due to limited available data compared to the aluminium and iron and steel supply chains, and it draws on specific metals analysis from BloombergNEF.

See Figures 12 through 15 for production trajectories.

Figure 12: Copper production trajectory

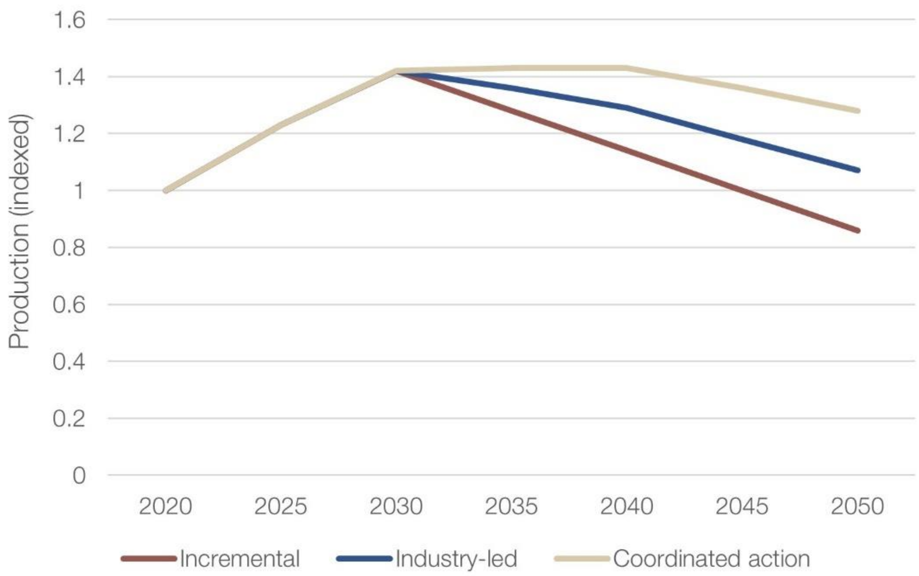


Figure 13: Lithium production trajectory

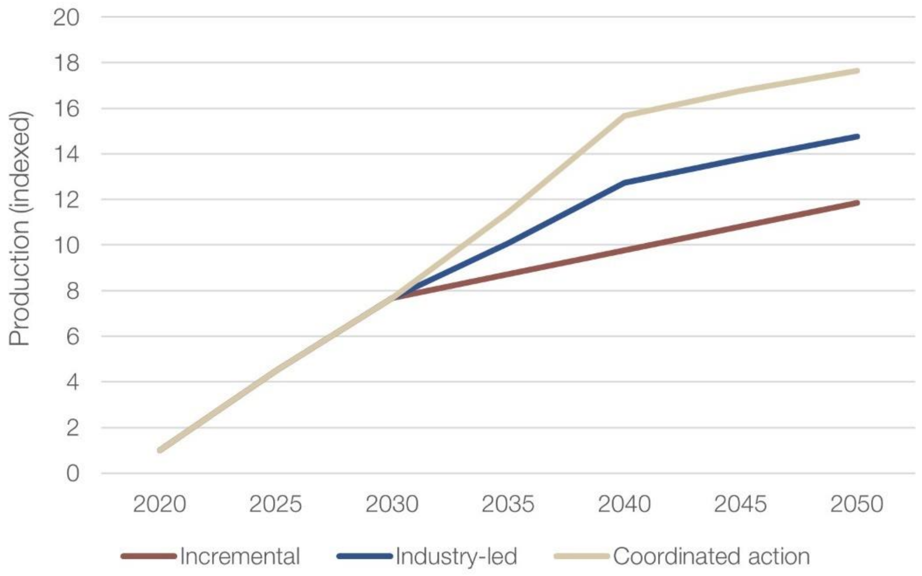


Figure 14: Nickel production trajectory

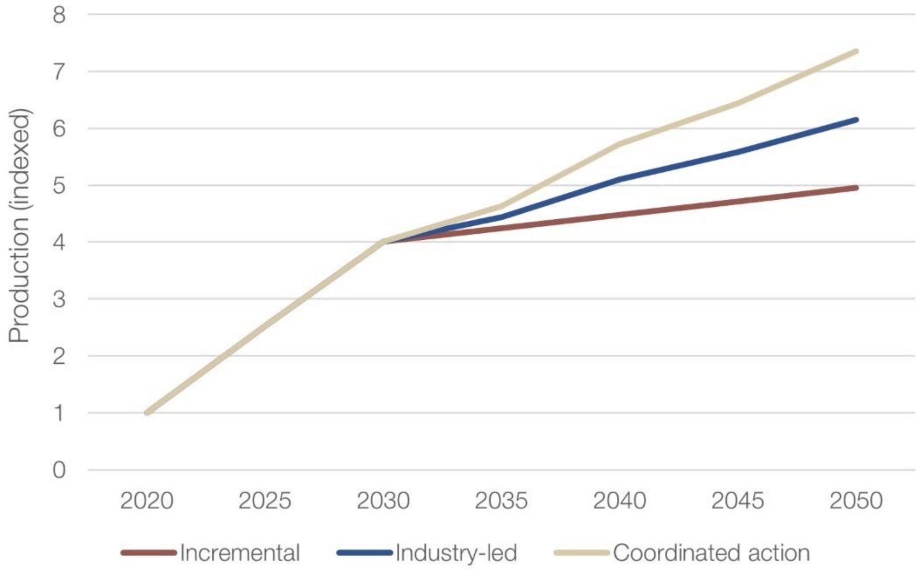
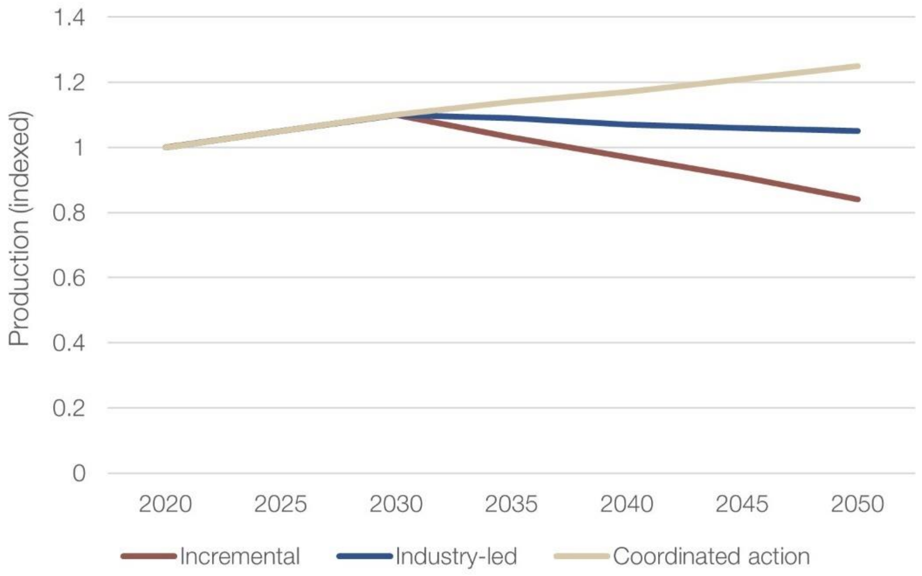


Figure 15: Zinc production trajectory



Technology options and assumptions

Copper, lithium, nickel and zinc

Table 15 provides the technology assumptions for the supply chain. The start year listed is for the 'Coordinated action' scenario; 'Industry-led' and 'Incremental' have two and five-year delays applied respectively. Shaded cells show the incumbent technologies used in Australia.

Table 15: Other metals technology assumptions

Process	Technology details	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Mine site haulage	Diesel haulage	-	7	Cost of ownership	119	118	116	$/hr	Incumbent technology	(Advisian 2021)
				Energy intensity	0.003	0.003	0.003	GJ/tonne-km		(Department of Resources, Energy and Tourism n.d.)
	Biodiesel haulage	2020	12.5	CAPEX	0.0	0.0	0.0	$M/PJ	Applicable to 67% of diesel use	
				Cost of ownership	119	118	116	$/hr		(Advisian 2021)
				Energy intensity	0.003	0.003	0.003	GJ/tonne-km		(Department of Resources, Energy and Tourism n.d.)
	Battery-electric trucks + trolley assist	2028	12.5	CAPEX	4.6	4.5	4.4	$M/vehicle	Applicable to 67% of diesel use	(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				O&M (not including energy use)	0.5	0.5	0.5	% CAPEX		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				Energy intensity	0.0013	0.0013	0.0012	GJ/tonne-km		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)

	Fuel cell electric trucks	2028	12.5	CAPEX	5.1	4.8	4.3	$/vehicle	Applicable to 67% of diesel use	(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				O&M (not including energy use)	0.4	0.4	0.3	% CAPEX		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
				Energy intensity	0.0035	0.0033	0.0029	GJ/tonne-km		(Advisian 2021) and (Department of Resources, Energy and Tourism n.d.)
Other mine site equipment	Electrification	2020	1	Maximum potential	-	100	100	% of fuel demand	Applicable to 33% of diesel use	(Madeddu et al. 2020)
	Energy efficiency	2020	1	Energy efficiency potential	-	3	7	% of each type of fuel use		Based on previous Climateworks Centre industry analysis
Other	Mineral carbonation	2030	1	Cost	136	136	136	$/t$CO_2$e	Applicable to nickel mining only	(Li & Hitch 2018)

Chemicals

Sector overview

The chemicals supply chain is represented in the modelling through three subsectors: ammonia, commercial explosives and fertilisers (see Figure 16). In the ammonia subsector, production is initially assumed to be through steam methane reforming, though the production method changes over the modelling timeframe. The commercial explosives subsector includes nitric acid and ammonium nitrate production. The fertilisers subsector includes nitrogen-based fertilisers only, with assumptions based on the urea production process.

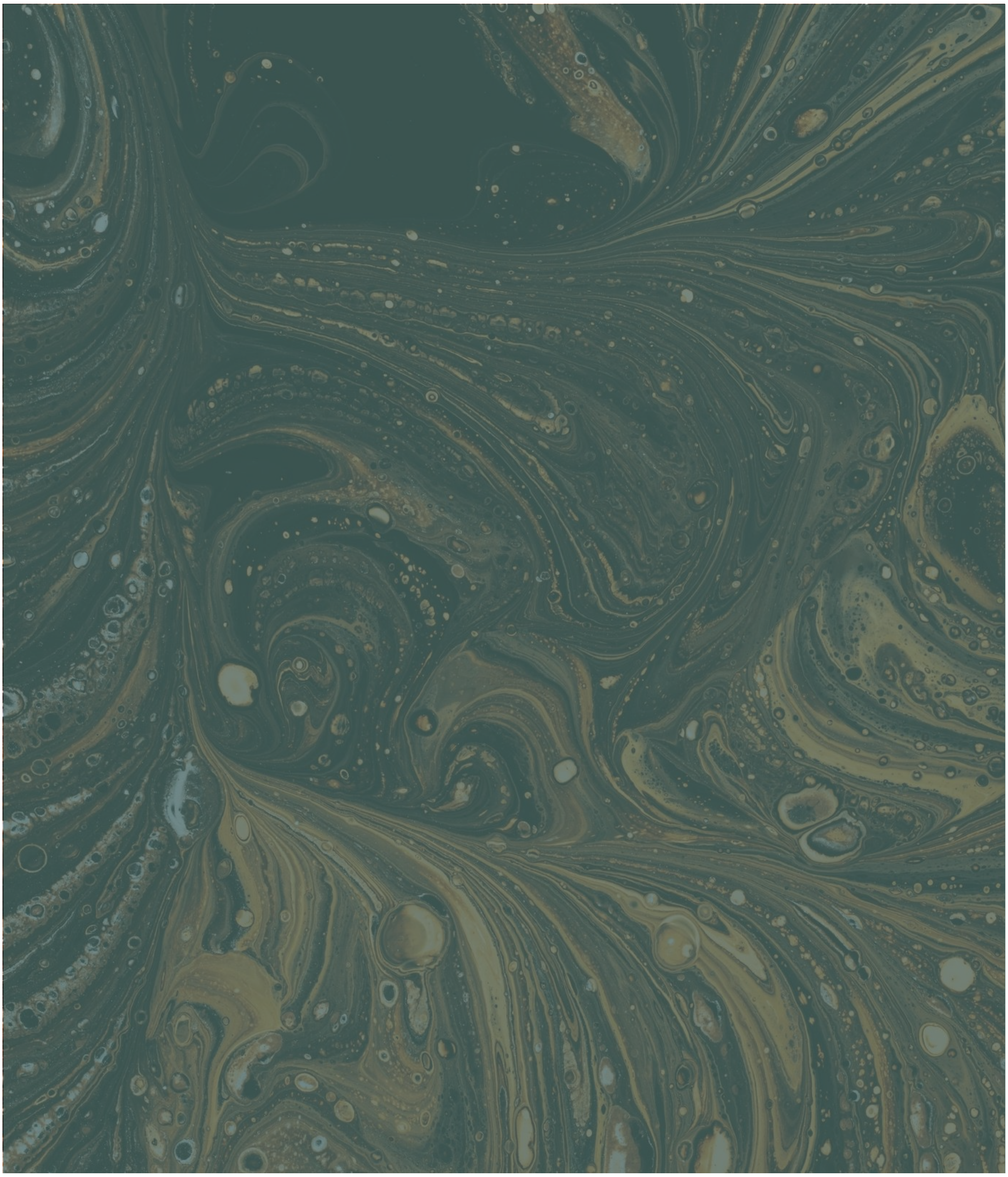
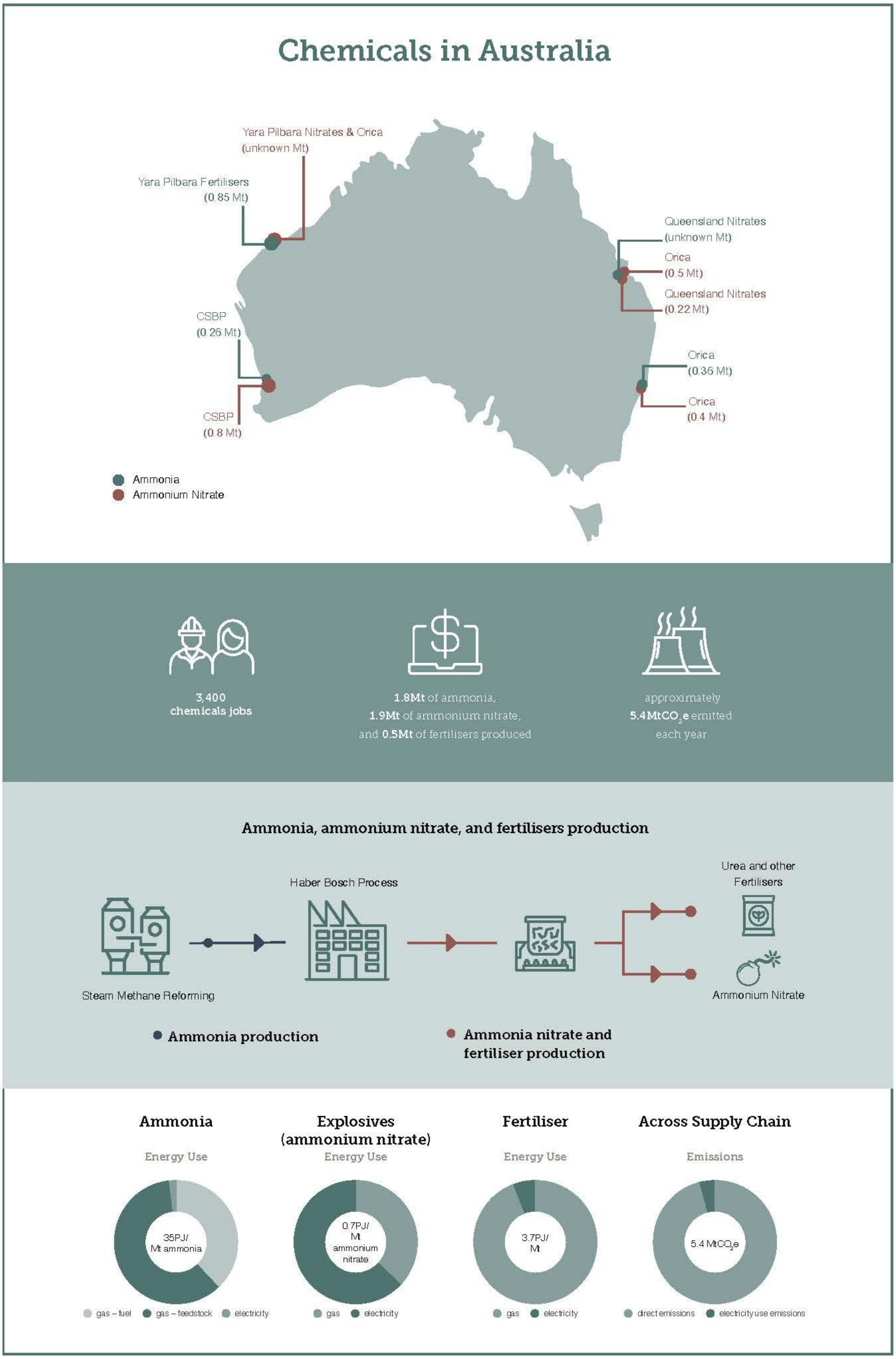


Figure 16: Chemicals overview



Scenario activity assumptions

Ammonia

Imposed model inputs for demand from 2020 to 2050 are based on historical global ammonia demand growth and additional assumptions regarding Australia's share of the global market, following scenario narratives.

The assumption for 'Coordinated action' is that Australia maintains current global market share, with demand growing at a rate of 2 per cent per annum. For 'Incremental', demand is assumed to stay flat from 2030. Production in 'Industry-led' is the mid-point of these two scenarios. See Figure 17 for production trajectories.

The modelling approach does not include the potential role of ammonia in a hydrogen export market. This means that the demand profiles do not include ammonia being used as a carrier for energy exports.

Explosives and fertilisers

Demand was assumed to be flat for explosives due to limited published information on potential demand. Fertilisers demand growth follows the growth of the other chemicals sector in *Australian National Outlook* modelling (CSIRO 2019).

For explosives, a shift away from coal as an energy source (which is a large consumer of explosives) could offset the increased explosive use required for more difficult-to-reach mineral deposits that will need to be accessed in the future.

See Figures 18 and 19 for production trajectories.

Figure 17: Ammonia production trajectory

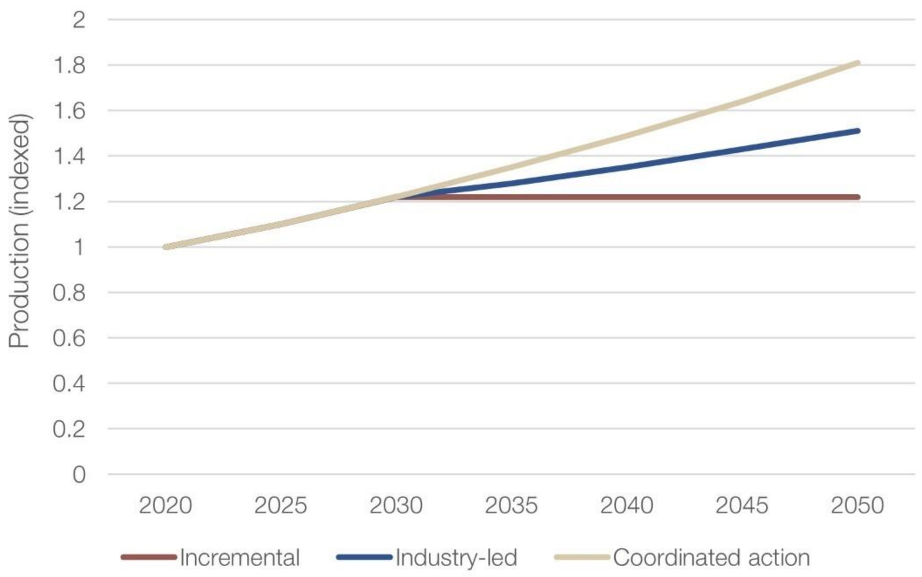


Figure 18: Commercial explosives production trajectory (consistent across all scenarios)

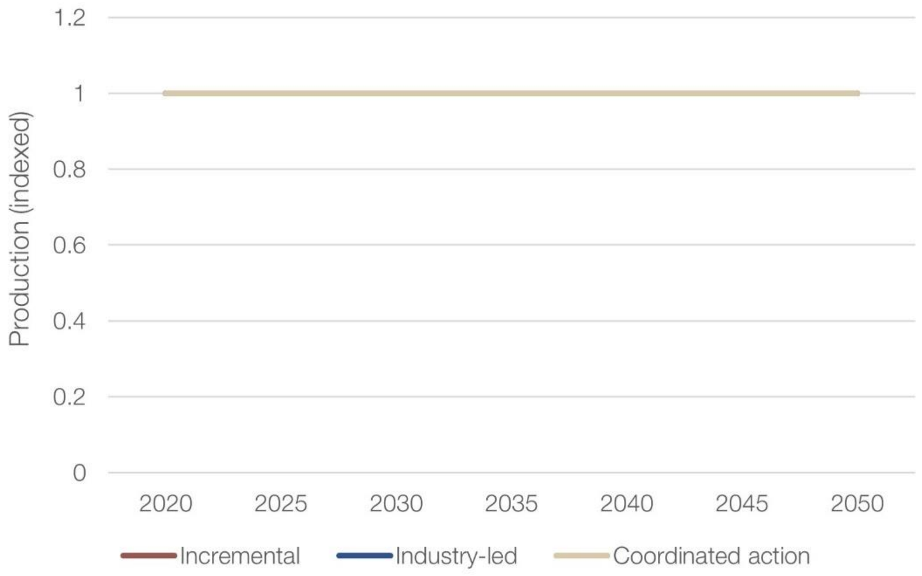
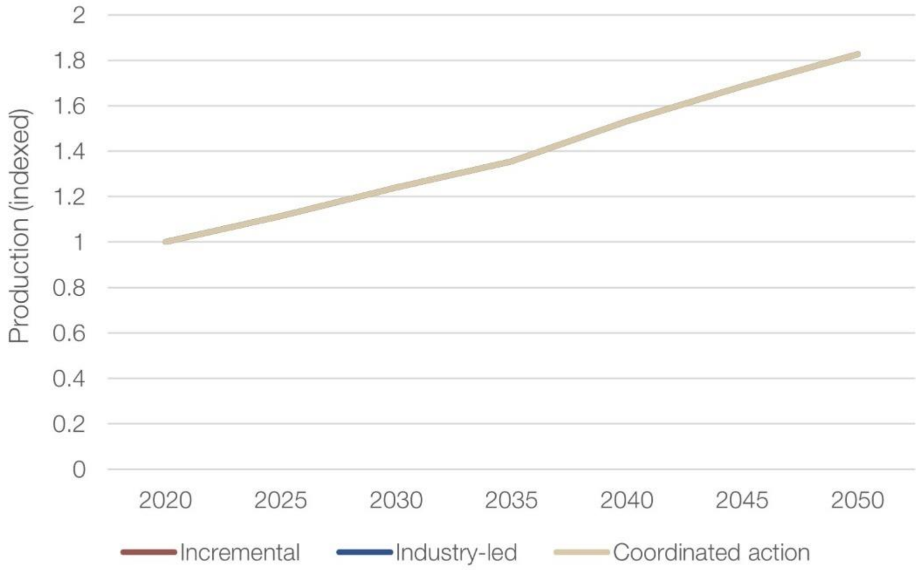


Figure 19: Fertilisers production trajectory (consistent across all scenarios)



Technology options and assumptions

Chemicals

Table 16 provides the technology assumptions for the supply chain. The start year listed is for the 'Coordinated action' scenario; 'Industry-led' and 'Incremental' have two and five-year delays applied respectively. Shaded cells show the incumbent technologies used in Australia.

Table 16: Chemicals technology assumptions

Process	Technology details	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Ammonia - Haber Bosch	Steam methane reforming (SMR) and Haber Bosch process	-	25	CAPEX	1168	1168	1168	$/t ammonia	Incumbent technology	(International Energy Agency 2020a)
				OPEX	29	29	29	$/t ammonia		(International Energy Agency 2020a)
				Energy intensity	35.0	33.6	31.0	GJ/t ammonia		(International Energy Agency 2020a)
				Non-energy emissions intensity	1.5	1.5	1.4	tCO_2e/t ammonia		(Bazzanella & Ausfelder 2017) and (National Greenhouse and Energy Reporting (Safeguard Mechanism) Rule 2015)
	Biomethane SMR	2020	25	Retrofit CAPEX	0	0	0	$/t ammonia	Applicable to 100% of sector energy use and feedstock.	
				Additional OPEX	0	0	0	$/t ammonia	Costs assumed equivalent to gas (other than fuel input cost)	
				Energy intensity	35.0	33.6	31.0	GJ/t ammonia		
		2025	25	CAPEX	290	290	290	$/t ammonia	Applicable to 100% of sector feedstock.	

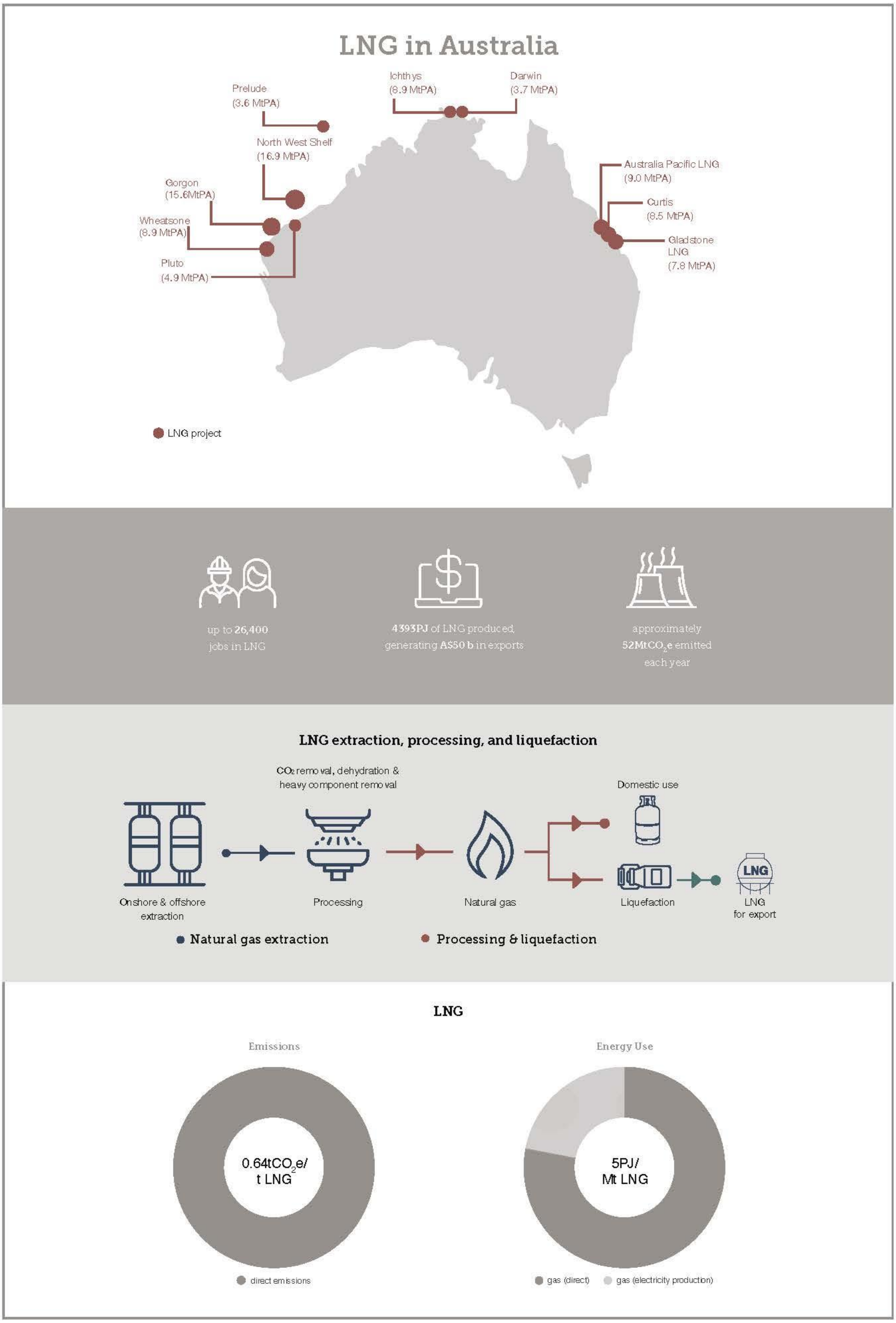
	Hydrogen replacement for SMR			OPEX	0	0	0	$/t ammonia	Lack of data available, assumed 25% of ammonia plant CAPEX	
				Energy intensity	45.1	43.3	40.0	GJ/t ammonia		(Bazzanella & Ausfelder 2017)
	Gas-SMR+CCS	2025	25	Additional cost	87.6	81	69	$/t$CO_2$	Reduces non-energy emissions by 90% (applicable to 100% of ammonia non-energy emissions, which is 16% of total supply chain emissions)	(International Energy Agency 2020a)
				Additional energy intensity	1.0	1.0	0.9	GJ/t ammonia		(International Energy Agency 2020a) and (Brown 2021)
	Post combustion CCS Assumed available in 2025, 25 year lifetime,	2025	25	Additional cost	156.0	136	95.4	$/t$CO_2$	Reduces energy emissions by 90% (applicable to 100% of ammonia energy emissions, which is 52% of total supply chain energy emissions)	(BloombergNEF 2020)
				Additional energy intensity	1.4	1.4	1.4	GJ/t ammonia		(BloombergNEF 2020)
	Novel ammonia production	Insufficient data available for emerging low-pressure, small-scale ammonia production methods								
Commercial explosives	Tertiary catalysts	2020	15	CAPEX	75.0	75.0	75.0	$/t ammonium nitrate (AN)	Reduces process emissions by 95% (applicable to 100% of commercial explosives process emissions, which is 13% of total supply chain emissions)	Partner feedback
				OPEX	5.8	5.8	5.8	$/t AN		Partner feedback
				Energy intensity	0.0	0.0	0.0	GJ/t AN		Assumed zero

LNG

Sector overview

The LNG supply chain is represented in the modelling by two subsectors: gas extraction and LNG production (see Figure 20). The gas extraction subsector is modelled based on data that represents the entirety of extraction in Australia, i.e. includes gas extracted for domestic use as well as export. It covers the extraction from wells and early stages of processing, including separation of water and carbon dioxide. The LNG production subsector represents processes required to liquefy and compress the gas for export but does not include shipping.

Figure 20: LNG overview



Scenario activity assumptions

Common assumptions are used for LNG exports in all modelled Australian Industry ETI scenarios, with a 73 per cent reduction by 2050 informed by the IEA's 'Net Zero Emissions' scenario (2021). Most global modelling of a 1.5°C-aligned pathway indicates significant reductions in LNG demand, in line with the need for global energy use to transition away from fossil fuels. The IEA-based trajectory is used to ensure the modelling and core scenarios exist within a macro context aligned to limiting global warming to 1.5°C. This trajectory includes a 36 per cent reduction by 2030, and 73 per cent by 2050 (see Figure 22).

In reality, demand for Australian LNG may not decrease as much as is assumed in the Australian Industry ETI modelling. The IPCC finds that modelling of global natural gas and LNG usage varies significantly in 1.5°C aligned scenarios, with a median of a 45 per cent reduction in global production on 2019 levels (IPCC 2022).

To develop the demand assumptions for this sector, 2020–2023 assumptions for production of LNG in Australia are derived from the Australian Government's *Resources and Energy Quarterly* (DISER 2021b). The 2024–2050 assumptions are from the IEA's 'Net Zero Emissions' scenario (2021). The benefit of combining these sources is that accurate short-term data is used as well as ensuring long-term 1.5°C alignment.

Gas extraction activity is determined based on the above assumptions for LNG exports, plus the modelled domestic demand for natural gas across all sectors (buildings, industry, transport, power generation and hydrogen production). See Figure 21 for the activity trajectory.

Figure 21: Gas extraction trajectory

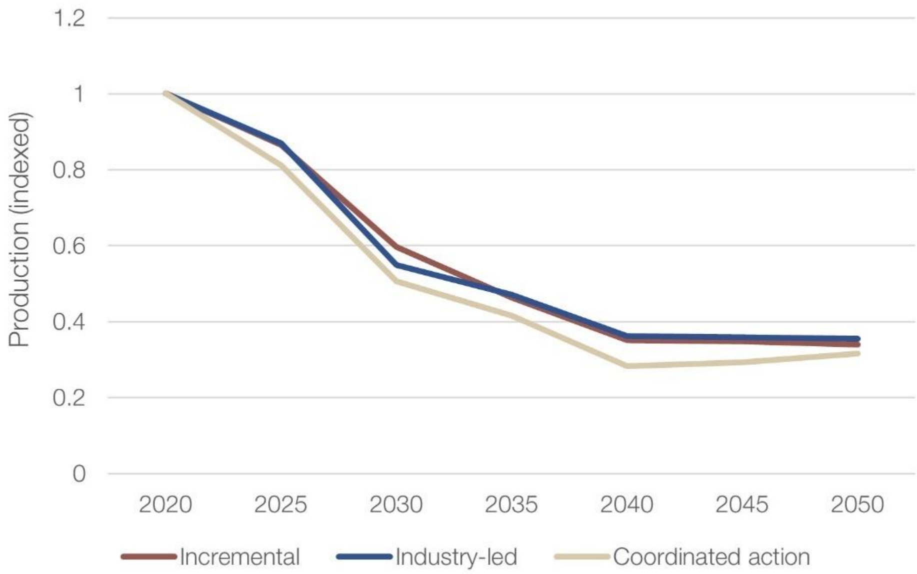
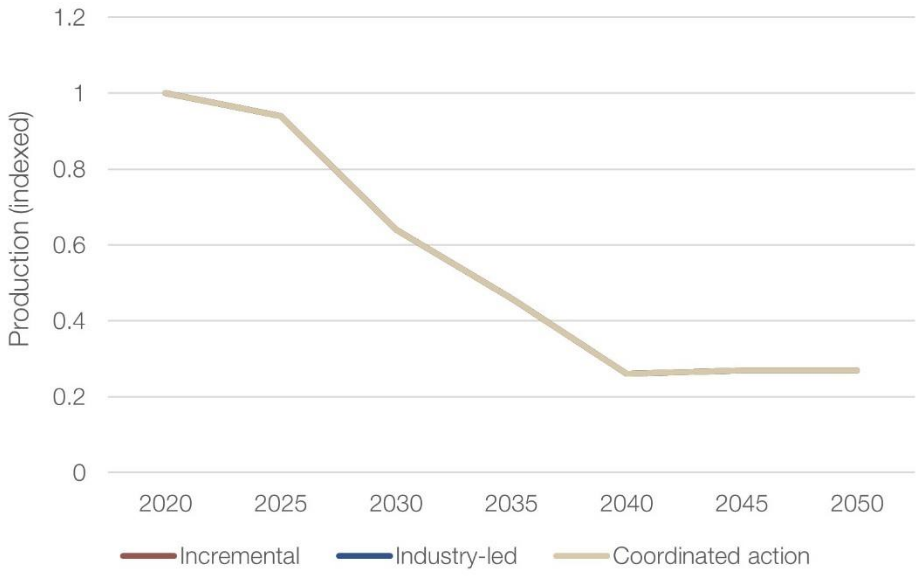


Figure 22: LNG production trajectory



Technology options and assumptions

Gas extraction and LNG production

Table 17 provides the technology assumptions for the supply chain. The start year listed is for the 'Coordinated action' scenario; 'Industry-led' and 'Incremental' have two and five-year delays applied respectively. Shaded cells show the incumbent technologies used in Australia.

Table 17: Gas extraction and LNG production technology assumptions

Process	Technology details	Start year	Lifetime (years)	Metric	2020	2030	2050	Unit	Comment	Source
Leaks, venting and flaring (from gas extraction to liquefaction)	Reservoir CCS	2025	25	Additional cost (capture only)	75	71	62.6	$/tCO_2$	Additional energy intensity considered zero as CO_2 separation already occurs.	(International Energy Agency 2020b)
				Additional energy intensity	0.0	0.0	0.0	GJ/tCO_2		(International Energy Agency 2020b)
				Emissions reduction (non-energy)	-90%	-90%	-90%	% reduction in gas extraction sector emissions		(Chevron 2015) and (Chevron 2011)
	Costed abatement (range of technologies)	2020	1	Cost	200	200	200	$/t LNG	Reduces leaks, other venting and flaring by up to 33% Due to range of technologies modelled, simplified assumption of no additional energy intensity	Calculated from references including (International Energy Agency 2022) and (United Nations Environment Programme and Climate and Clean Air Coalition 2021)
				Energy intensity	0	0	0	GJ/t LNG		
	Zero or negative cost abatement (range of technologies)	2020	1	Cost	0	0	0	$/t LNG	Reduces leaks, other venting and flaring by up to 33% Due to range of technologies modelled, simplified assumption of no additional energy intensity	Calculated from references including (International Energy Agency 2022) and (United Nations Environment Programme and Climate and Clean Air Coalition 2021)
				Energy intensity	0	0	0	GJ/t LNG		

Energy use for gas liquefaction	Gas compression turbines	-	25	CAPEX	9.5	9.5	9.5	$/t LNG	(incumbent technology)	(Devold et al. n.d.)
				OPEX	2.1	2.1	2.1	$/t LNG		(Devold et al. n.d.)
				Energy intensity	1.2	1.2	1.1	GJ/t LNG		(Khan et al. 2017)
	Electric drives	2030	25	CAPEX	12	12	12	$/t LNG	Applicable to 66% of sector energy use	(Devold et al. n.d.)
				OPEX	0.8	0.8	0.8	$/t LNG		(Devold et al. n.d.)
				Energy intensity	0.4	0.4	0.4	GJ/t LNG		Assumed
	Waste heat recovery	2020	20	CAPEX	733	733	733	$/PJ LNG	Applicable to 10% of sector energy use	(Bogliolo et al. 2017)
				OPEX	15	15	15	$/PJ LNG		(Bogliolo et al. 2017)
				Energy intensity	1.1	1.0	1.0	GJ/t LNG		(Arzbaecher et al. 2007)
	CCS (post combustion)	2025	25	Additional cost	156.0	136	95.4	$/tCO$_2$	Reduces energy emissions by 90% (applicable to 100% of liquefaction energy emissions)	(BloombergNEF 2020)
				Additional energy intensity	1.4	1.4	1.4	GJ/tCO$_2$		(BloombergNEF 2020)

Results

Overall economy

Figure 23: Economy-wide energy use

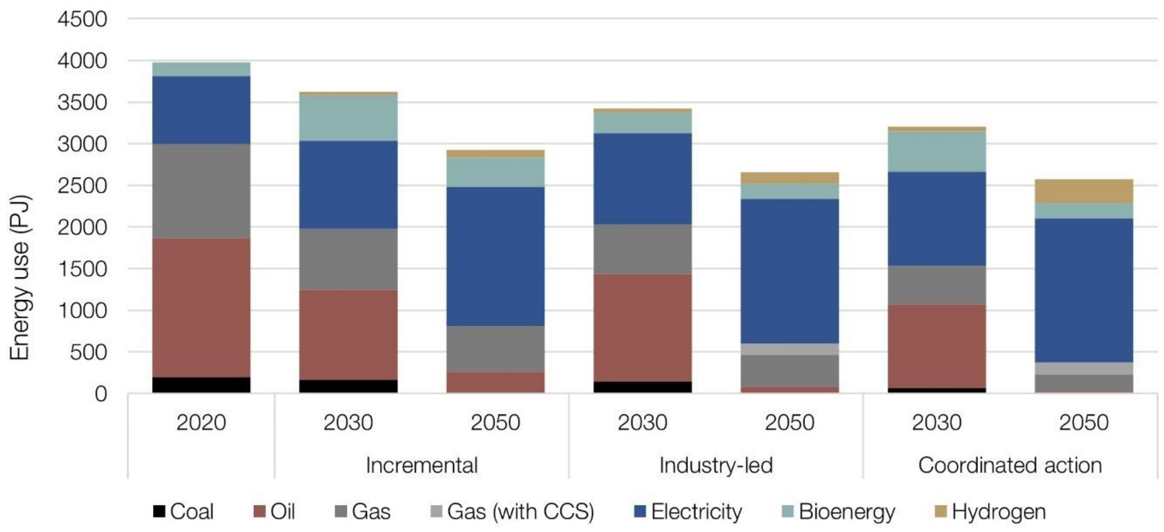


Figure 24: Economy-wide annual emissions

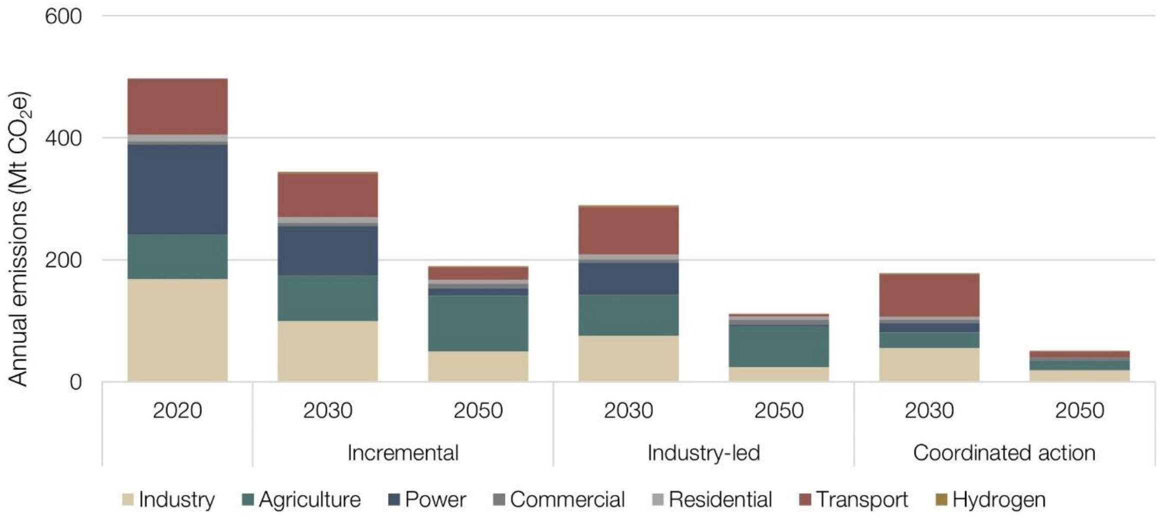
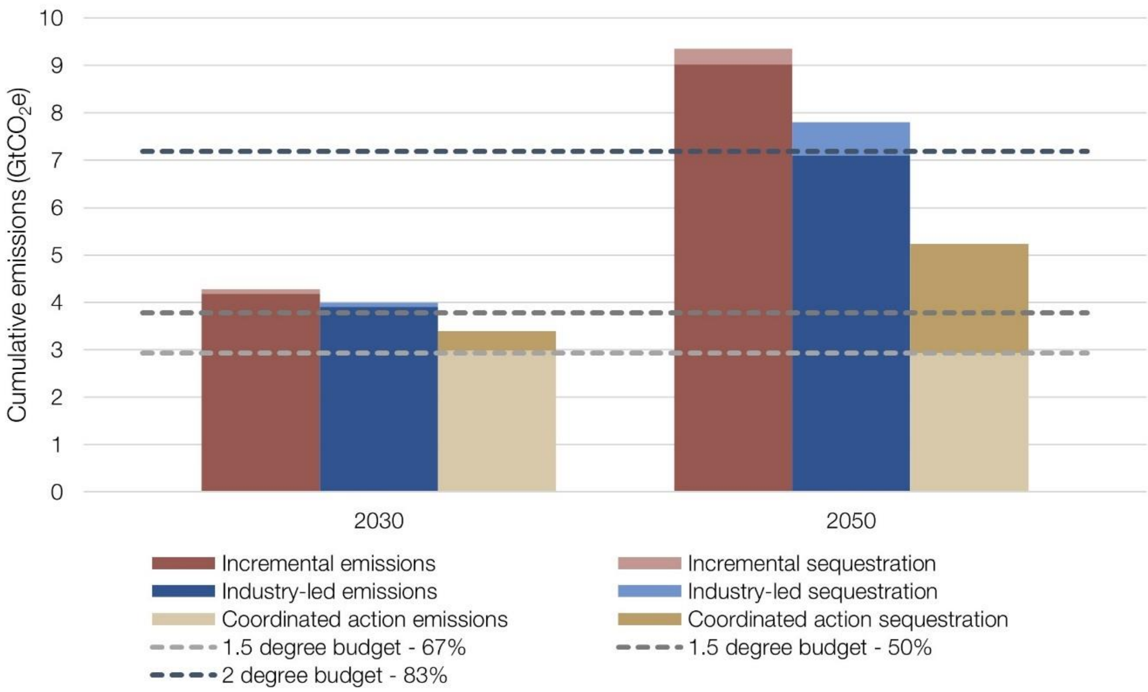


Figure 25: Economy-wide cumulative emissions



Industry

Figure 26: Industry energy use

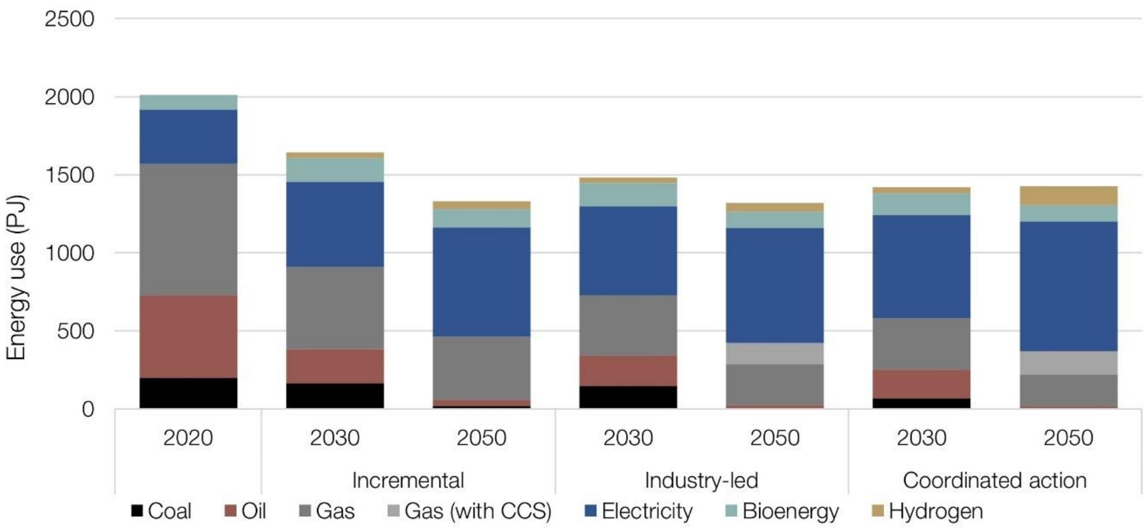


Figure 27: Industry annual emissions

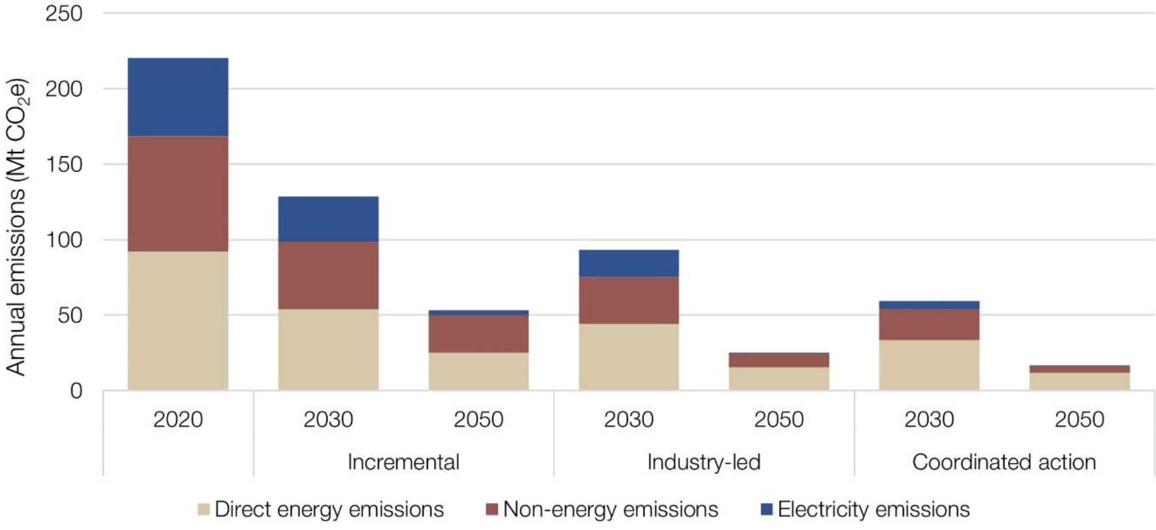
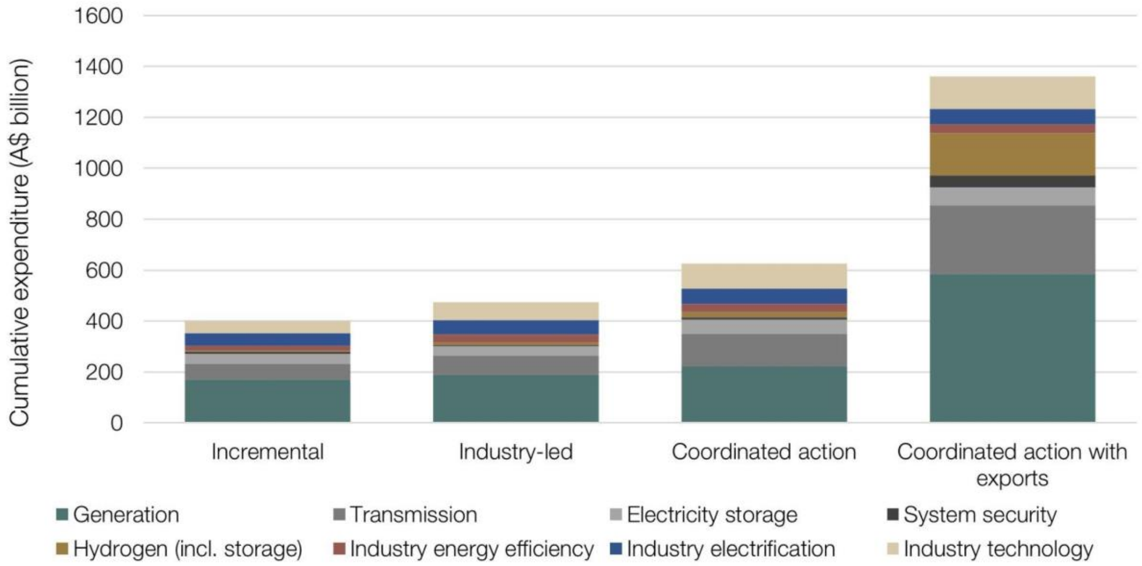


Figure 28: Cumulative expenditure for industry and the energy system



Energy system and energy infrastructure

Electricity

Figure 29: Economy-wide electricity generation

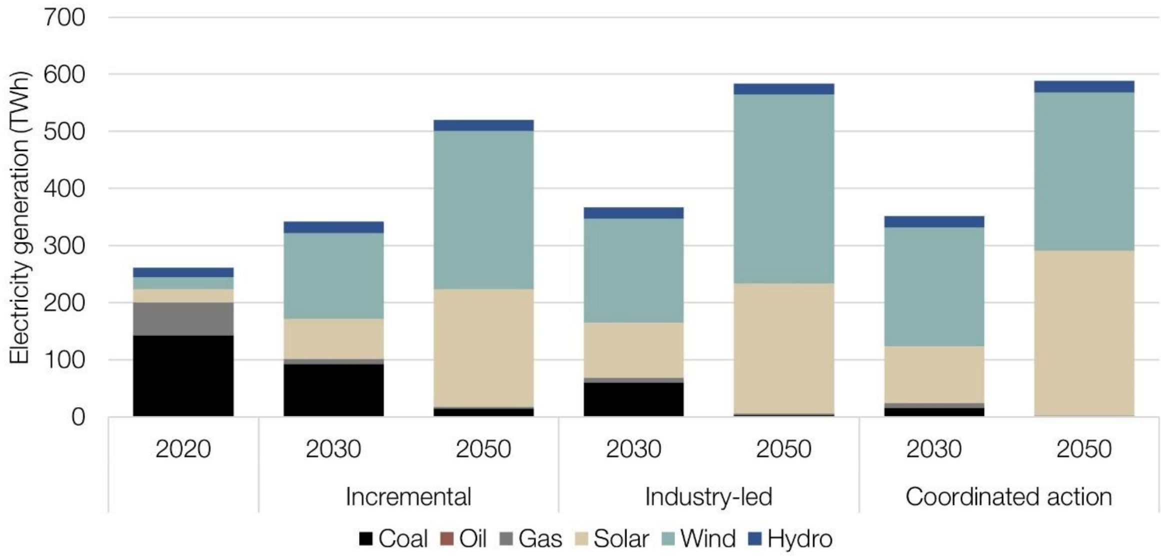


Figure 30: Cumulative electricity system expenditure

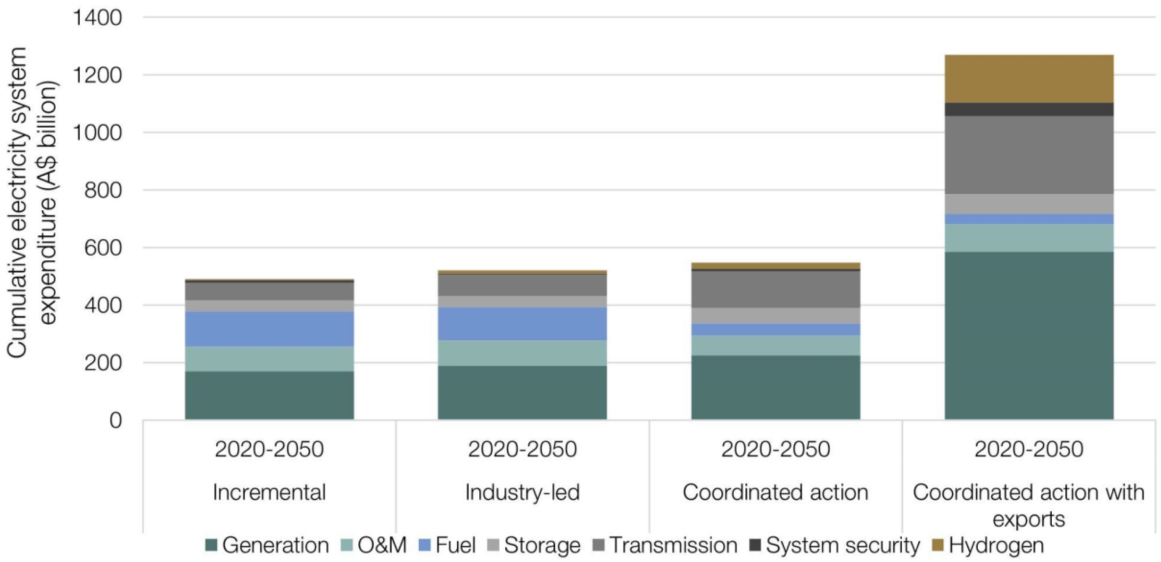


Figure 31: Generation required for the 'Coordinated action' and 'Coordinated action with exports' scenarios

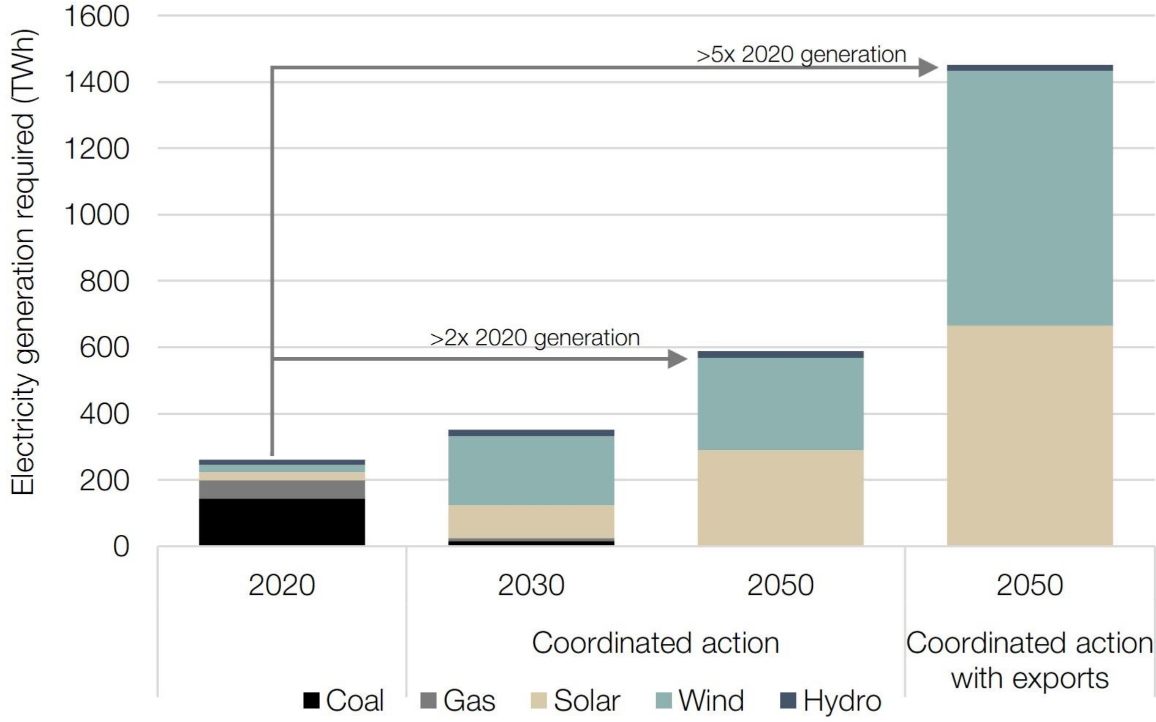


Figure 32: Generation capacity required for 'Incremental' (left) and 'Industry-led' (right) scenarios

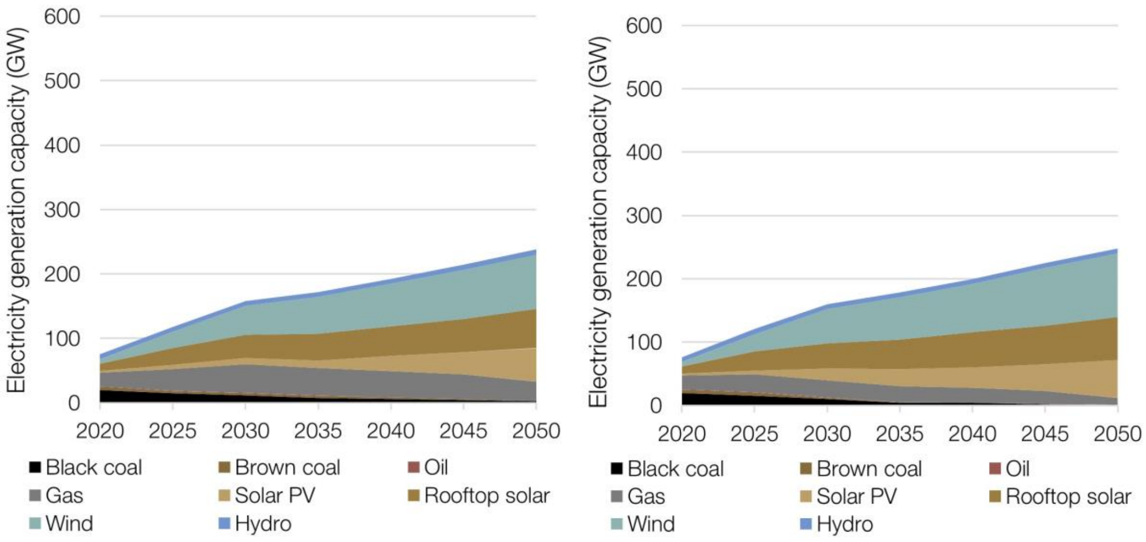
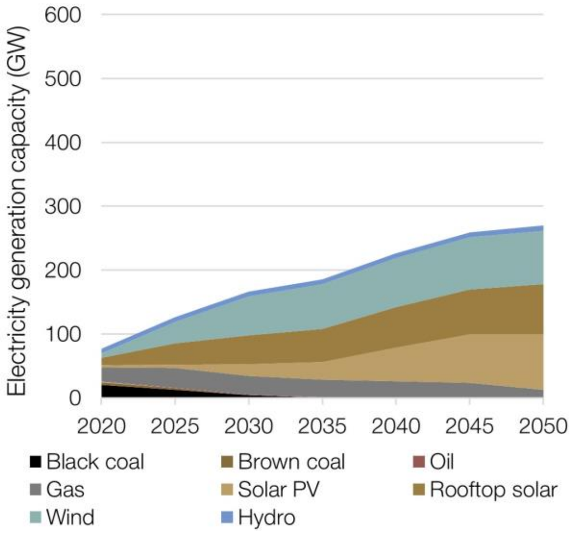
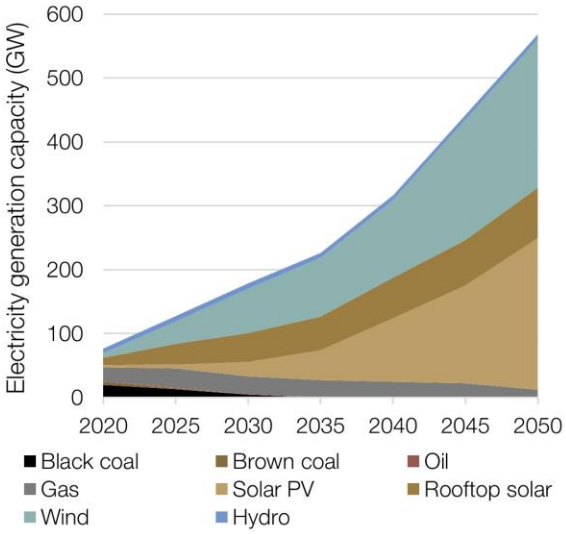


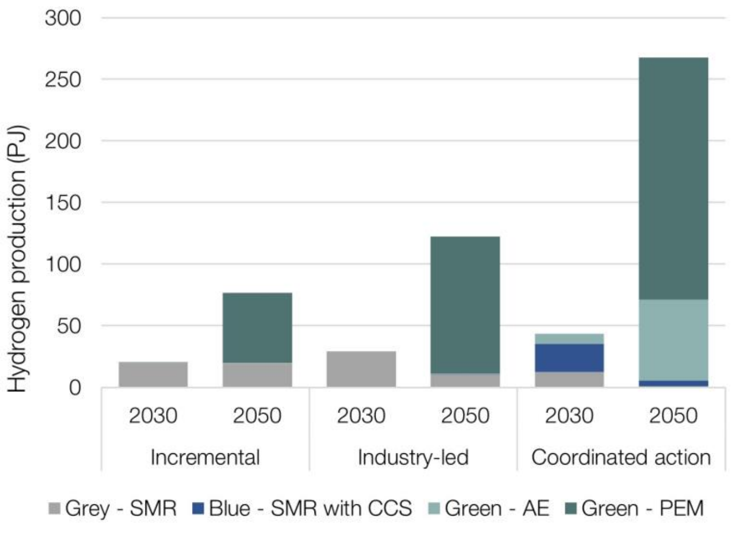
Figure 33: Generation capacity required for the 'Coordinated action' (left) and 'Coordinated action with exports' (right) scenarios





Hydrogen

Figure 34: Hydrogen production



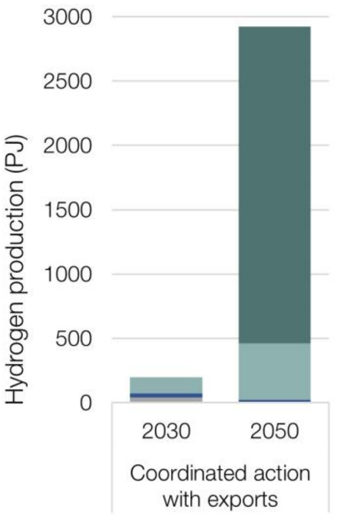
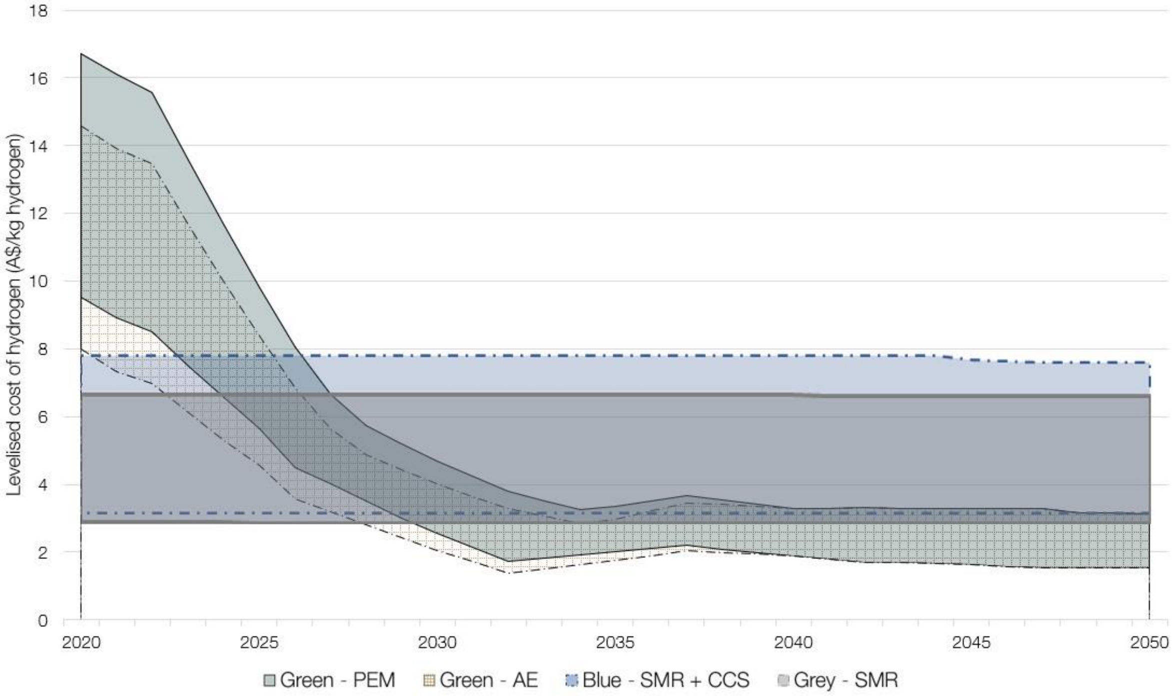


Figure 35: Levelised cost of hydrogen production in the ‘Coordinated action scenario’



Energy infrastructure

Figure 36: Regional energy infrastructure for the ‘Incremental scenario’ in 2050

The brown circles represent the amount of hydrogen production in each region. Hydrogen circles are placed outside the map for clarity but refer to areas labelled.

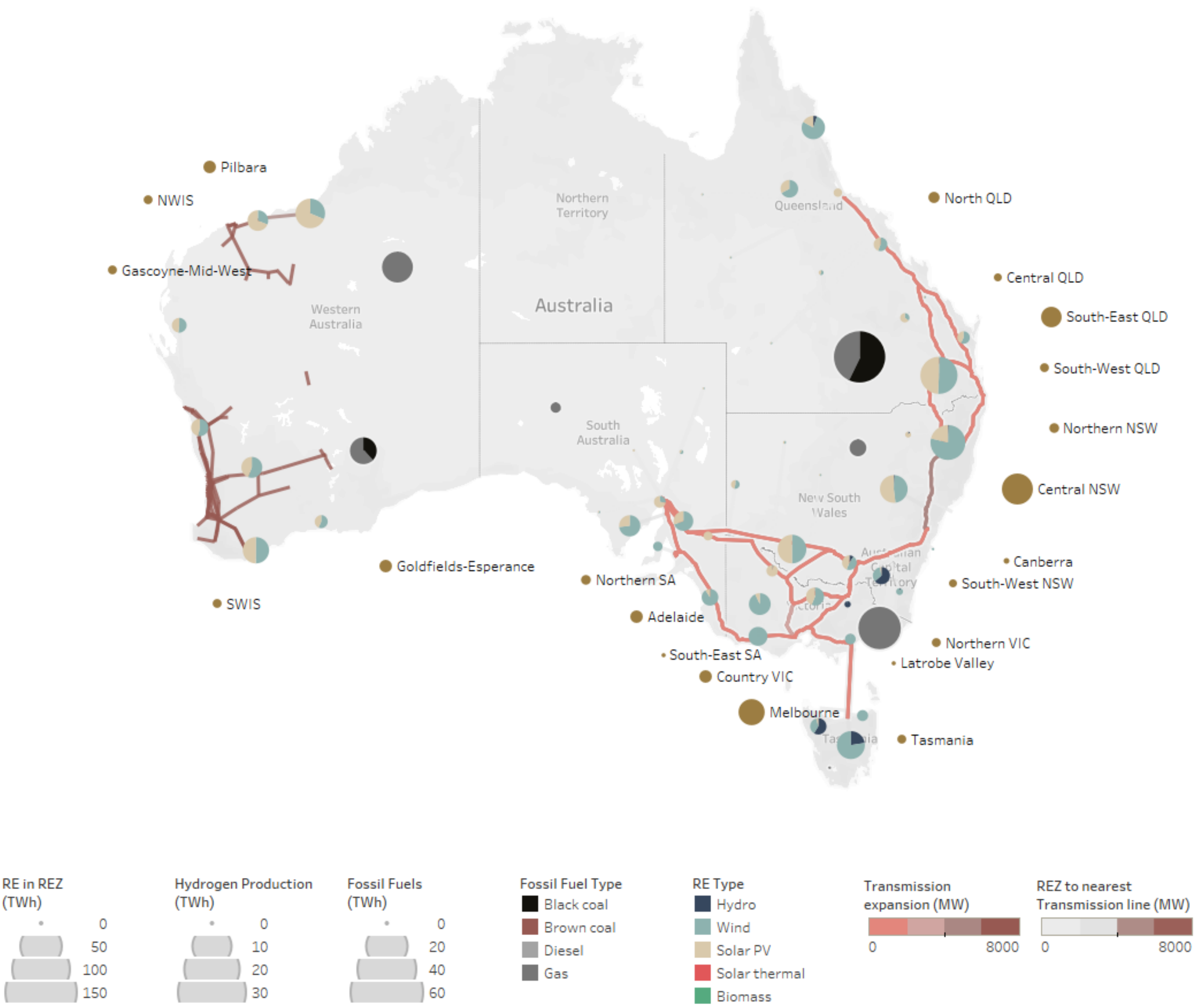


Figure 37: Regional energy infrastructure for the ‘Industry-led scenario’ in 2050

The brown circles represent the amount of hydrogen production in each region. Hydrogen circles are placed outside the map for clarity but refer to areas labelled.

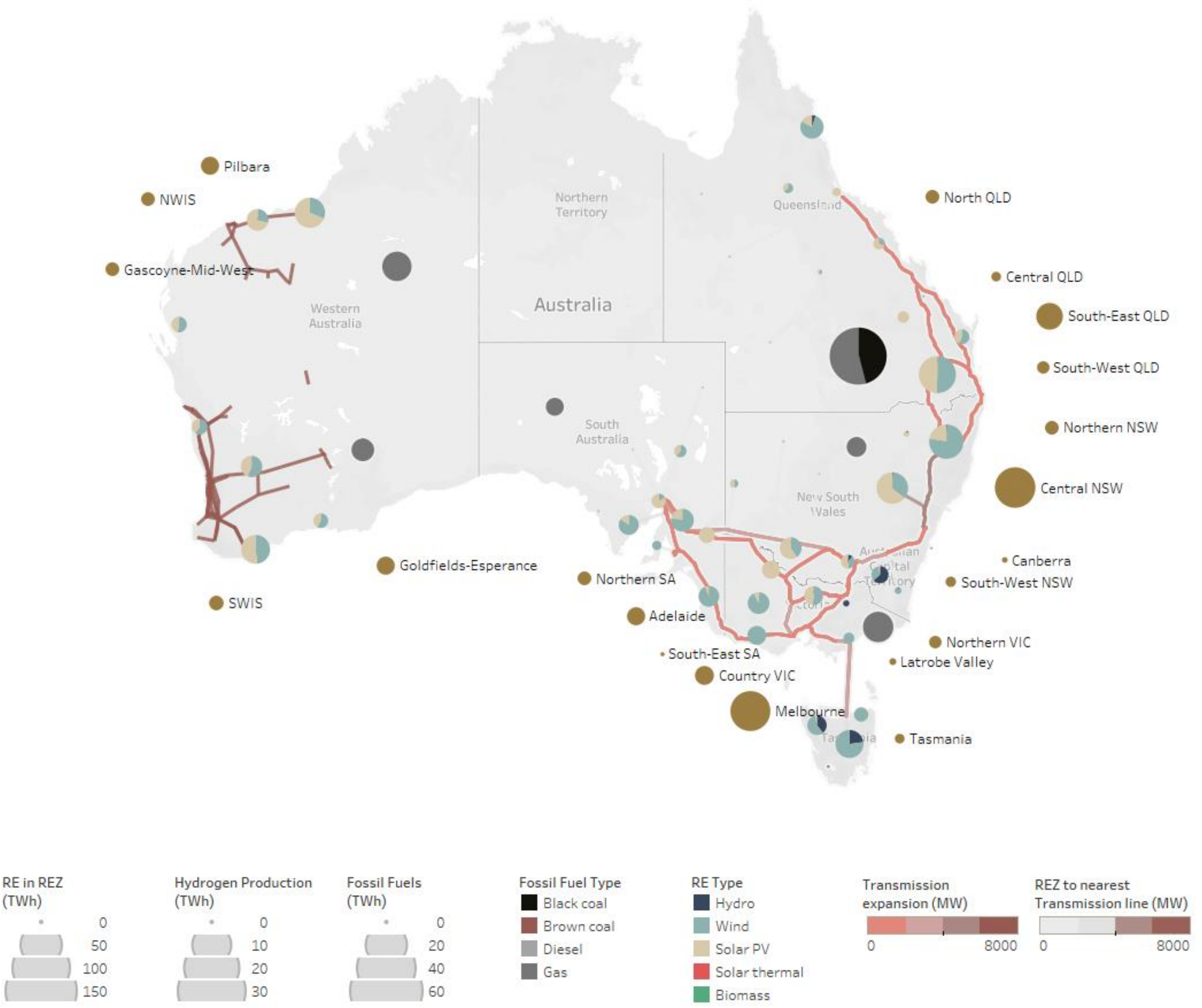


Figure 38: Regional energy infrastructure for the 'Coordinated action scenario' in 2050

The brown circles represent the amount of hydrogen production in each region. Hydrogen circles are placed outside the map for clarity but refer to areas labelled.

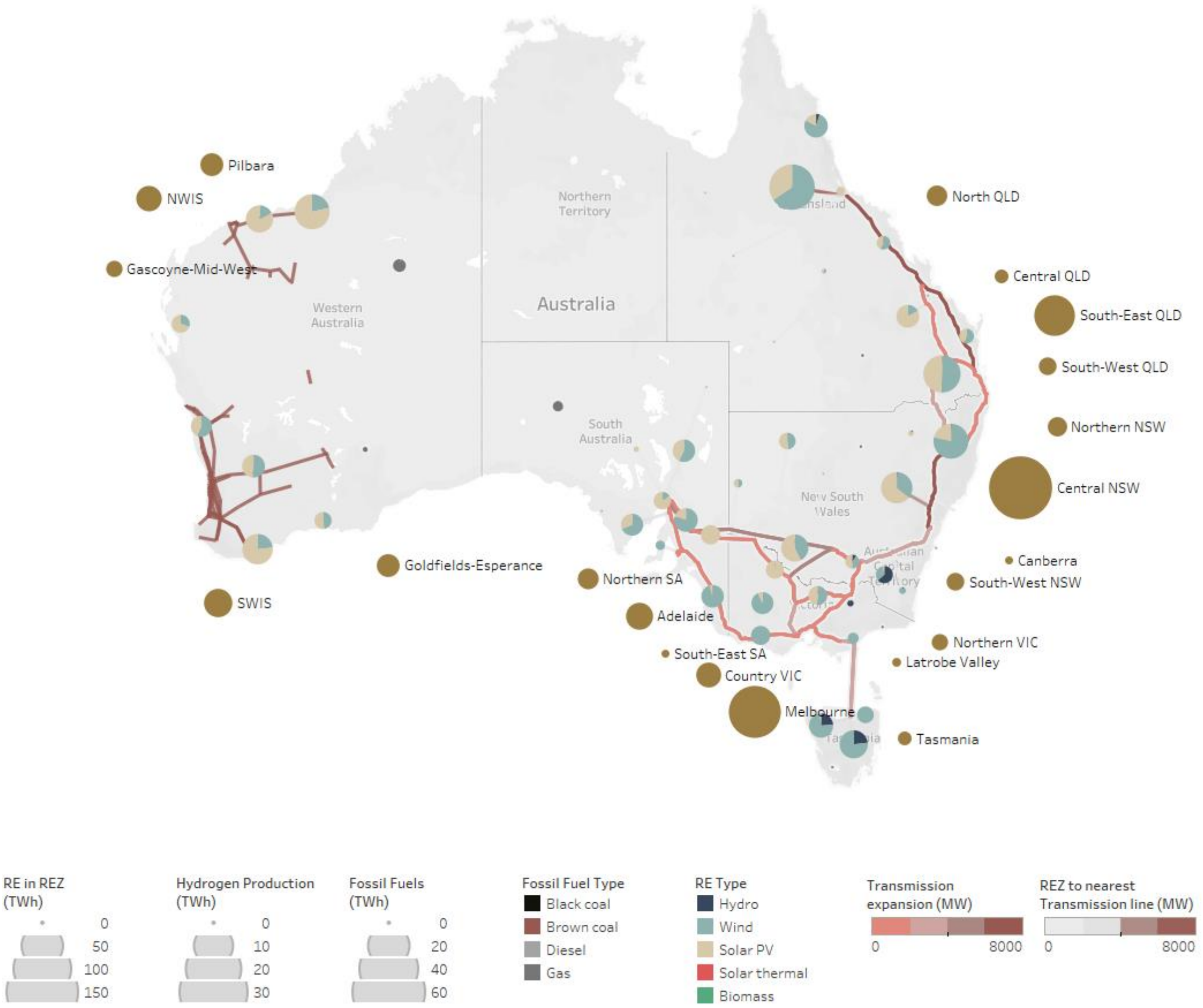
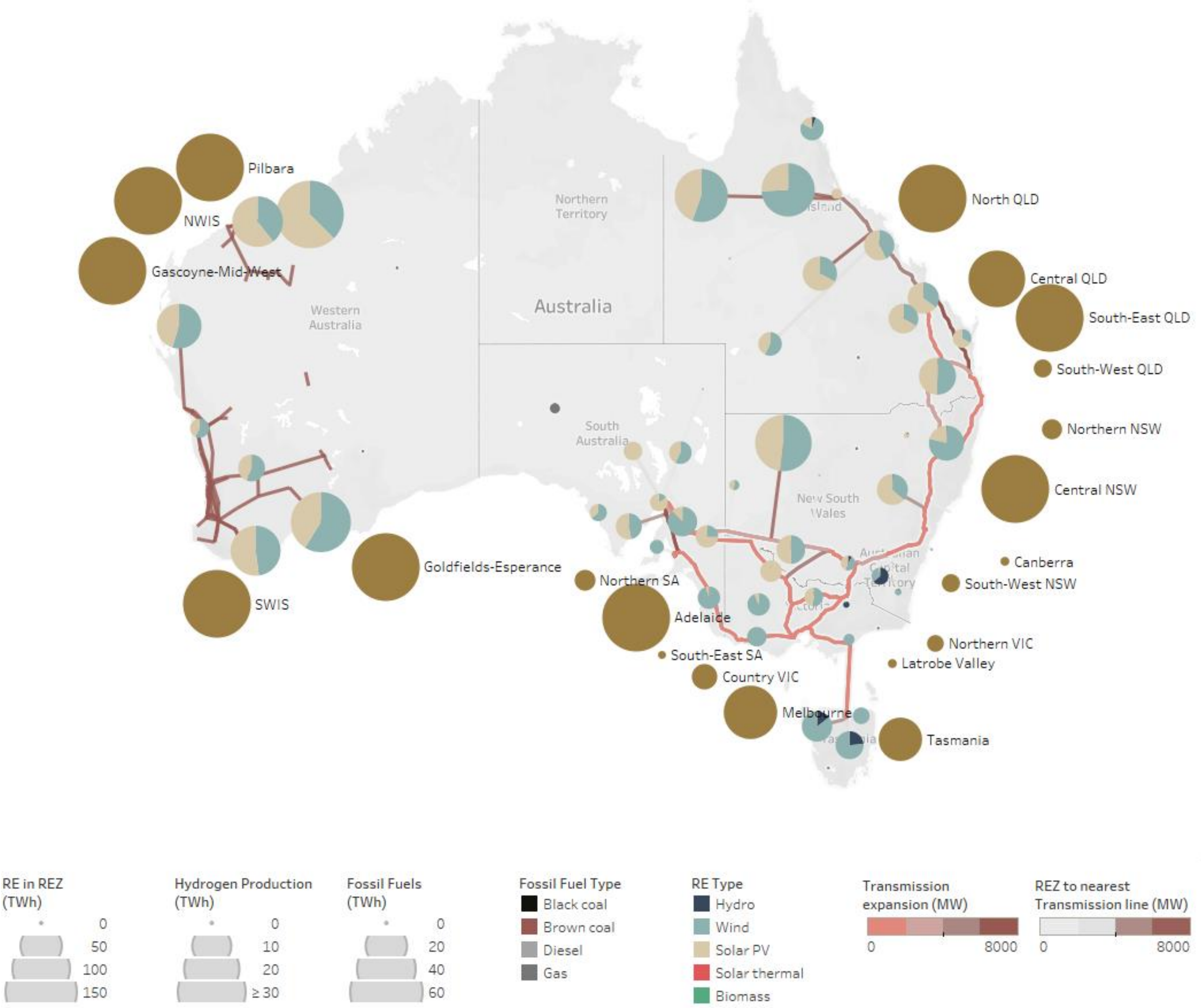


Figure 39: Regional energy infrastructure for the ‘Coordinated action with exports scenario’ in 2050

The brown circles represent the amount of hydrogen production in each region. Hydrogen circles are placed outside the map for clarity but refer to areas labelled.



Supply chain energy and emission results

Iron and steel

Figure 40: Energy use for iron ore mining

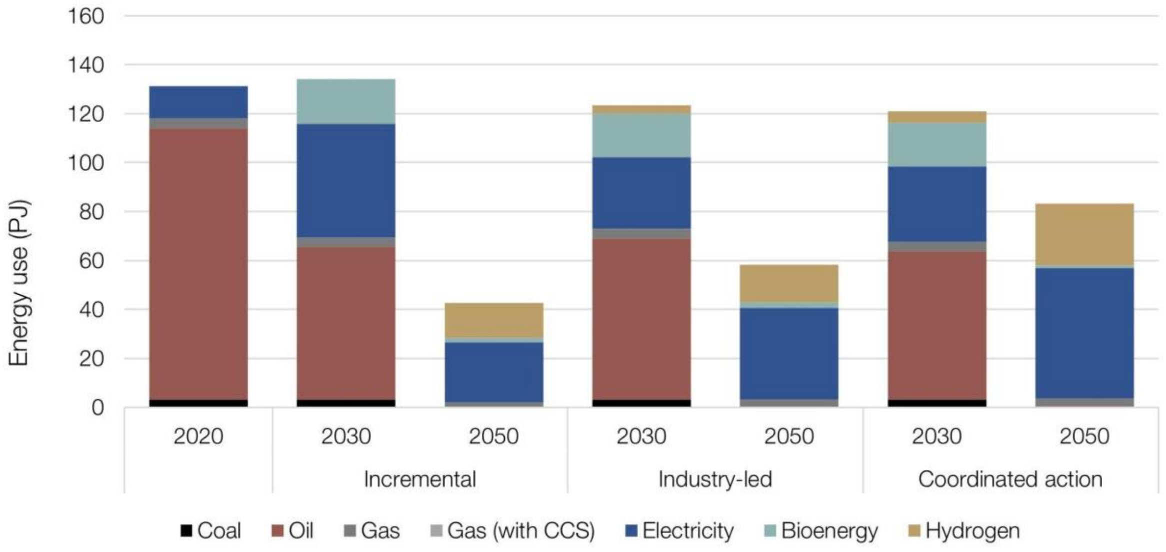


Figure 41: Energy use for steel production

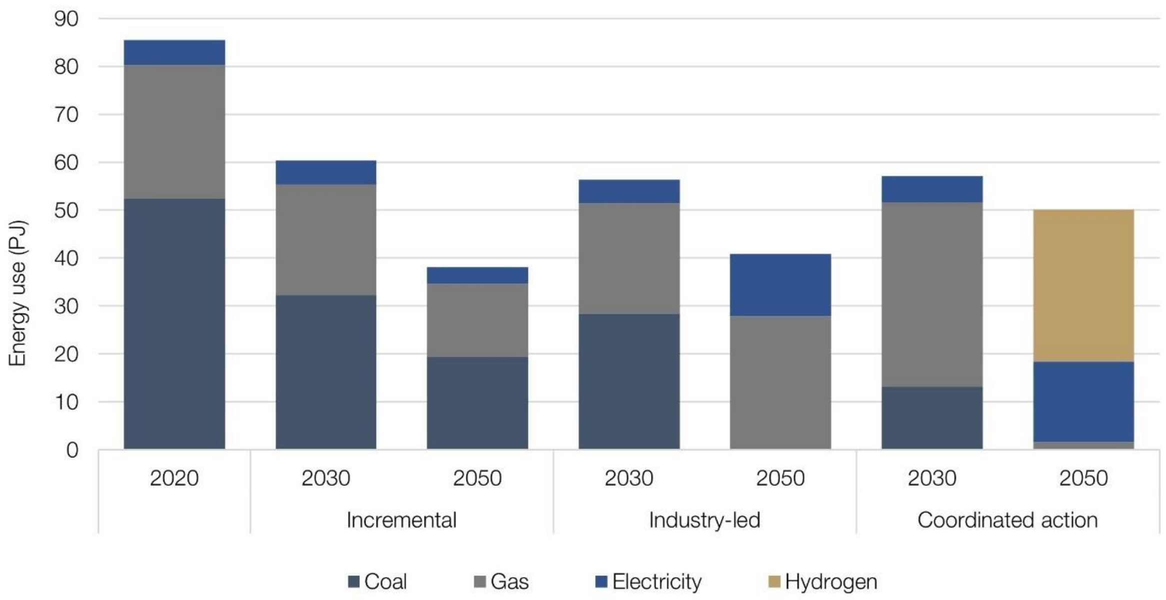


Figure 42: Energy use for steel production in the ‘Coordinated action scenario’ and ‘Coordinated action with exports’ sensitivity

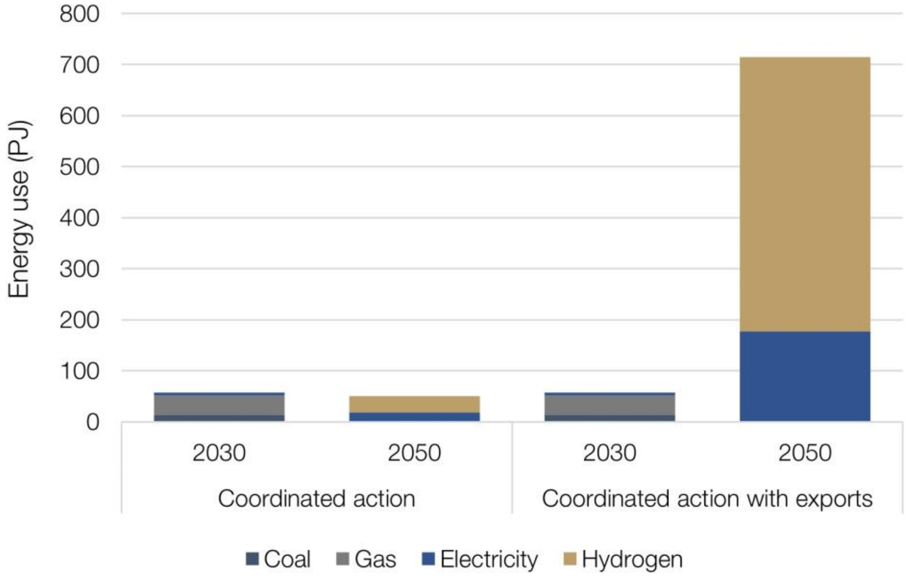


Figure 43: Emissions from iron ore mining

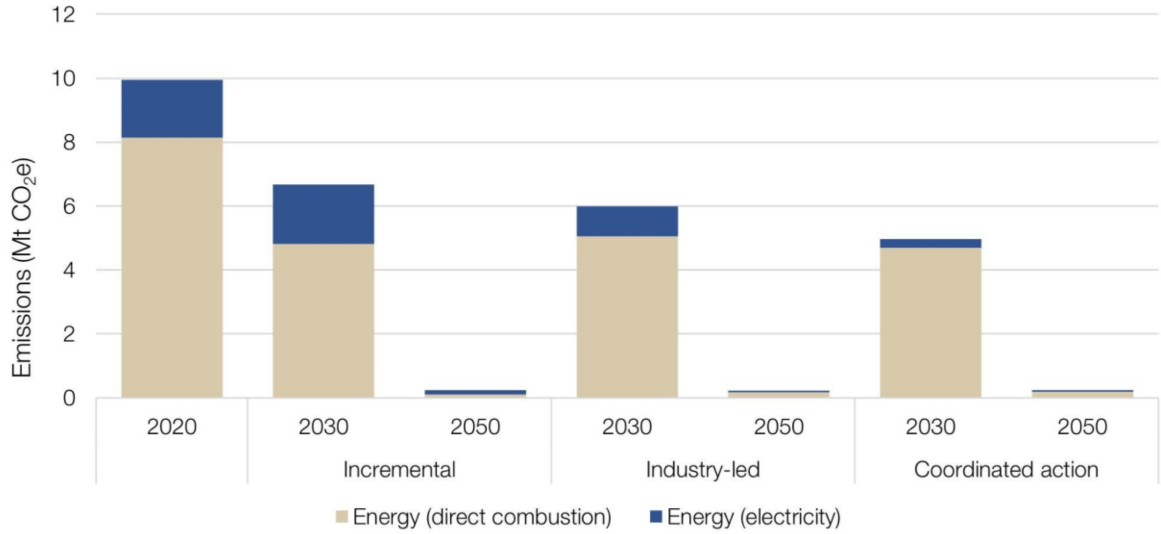


Figure 44: Emissions from steel production

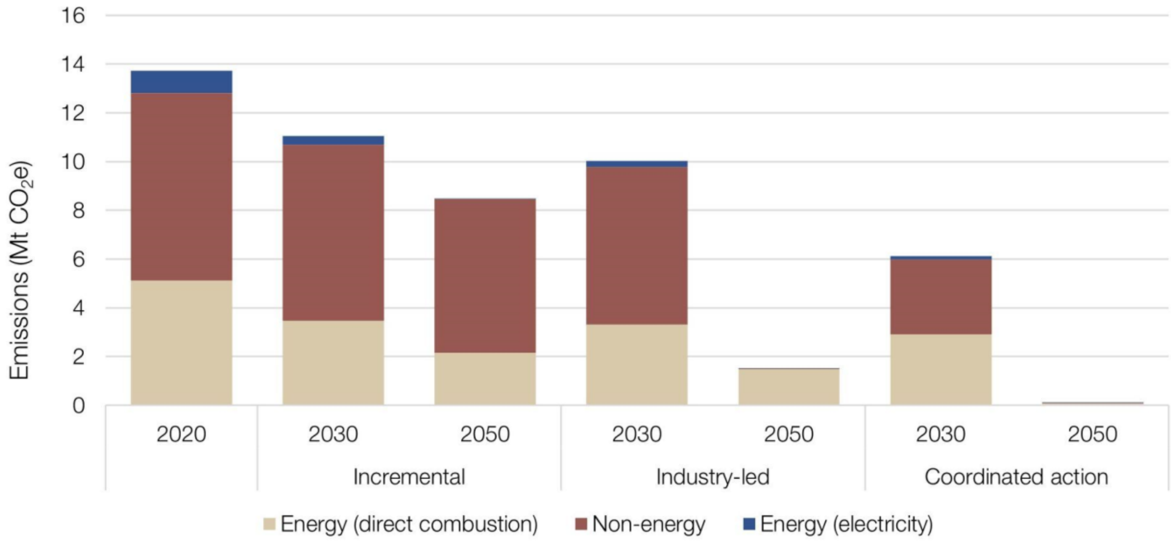


Figure 45: Investment required for iron ore production

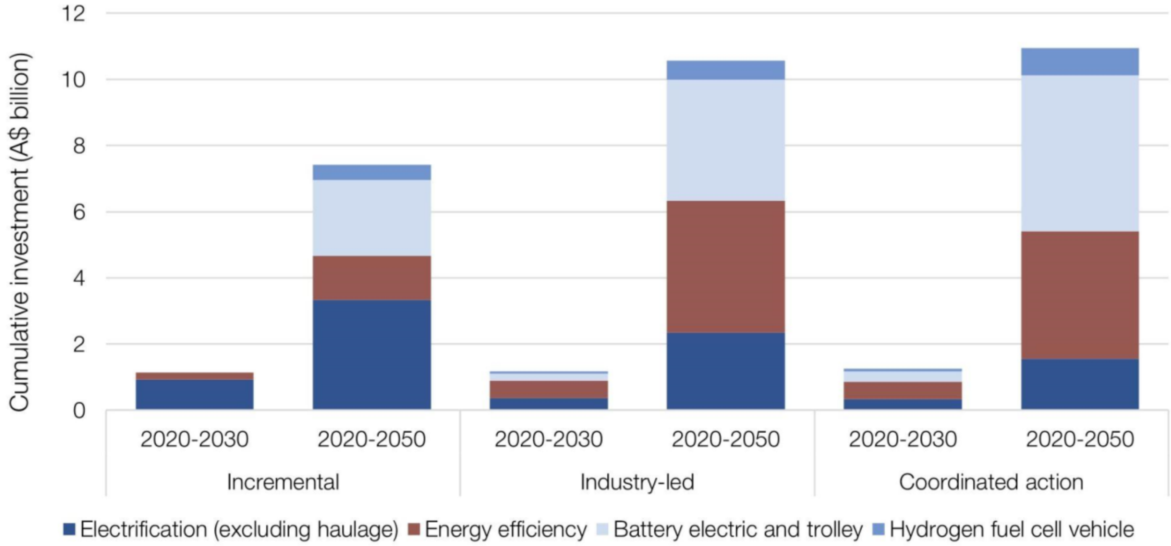
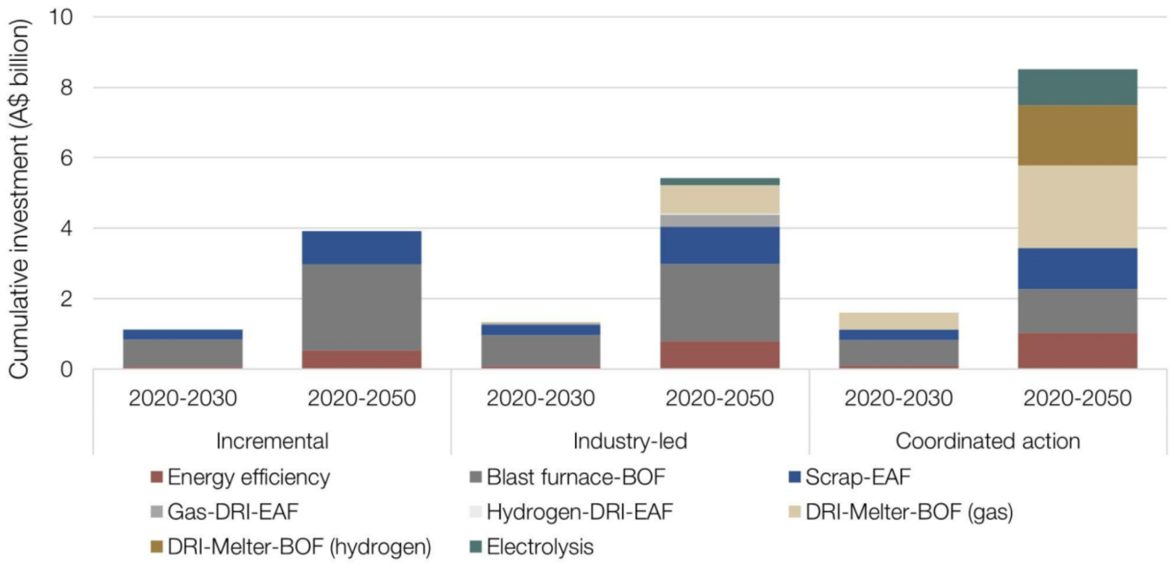


Figure 46: Investment required for steel production



Aluminium

Figure 47: Energy use for bauxite mining

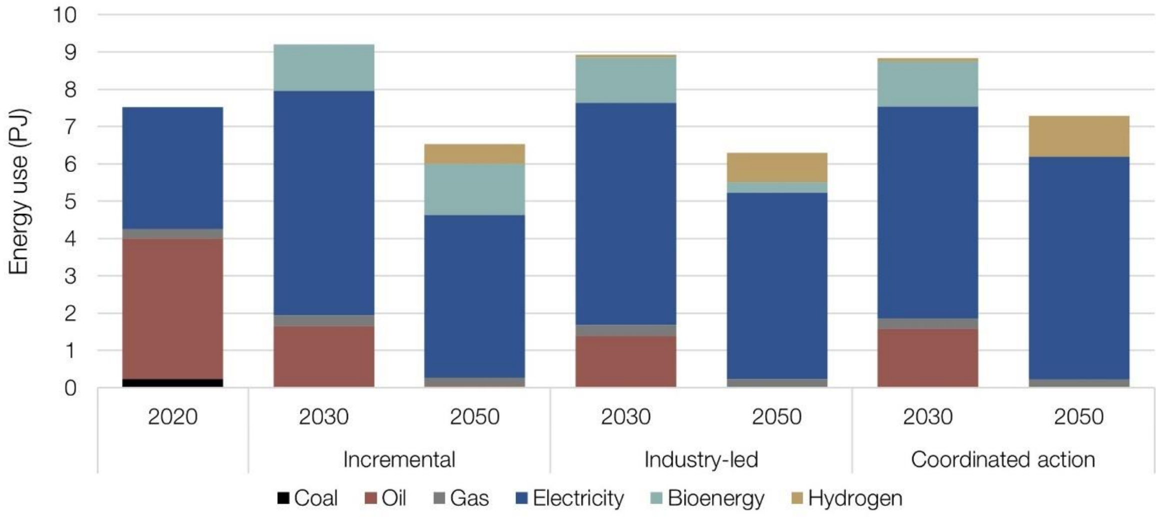


Figure 48: Energy use for alumina production

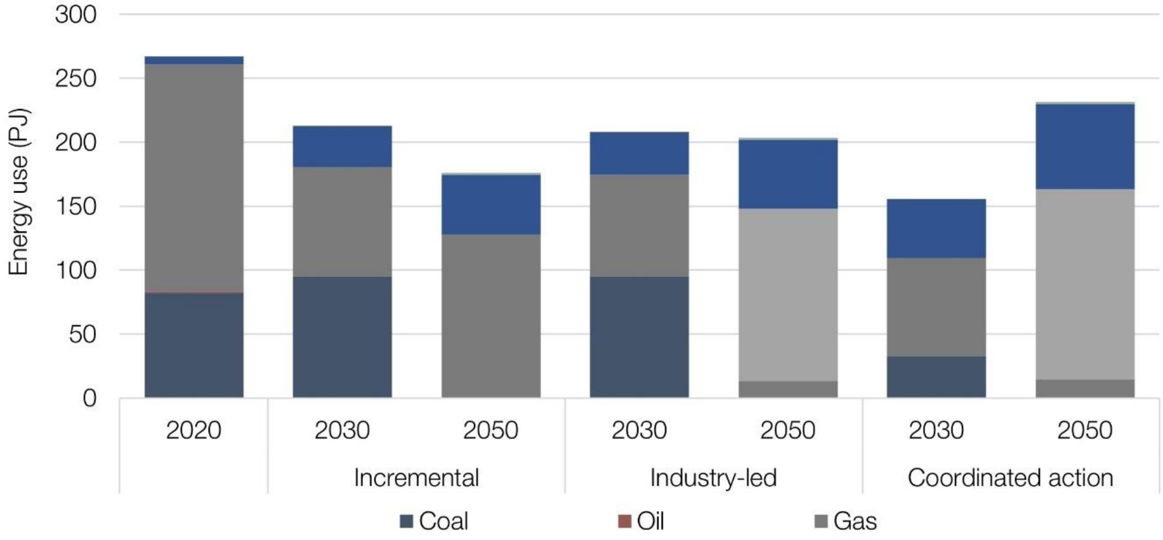


Figure 49: Energy use for aluminium production

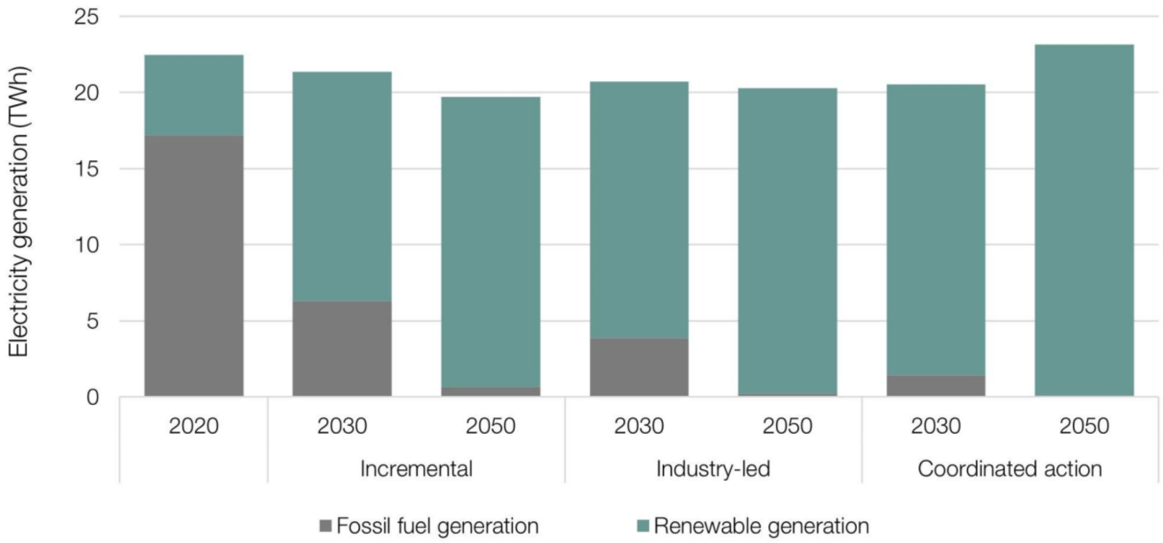


Figure 50: Emissions from bauxite mining

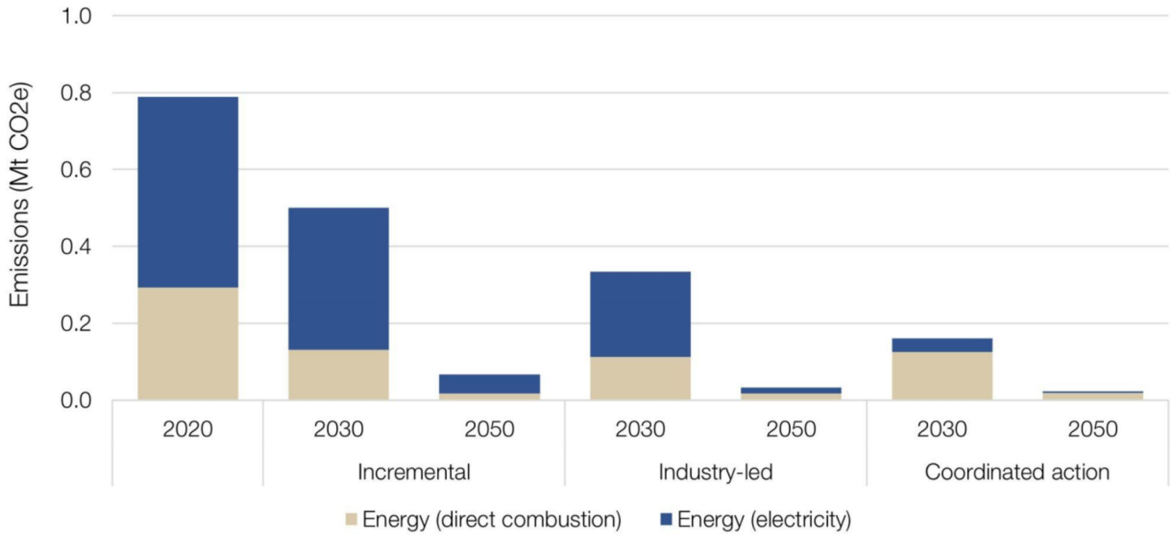


Figure 51: Emissions from alumina production

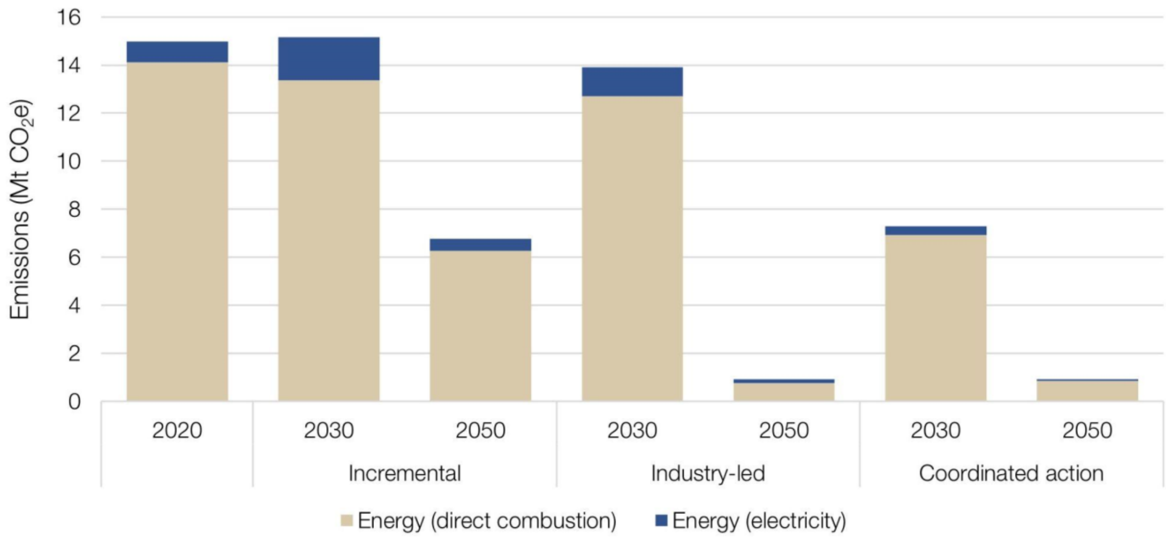


Figure 52: Emissions from aluminium production

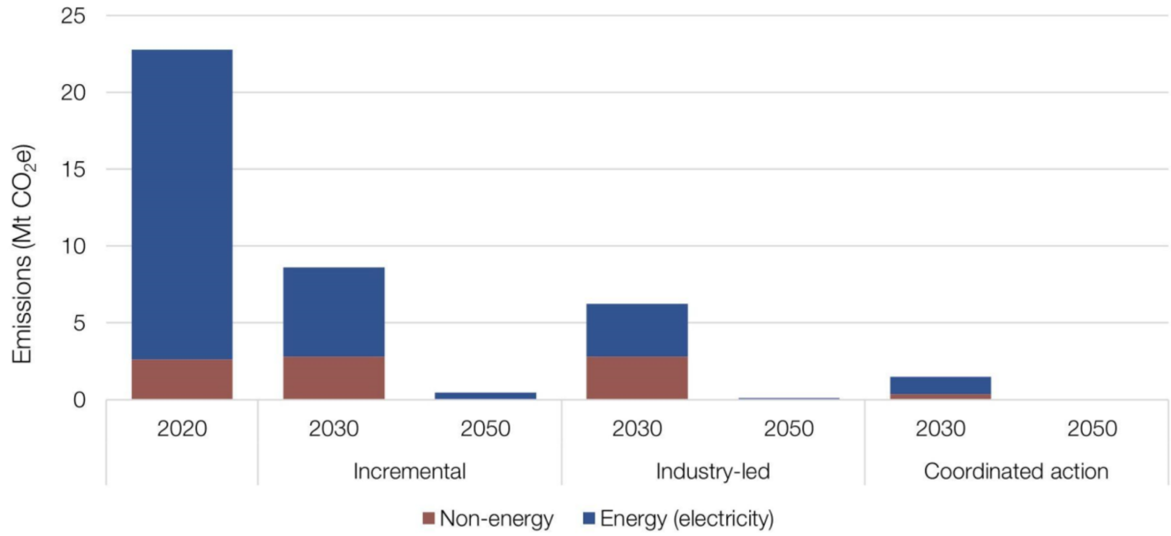


Figure 53: Investment required for bauxite mining

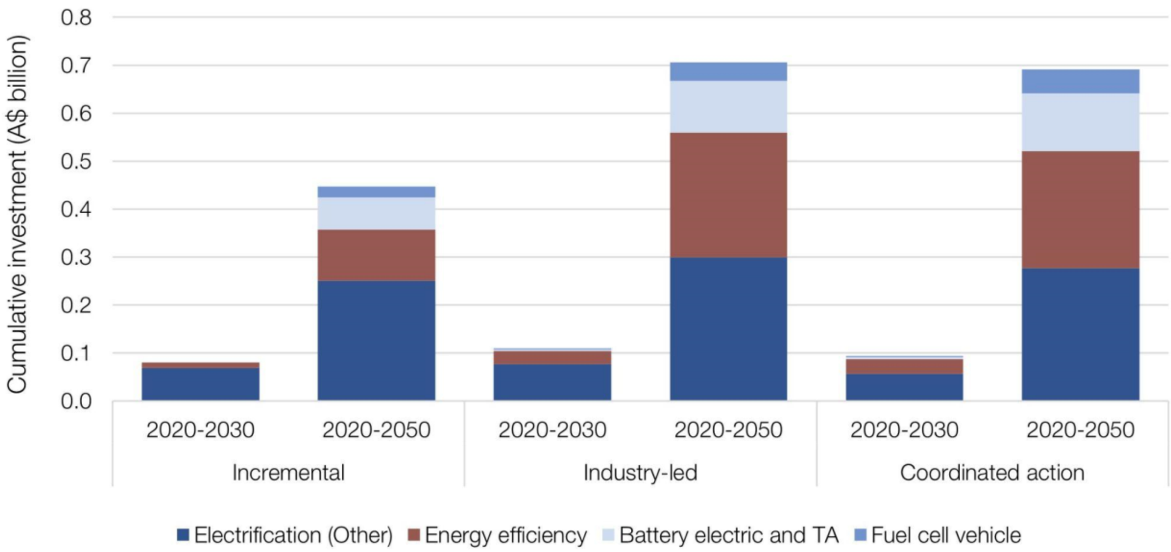


Figure 54: Investment required for alumina production

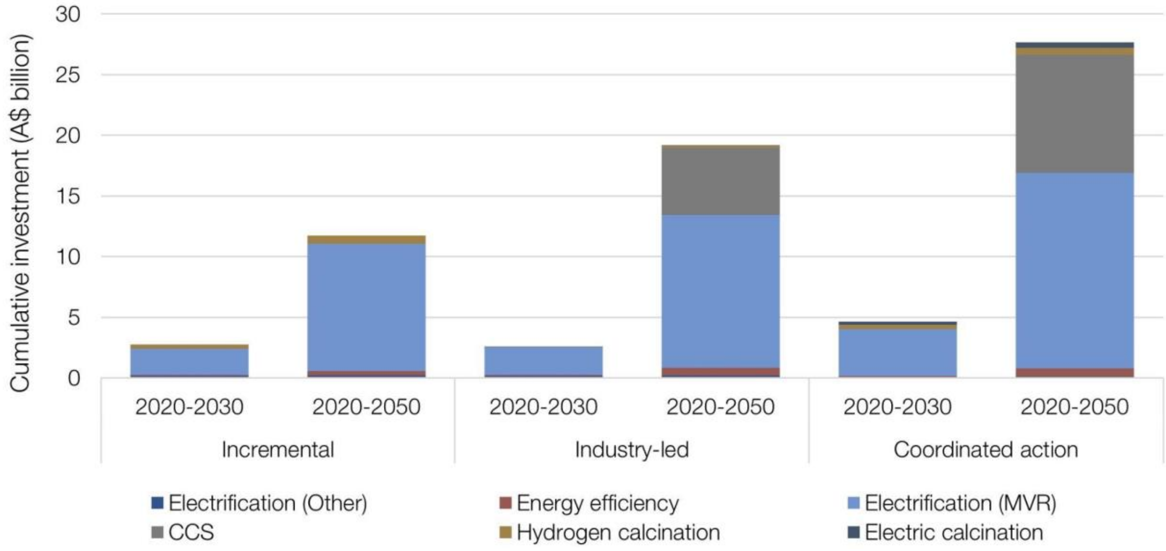
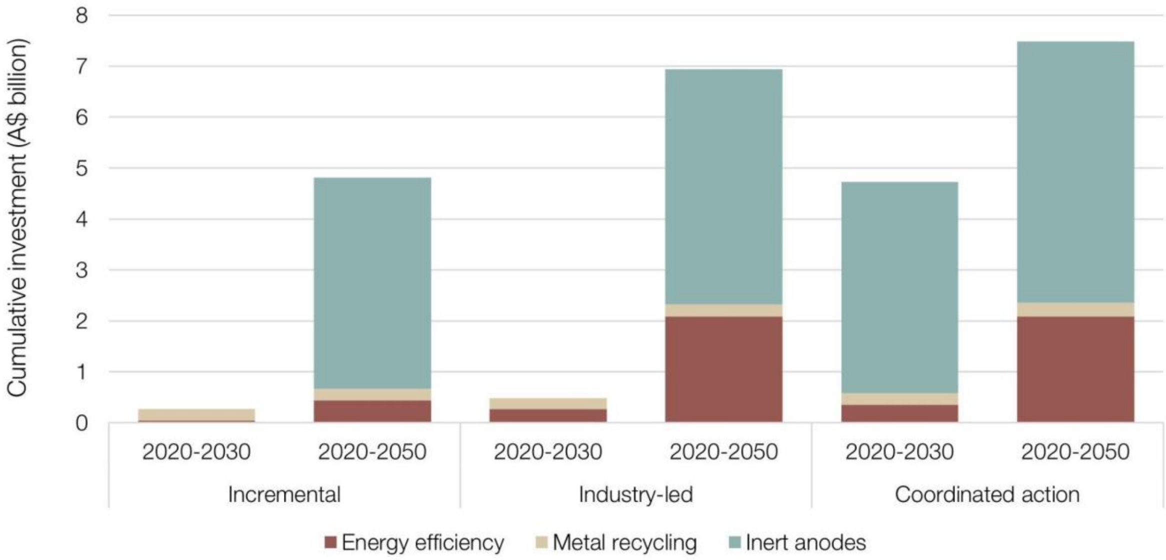


Figure 55: Investment required for aluminium production



Other metals

Figure 56: Energy use for other metals production

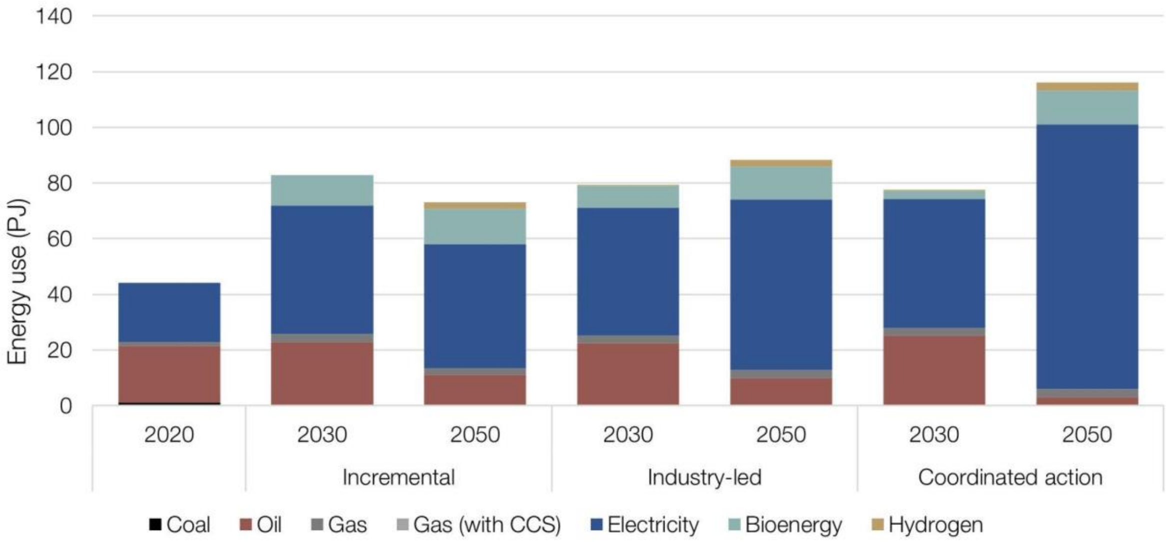


Figure 57: Emissions from other metals production

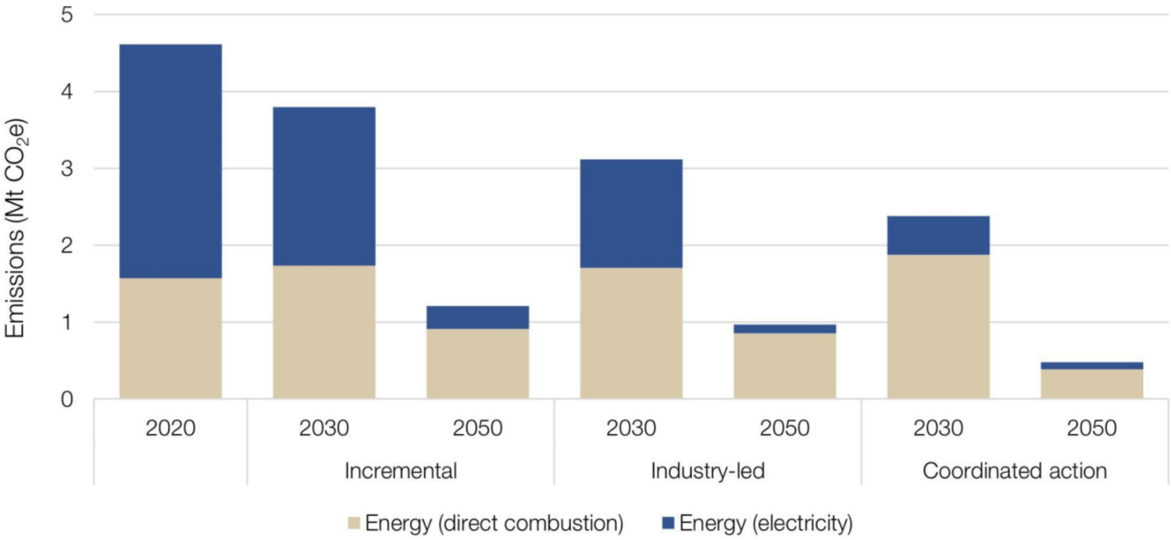
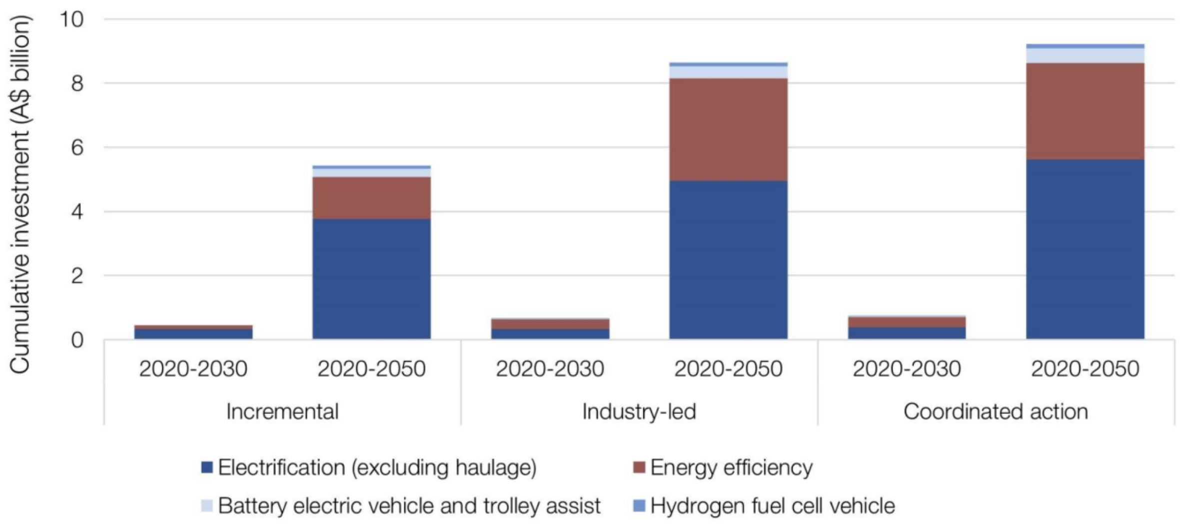


Figure 58: Investment required for other metals



Chemicals

Figure 59: Energy use for ammonia production

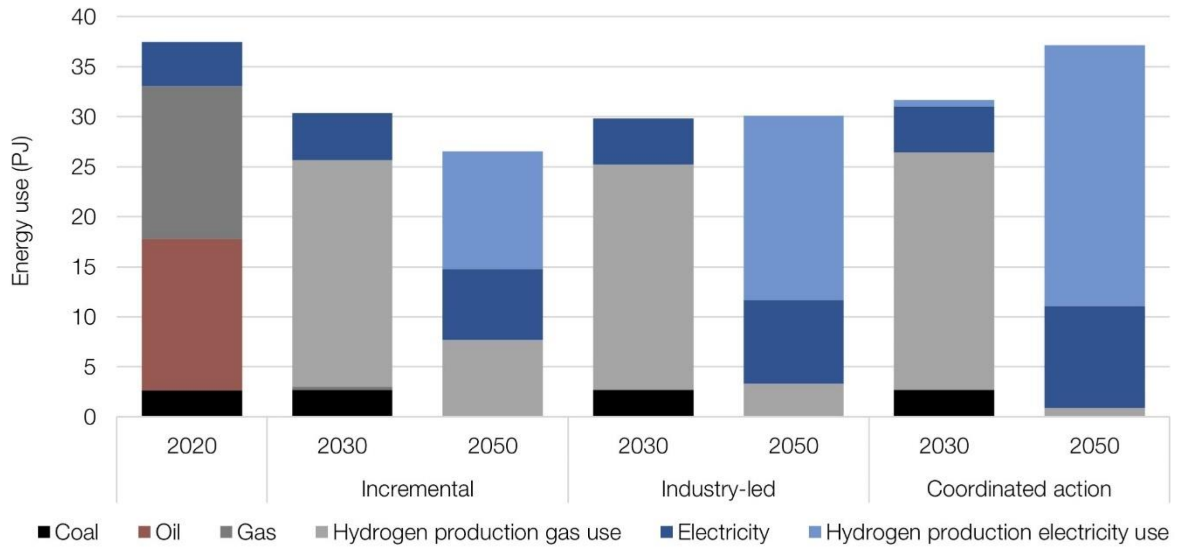


Figure 60: Energy use for commercial explosive production

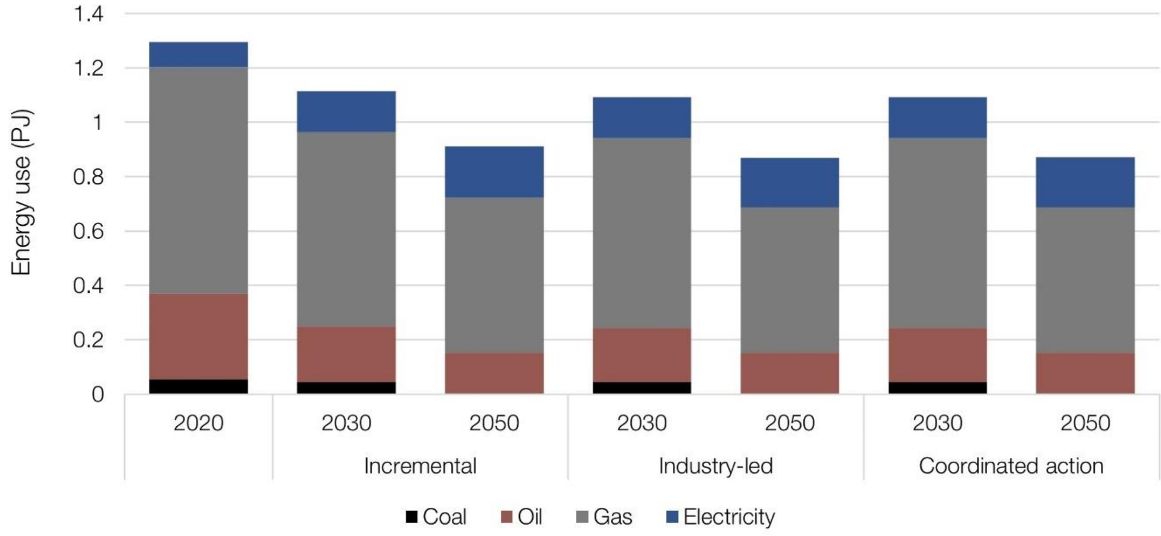


Figure 61: Energy use for fertiliser production

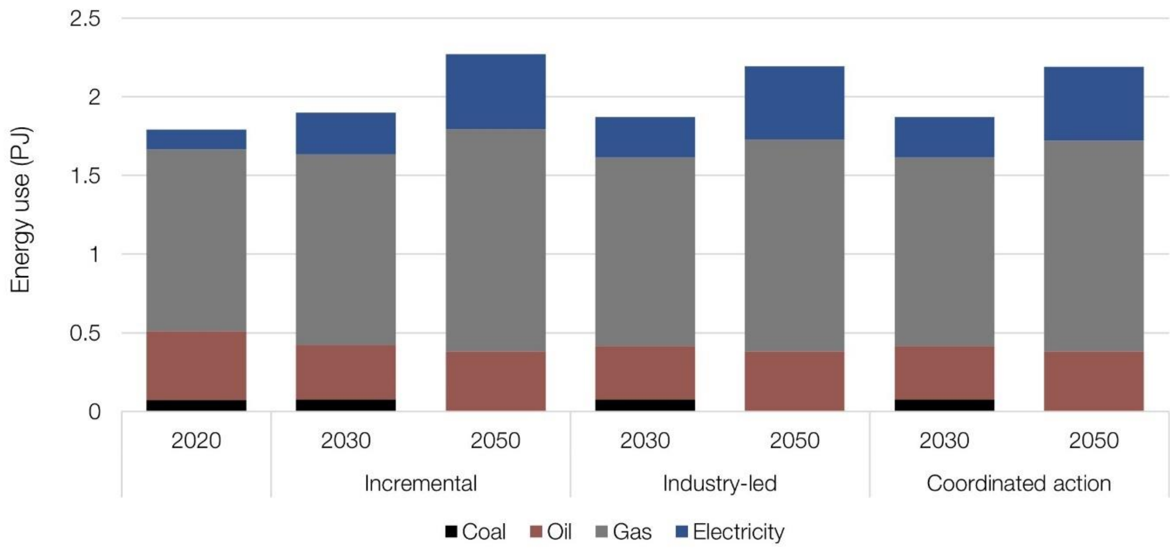


Figure 62: Emissions from ammonia production

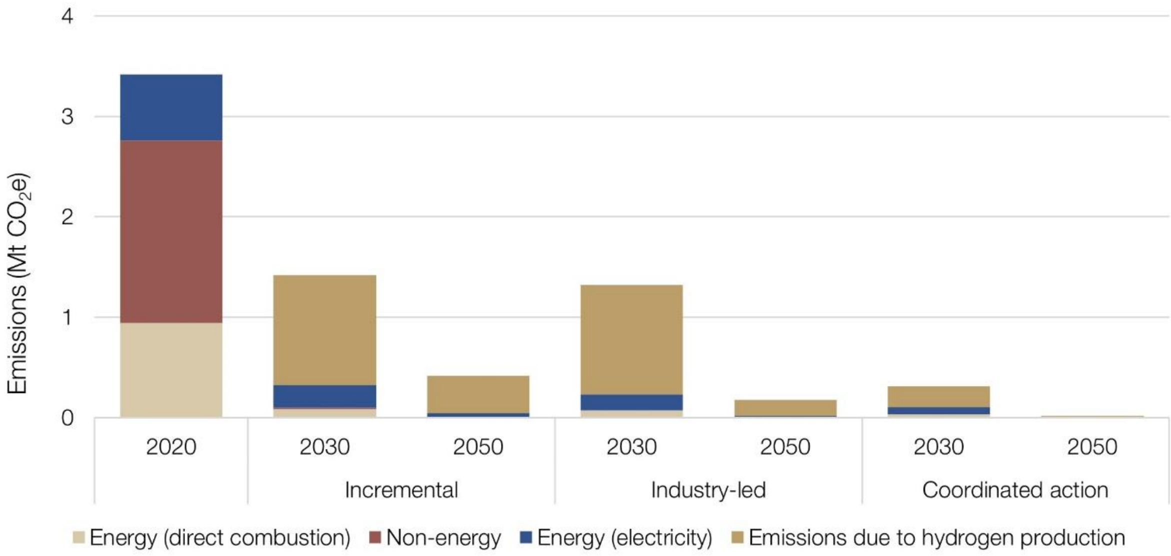


Figure 63: Emissions from commercial explosive production

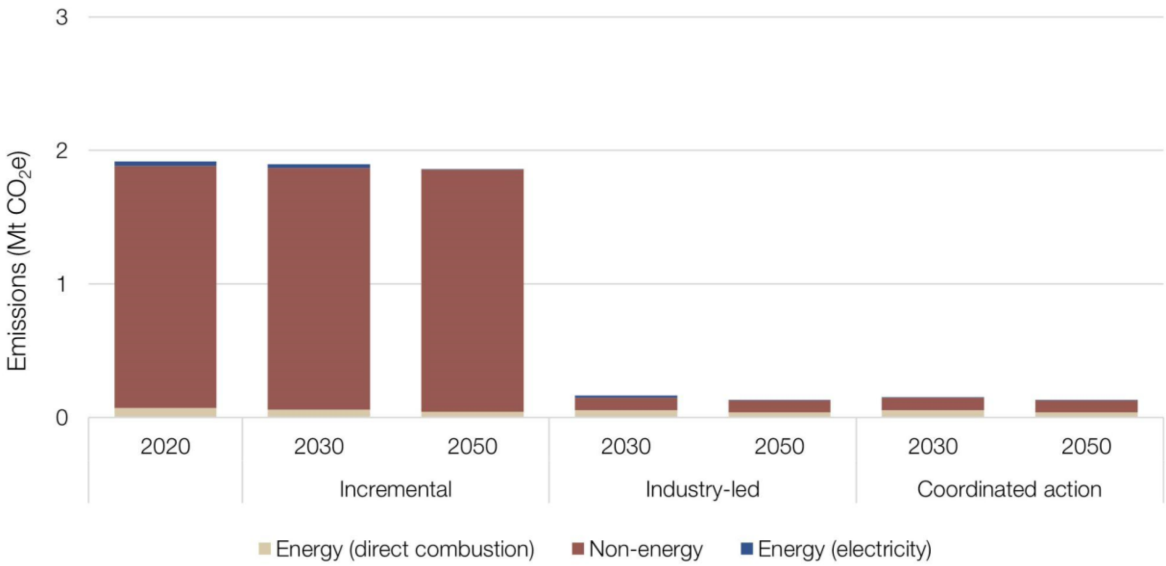


Figure 64: Emissions from fertiliser production

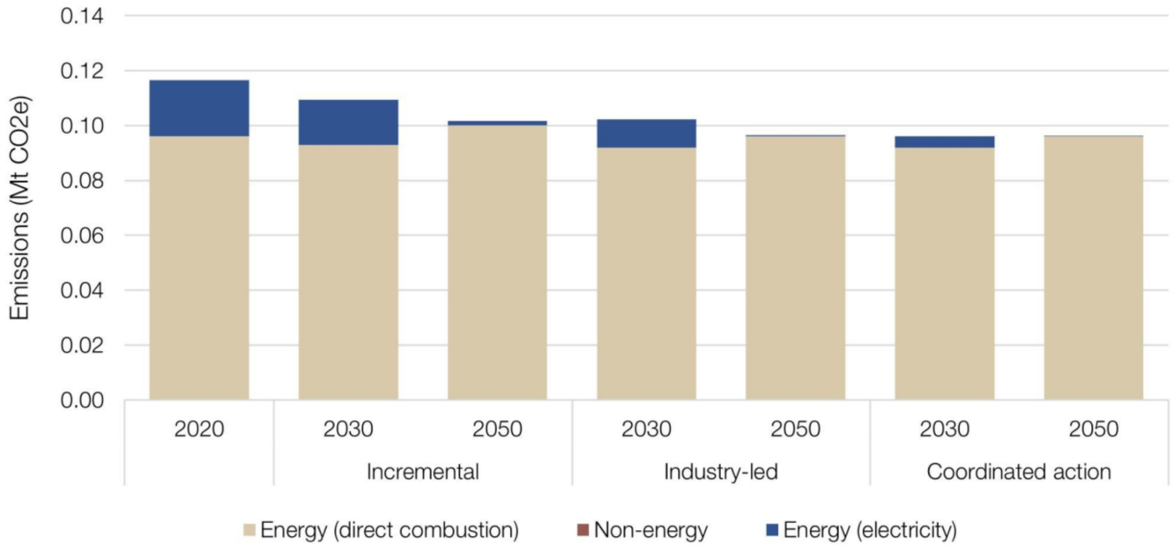
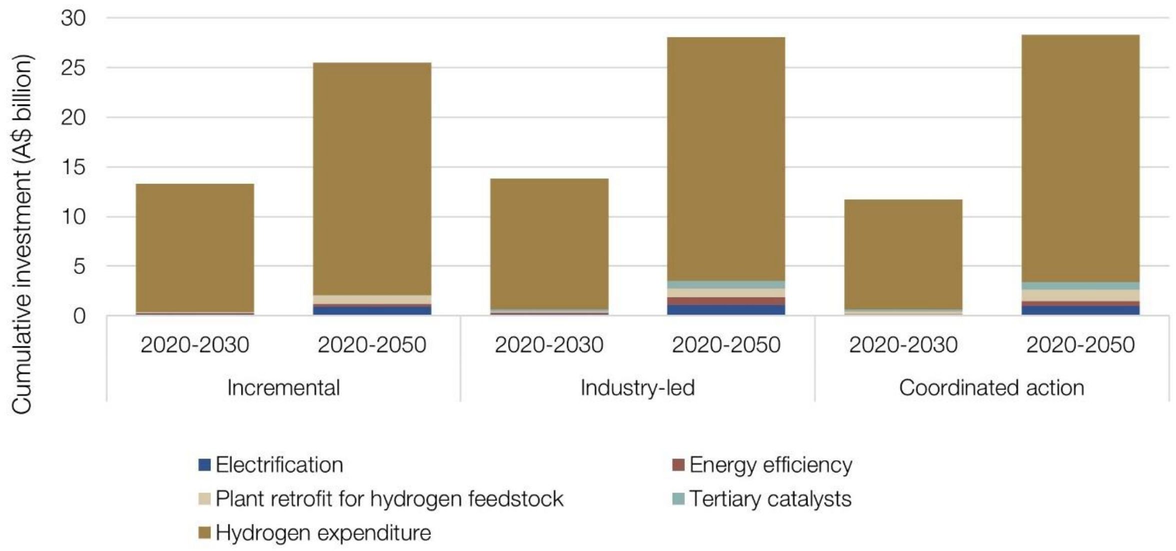


Figure 65: Investment required for ammonia, commercial explosives, and fertiliser production



LNG

Figure 66: Energy use for gas extraction and LNG production

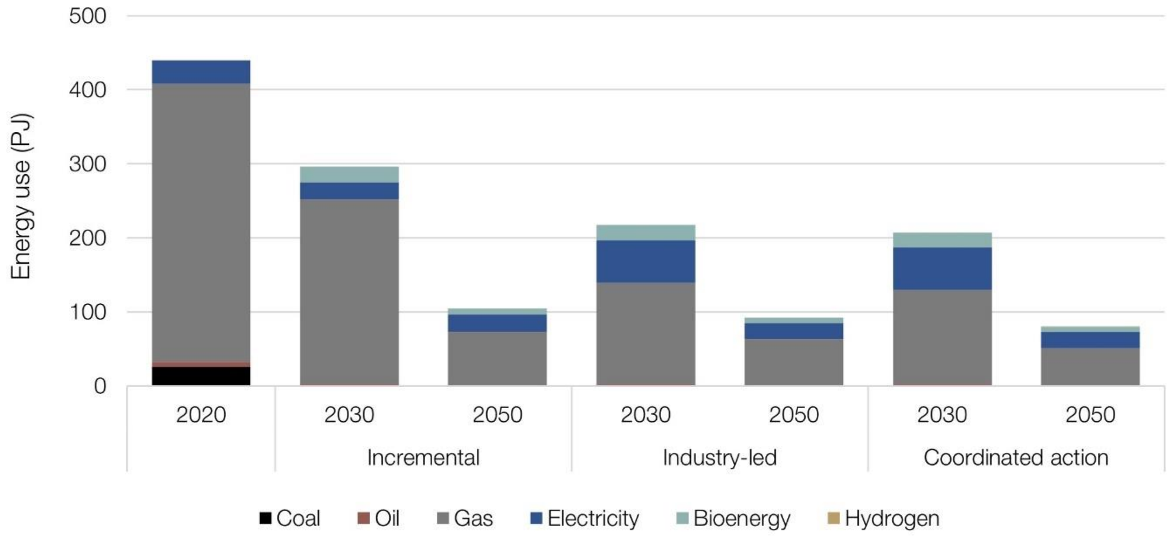


Figure 67: Emissions from gas extraction and LNG production

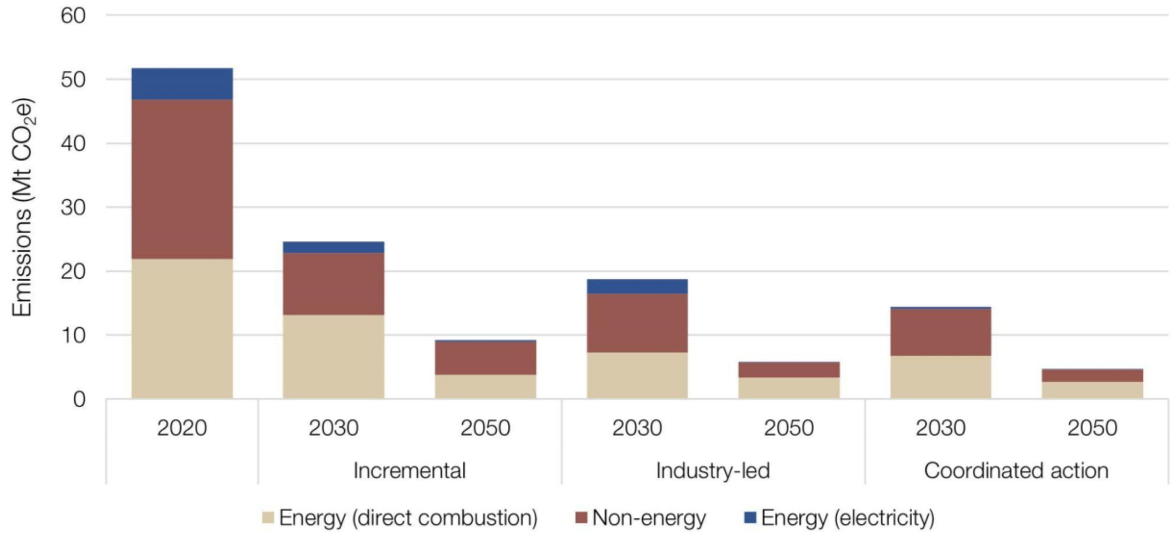
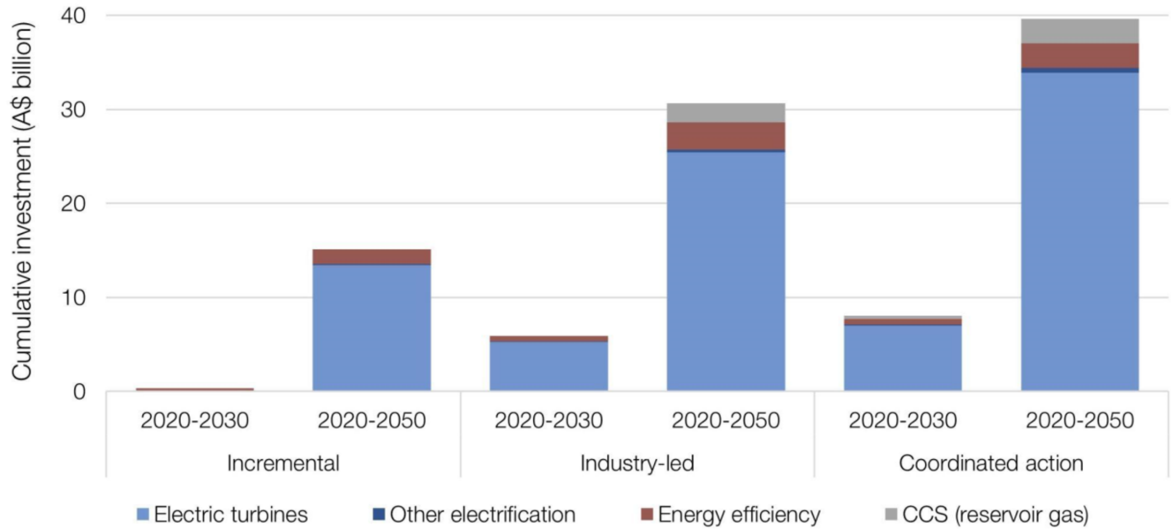
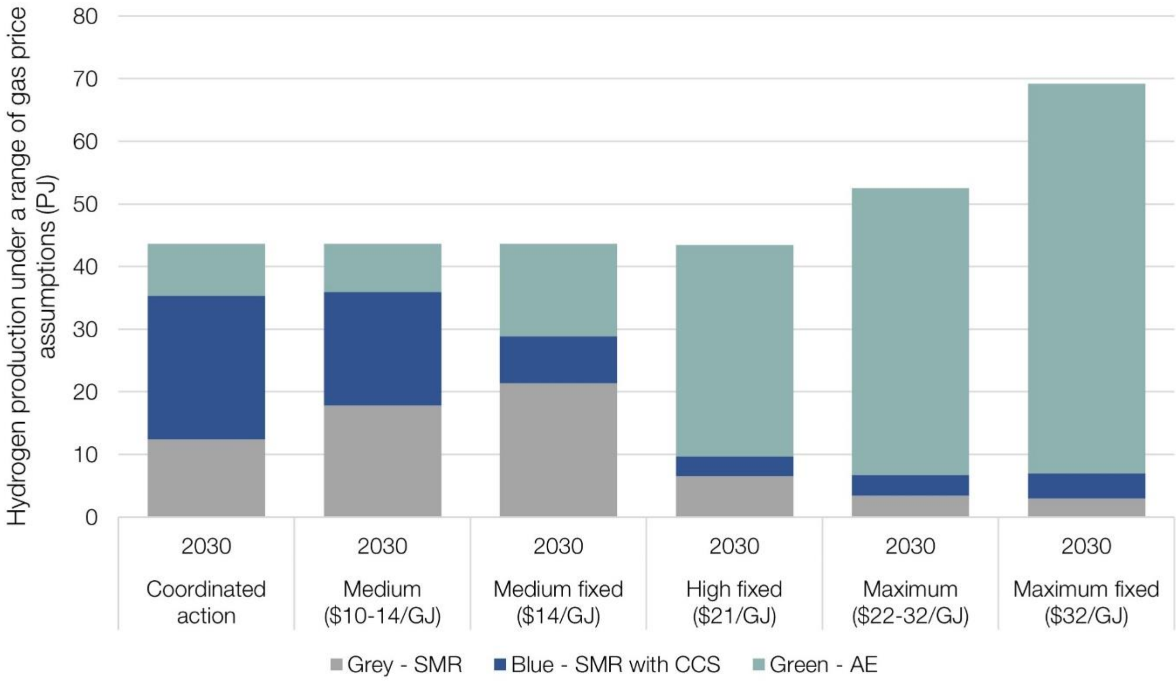


Figure 68: Investment required for gas extraction and LNG production



Sensitivity analyses results

Figure 69: Hydrogen production at differing gas prices, based on the 'Coordinated action scenario'



References

Advisian 2021, Australian hydrogen market study. Available from: https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf. [3 October 2022].

Allen, Axelsson, Caldecott, Hale, Hepburn, Hickey, & Smith 2020, “The Oxford principles for net zero aligned carbon offsetting,” University of Oxford.

Allinson, G, Cinar, Y, Hou, W, & Neal, P 2009, The Costs of CO_2 Transport and Injection in Australia. Available from: https://www.researchgate.net/profile/Peter_Neal/publication/254532325_Costs_of_CO2_Transport_and_Injection_in_Australia/links/53f7372f0cf22be01c454d93/Costs-of-CO2-Transport-and-Injection-in-Australia.pdf. [3 October 2022].

Arias, PA, N. Bellouin, E, Coppola, RG, Jones, G, Krinner, J, Marotzke, V, Naik, Palmer, G-K, Plattner, J, Rogelj, M, Rojas, J, Sillmann, T, Storelvmo, PW, Thorne, B, Trewin, K, Achuta Rao, B, Adhikary, RP, Allan, K, Armour, G, Bala, R, Barimalala, S, Berger, JG, Canadell, C, Cassou, A, Cherchi, W, Collins, WD, Collins, SL, Connors, S, Corti, F, Cruz, FJ, Dentener, C, Dereczynski, A, Di Luca, A, Diongue Niang, FJ, Doblas-Reyes, A, Dosio, H, Douville, F, Engelbrecht, V, Eyring, E, Fischer, P, Forster, B, Fox-Kemper, JS, Fuglestvedt, JC, Fyfe, NP, Gillett, L, Goldfarb, I, Gorodetskaya, JM, Gutierrez, R, Hamdi, E, Hawkins, HT, Hewitt, P, Hope, AS, Islam, C, Jones, DS, Kaufman, RE, Kopp, Y, Kosaka, J, Kossin, S, Krakovska, J-Y, Lee, J, Li, T, Mauritsen, TK, Maycock, M, Meinshausen, S-K, Min, PMS, Monteiro, T, Ngo-Duc, F, Otto, I, Pinto, A, Prani, K, Raghavan, R, Ranasinghe, AC, Ruane, L, Ruiz, J-B, Sallée, BH, Samset, S, Sathyendranath, SI, Seneviratne, AA, Sörensson, S, Szopa, I, Takayabu, A-M, Tréguier, B, van den Hurk, R, Vautard, K, von Schuckmann, S, Zaehle, X, Zhang, & Zickfeld, K 2021,“Technical Summary,” in, Climate Change 2021: The Physical Science Basis : Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. WMO, IPCC Secretariat.

Arzbaecher, C, Fouche, E, & Parmenter, K 2007, “Industrial Waste-Heat Recovery: Benefits and Recent Advancements in Technology and Applications,” European council for an energy efficient economy. Available from: https://www.eceee.org/static/media/uploads/site-2/library/conference_proceedings/ACEEE_industry/2007/Panel_2/p2_1/paper.pdf. [3 October 2022].

Australian Aluminium Council 2021, “Sustainability Data Tables.” Available from: https://aluminium.org.au/sustainability/. [3 October 2022].

Australian Bureau of Statistics 2020, Australia’s trade in goods with China in 2020. Available from: https://www.abs.gov.au/articles/australias-trade-goods-china-2020. [3 October 2022].

Australian Bureau of Statistics 2021, “Motor vehicle census, Australia.” Available from: https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/latest-release. [3 October 2022].

Australian Bureau of Statistics 2022a, Australian industry: annual estimates of key economic and financial performance of industries in Australia, including income, expenses, profit and capital expenditure. Available from: https://www.abs.gov.au/statistics/industry/industry-overview/australian-industry/latest-release. [3 October 2022].

Australian Bureau of Statistics 2022b, Labour force, Australia. Available from: https://www.abs.gov.au/statistics/labour/employment-and-unemployment/labour-force-australia-detailed/latest-release. [29 September 2022].

Australian Competition and Consumer Commission 2022, Gas inquiry 2017-2025: interim report-July 2022. Australian Competition and Consumer Commission. Available from: https://apo.org.au/node/318857. [3 October 2022].

Australian Energy Council n.d., Electricity Gas Australia. Available from: https://www.energycouncil.com.au/electricity-gas-australia/. [3 October 2022].

Australian Energy Market Operator 2020, AEMO virtual power plant demonstration: Knowledge sharing report No.1. Available from: https://aemo.com.au/-/media/files/electricity/der/2020/aemo-knowledge-sharing-stage-1-report.pdf?la=en. [13 October 2022].

Australian Energy Market Operator 2021, 2021 Inputs, Assumptions and Scenarios Report. Available from: https://aemo.com.au/-/media/files/major-publications/isp/2021/2021-inputs-assumptions-and-scenarios-report.pdf?la=en. [3 October 2022].

Australian Energy Market Operator 2022a, “Inputs assumptions and scenarios workbook.” Available from: https://aemo.com.au/-/media/files/major-publications/isp/2022/2022-documents/inputs-assumptions-and-scenarios-workbook.xlsx?la=en. [3 October 2022].

Australian Energy Market Operator 2022b, Quarterly energy dynamics Q2 2022. Australian Energy Market Operator Limited. Available from: https://aemo.com.au/-/media/files/major-publications/qed/2022/qed-q2-2022.pdf?la=en. [4 October 2022].

Australian Industry Energy Transitions Initiative 2021, Setting up industry for net zero: Phase 1 Highlights Report. Available from: https://energytransitionsinitiative.org/wp-content/uploads/2021/06/Phase-1-Highlights-Report-June-2021.pdf. [3 October 2022].

Australian Industry Energy Transitions Initiative 2022, Setting up industrial regions for net zero: Phase 2 report. Available from: https://energytransitionsinitiative.org/. [3 October 2022].

Australian Renewable Energy Agency 2019, Renewable Energy Options for Industrial Process Heat. Available from: https://arena.gov.au/assets/2019/11/appendices-renewable-energy-options-for-industrial-process-heat.pdf. [3 October 2022].

Australian Renewable Energy Agency 2022, A Roadmap for Decarbonising Australian Alumina Refining. Available from: https://arena.gov.au/knowledge-bank/a-roadmap-for-decarbonising-australian-alumina-refining/. [1 December 2022]

Azevedo, M, Goffaux, N, & Hoffman, K 2020, “How clean can the nickel industry become,” Insights, McKinsey. Available from: https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become. [3 October 2022].

Bazzanella, AM & Ausfelder, F 2017, Low Carbon Energy and Feedstock for the European Chemical Industry: Technology Study. DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V. Available from: https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf. [3 October 2022].

BloombergNEF 2020, “CCUS Costs and Opportunities for Long-term CO_2 Disposal.”

BloombergNEF 2021a, “Decarbonizing Aluminum Technologies and Costs.”

BloombergNEF 2021b, New Energy Outlook 2021. Available from: https://about.bnef.com/new-energy-outlook/. [29 September 2022].

BloombergNEF 2021c, “Decarbonizing Steel Technologies and Costs.”

Bogliolo, M, Leo Servidio, S, & Ricchetti, P 2017, Energy Efficiency Investments in the Gas Midstream Sector in Egypt: Feasibility Study and Project Preparation. European Bank for Reconstruction and Development. Available from: https://www.ebrd.com/documents/procurement/feasibility-study.pdf. [3 October 2022].

Brown, T 2021, Carbon intensity of fossil ammonia in a net-zero world, Ammonia Energy Association. Available from: https://www.ammoniaenergy.org/articles/carbon-intensity-of-fossil-ammonia-in-a-net-zero-world/. [3 October 2022].

Bruce, S, Temminghoff, M, Hayward, J, Schmidt, E, Munnings, C, Palfreyman, D, & Hartley, P 2018, National Hydrogen Roadmap. CSIRO. Available from: https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/energy-and-resources/national-hydrogen-roadmap. [3 October 2022].

Byers, E, Krey, V, Kriegler, E, Riahi, K, Schaeffer, R, Kikstra, J, Lamboll, R, Nicholls, Z, Sandstad, M, Smith, C, van der Wijst, K, Lecocq, F, Portugal-Pereira, J, Saheb, Y, Stromann, A, Winkler, H, Auer, C, Brutschin, E, Lepault, C, Müller-Casseres, E, Gidden, M, Huppmann, D, Kolp, P, Marangoni, G, Werning, M, Calvin, K, Guivarch, C, Hasegawa, T, Peters, G, Steinberger, J, Tavoni, M, van Vuuren, D, Al -Khourdajie, A, Forster, P, Lewis, J, Meinshausen, M, Rogelj, J, Samset, B, & Skeie, R 2022, "AR6 Scenarios Database." Available from: https://zenodo.org/record/5886912.

Chan, Y, Petithuguenin, L, Fleiter, T, Herbst, A, Arens, M, & Stevenson, P 2019, Industrial innovation: Pathways to deep decarbonisation of industry. Pt. 1: Technology analysis. ICF. Available from: https://climate.ec.europa.eu/system/files/2019-03/industrial_innovation_part_1_en.pdf. [3 October 2022].

Chatfield, Ray 2022, Mechanical Vapour Recompression for Low Carbon Alumina Refining. Available from: https://arena.gov.au/knowledge-bank/mvr-retrofit-and-commercialisation-report/. [1 December 2022].

Chevron 2011, Gorgon Project Overview - Producing Liquefied Natural Gas in Australia. Available from: https://www.chevron.com/projects/gorgon. [3 October 2022].

Chevron 2015, Gorgon Gas Development and Jansz Feed Gas Pipeline: Greenhouse Gas Abatement Program. Available from: https://australia.chevron.com/-/media/australia/our-businesses/documents/gorgon-emp-greenhouse-gas-abatement-program.pdf. [3 October 2022].

Climateworks Centre 2020, Decarbonisation futures: Solutions, actions and benchmarks for a net zero emissions Australia. Available from: https://www.climateworkscentre.org/wp-content/uploads/2020/04/Decarbonisation-Futures-March-2020-full-report-.pdf. [3 October 2022].

Climateworks Centre, ANU, CSIRO and CoPS 2014, Pathways to deep decarbonisation in 2050: how Australia can prosper in a low carbon world: technical report. Available from: https://www.climateworkscentre.org/wp-content/uploads/2014/09/climateworks_pdd2050_technicalreport_20140923-1.pdf. [3 October 2022].

Connor, JD, Bryan, BA, Nolan, M, Stock, F, Gao, L, Dunstall, S, Graham, P, Ernst, A, Newth, D, Grundy, M, & Hatfield-Dodds, S 2015, "Modelling Australian land use competition and ecosystem services with food price feedbacks at high spatial resolution," Environmental Modelling & Software, vol. 69, pp. 141–154.

CSIRO 2019, Australian National Outlook 2019. Commonwealth Scientific and Industrial Research Organisation. Available from: https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Innovation-Business-Growth/Australian-National-Outlook. [3 October 2022].

van Dam, D, Palacios, SG, & Wetzels, W 2021, "Manufacturing Industry Decarbonisation Data Exchange Network database." Available from: https://www.pbl.nl/en/publications/manufacturing-industry-decarbonisation-data-exchange-network-the-database-version-0.3. [3 October 2022].

De Santis, M, Donato, AD, Kempken, T, Hauck, T, & Draxler, M 2021, Investment Needs. Greensteel for Europe Consortium. Available from: https://www.estep.eu/assets/Uploads/GreenSteel-D2.2-Investment-Needs-Publishable-version.pdf. [3 October 2022].

De Vita, Kielichowska, & Mandatowa 2018, Technology pathways in decarbonisation scenarios. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf. [29 September 2022].

Deloitte 2022, Oil and gas price forecast Strategic transitioning: The future of oil and gas in a decarbonized world. Deloitte. Available from: https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/energy-resources/ca-en-energy-resources-industrials-o-g-price-forecast-report-Q1-aoda.pdf. [29 September 2022].

Department of Climate Change, Energy, the Environment and Water 2022, Australian energy statistics. Available from: https://www.energy.gov.au/government-priorities/energy-data/australian-energy-statistics. [Oct, 03 2022].

Department of Industry, Science, Energy and Resources 2019, Australia's National Hydrogen Strategy. Australian Government - Department of Industry and Science.

Department of Industry, Science, Energy and Resources 2021a, Australia's Long-Term Emissions Reduction Plan: Modelling and Analysis. Available from: https://www.dcceew.gov.au/sites/default/files/documents/australias-long-term-emissions-reduction-plan-modelling.pdf. [December 2021].

Department of Industry, Science, Energy and Resources 2021b, Resources and energy quarterly, D Thurtell (ed). Available from: https://www.industry.gov.au/sites/default/files/2022-08/resources-and-energy-quarterly-june-2021.pdf. [3 October 2022].

Department of Industry, Science, Energy and Resources 2021c, "Australian Energy Statistics Table F," Australian Energy Update 2021. Available from: https://www.energy.gov.au/sites/default/files/Australian%20Energy%20Statistics%202021%20Table%20F_0.xlsx. [3 October 2022].

Department of Resources, Energy and Tourism n.d., Analyses of Diesel Use for Mine Haul and Transport Operations. Available from: https://www.energy.gov.au/sites/default/files/analyses_of_diesel_use_for_mine_haul_and_transport_operations.pdf. [3 October 2022].

Department of the Environment and Energy 2017, "National greenhouse accounts factors." Available from: https://www.dcceew.gov.au/sites/default/files/documents/national-greenhouse-accounts-factors-july-2017.pdf. [3 October 2022].

Devold, H, Nestli, T, & Hurter, J n.d., "All electric LNG plants. Better, safer, more reliable-and profitable." Available from: https://library.e.abb.com/public/9e770a172afc8d7ec125779e004b9974/Paper%20LNG_Rev%20A_lowres.pdf. [3 October 2022].

Dialogue on European Decarbonisation Strategies 2020, "Industry - Iron and Steel." Available from: https://deeds.eu/wp-content/uploads/2020/05/Iron-and-Steel_web.pdf. [September 2021].

DIW Berlin n.d., DIW Berlin: Models. Available from: https://www.diw.de/en/diw_01.c.599753.en/models.html. [29 September 2022].

Energy Transitions Commission 2018, Mission Possible: reaching net-zero carbon emissions from harder-to-abate sectors by mid-century. Available from: https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC_MissionPossible_FullReport.pdf. [4 October 2022].

Fan, Z & Friedmann, SJ 2021, "Low-carbon production of iron and steel: Technology options, economic assessment, and policy," Joule, vol. 5, no. 4, pp. 829–862.

Fishbone, LG & Abilock, H 1981, “Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version,” International Journal of Energy Research, vol. 5, no. 4, pp. 353–375.

Fowler, E & Macdonald-Smith, A 2022, Industry faces crisis as gas contracts may triple, Australian Financial Review. Available from: https://www.afr.com/companies/energy/industry-faces-crisis-as-gas-contracts-may-triple-20220830-p5bdya. [29 September 2022].

GFG Alliance 2018, GFG Alliance Sustainability Report. Available from: https://www.infrabuild.com/resources/sustainability-resources/gfg-sustainability-report-2018/. [3 October 2022].

Ghenda, JT & Lüngen, HB 2013, “Potential for CO_2 Mitigation of the European Steel Industry.” Available from: https://ieaghg.org/docs/General_Docs/Iron%20and%20Steel%202%20Secured%20presentations/2_1550%20Jean%20Theo%20Ghenda.pdf. [3 October 2022].

Government of Western Australia 2022, Whole of System Plan, Wa.gov.au. Available from: https://www.wa.gov.au/government/document-collections/whole-of-system-plan. [3 October 2022].

Graham, P, Hayward, J, Foster, J and Havas, L 2022, GenCost 2021-22: Final report, CSIRO, Australia. Available from: https://publications.csiro.au/publications/publication/PIcsiro:EP2022-2576/SQGenCost/RP1/RS25/RORECENT/STsearch-by-keyword/LISEA/RI3/RT10. [29 September 2022].

Greening & Bataille 2009, “Bottom-up models of energy: across the spectrum,” Handbook on the economics of giving, reciprocity and altruism. Available from: https://www.elgaronline.com/downloadpdf/edcoll/9781847203526/9781847203526.00016.pdf.

Hoffman, KC & Jorgenson, DW 1977, “Economic and Technological Models for Evaluation of Energy Policy,” The Bell Journal of Economics, vol. 8, no. 2, pp. 444–466.

International Energy Agency 2020a, IEA G20 Hydrogen report: Assumptions. Available from: https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf. [3 October 2022].

International Energy Agency 2020b, Energy Technology Perspectives 2020 - Special Report on Carbon Capture Utilisation and Storage: CCUS in Clean Energy Transitions. OECD Publishing. Available from: https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf. [3 October 2022].

International Energy Agency 2021, Net Zero by 2050: A Roadmap for the Global Energy Sector. Available from: https://www.iea.org/reports/net-zero-by-2050. [3 October 2022].

International Energy Agency 2022, “Methane Tracker Data Explorer.” Available from: https://www.iea.org/data-and-statistics/data-tools/methane-tracker-data-explorer. [3 October 2022].

International Energy Agency Energy Technology Systems Analysis Program n.d., Energy Technology Systems Analysis Program. Available from: https://iea-etsap.org/. [28 September 2022].

International Monetary Fund 2021, World economic outlook. Available from: https://www.elibrary.imf.org/abstract/books/081/29821-9781513575025-en/front-1.xml. [21 September 2022].

IPCC 2022,“Summary for Policymakers,” in, Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Kerttu, M 2019, Evaluation of Electric and Hybrid Steam Generation for a Chemical Plant under Future Energy Market Scenarios. Available from: https://odr.chalmers.se/handle/20.500.12380/256671.

Khan, MS, Karimi, IA, & Wood, DA 2017, “Retrospective and future perspective of natural gas liquefaction and optimization technologies contributing to efficient LNG supply: A review,” Journal of Natural Gas Science and Engineering, vol. 45, pp. 165–188.

Li, J & Hitch, M 2018, “Economic analysis on the application of mechanical activation in an integrated mineral carbonation process,” International biodeterioration & biodegradation, vol. 128, pp. 63–71.

Madeddu, S, Ueckerdt, F, Pehl, M, Peterseim, J, Lord, M, Kumar, KA, Krüger, C, & Luderer, G 2020, “The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat),” Environmental research letters: ERL [Web site], vol. 15, no. 12, p. 124004.

Manne, AS 1976, “ETA: A Model for Energy Technology Assessment,” The Bell Journal of Economics, vol. 7, no. 2, pp. 379–406.

Marsidi, M 2018, “Technology Factsheet Industrial Mechanical Vapour Recompression (MVR).” Available from: https://energy.nl/wp-content/uploads/industrial-mechanical-vapour-recompression-1-7.pdf. [3 October 2022].

Mission Possible Partnership 2022a, Making net-zero steel possible. An industry-backed, 1.5°C-aligned transition strategy. Available from: https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-Net-Zero-Steel-possible.pdf. [4 October 2022].

Mission Possible Partnership 2022b, Making net-zero aluminium possible. An industry-backed, 1.5°C-aligned transition strategy. Available from: https://missionpossiblepartnership.org/wp-content/uploads/2022/10/Making-1.5-Aligned-Aluminium-possible.pdf. [3 October 2022].

National Greenhouse and Energy Reporting (Safeguard Mechanism) Rule 2015. Available from: https://www.legislation.gov.au/Details/F2020C00926. [3 October 2022].

Nieuwlaar, E, Roes, AL, & Patel, MK 2016, “Final energy requirements of steam for use in environmental life cycle assessment,” Journal of Industrial Ecology, vol. 20, no. 4, pp. 828–836.

Office of the Chief Economist 2022, Resources and energy quarterly March 2022: aluminium. Department of Industry, Science and Resources. Available from: https://www.industry.gov.au/sites/default/files/minisite/static/c439c60d-5be7-4d19-8353-d70c1e8515c0/resources-and-energy-quarterly-march-2022/documents/Resources-and-Energy-Quarterly-March-2022-Aluminium.pdf. [3 October 2022].

Paris Agreement inventory n.d., Australia’s National Greenhouse Accounts. Available from: https://ageis.climatechange.gov.au/. [3 October 2022].

Perander, Gasafi, & Scarsella 2018, “Cost and Energy Efficiency Improvment in Alumina Calcination,” Alumina Quality Workshop Inc. Available from: https://www.aqw.com.au/papers/item/cost-and-energy-efficiency-improvement-in-alumina-calcination. [3 October 2022].

Reedman, L, Chew, MS, Gordon, J, Sue, W, Brinsmead, T, Hayward, J, & Havas, L 2021, “Multi-sector energy modelling.” Available from: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/isp/2021/csiro-multi-sector-modelling.pdf. [21 September 2022].

Rogelj, J, Shindell, D, Jiang, K, Fifita, S, Forster, P, Ginzburg, V, Handa, C, Kheshgi, H, Kobayashi, S, Kriegler, E, Mundaca, L, Séférian, R, Vilarino, MV, Calvin, K, de Oliveira de Portugal Pereira, JC, Edelenbosch, O, Emmerling, J, Fuss, S, Gasser, T, Gillett, N, He, C, Hertwich, E, Höglund-Isaksson, L, Huppmann, D, Luderer, G, Markandya, A, Meinshausen, M, McCollum, D, Millar, R, Popp, A, Purohit, P, Riahi, K, Ribes, A, Saunders, H, Schädel, C, Smith, C, Smith, P, Trutnevyte, E, Xu, Y, Zhou, W, & Zickfeld, K 2018,“Mitigation Pathways Compatible with 1.5°C in the Context of

Sustainable Development," in, Global warming of 1.5 °C, pp.93–174. Intergovernmental Panel on Climate Change.

Scarsella, AA, Noack, S, Gasafi, E, Klett, C, & Koschnick, A 2016,"Energy in Alumina Refining: Setting New Limits," in M Hyland (ed), Light Metals 2015, pp.131–136. Springer International Publishing, Cham.

Soergel, B, Kriegler, E, Weindl, I, Rauner, S, Dirnaichner, A, Ruhe, C, Hofmann, M, Bauer, N, Bertram, C, Bodirsky, BL, Leimbach, M, Leininger, J, Levesque, A, Luderer, G, Pehl, M, Wingens, C, Baumstark, L, Beier, F, Dietrich, JP, Humpenöder, F, von Jeetze, P, Klein, D, Koch, J, Pietzcker, R, Strefler, J, Lotze-Campen, H, & Popp, A 2021, "A sustainable development pathway for climate action within the UN 2030 Agenda," Nature climate change, vol. 11, no. 8, pp. 656–664.

Task Force on Climate-Related Financial Disclosures 2017, Recommendations of the task force on climate-related financial disclosures. Task Force on Climate-Related Financial Disclosures. Available from: https://assets.bbhub.io/company/sites/60/2021/10/FINAL-2017-TCFD-Report.pdf.

The Danish Energy Agency 2021, "Datasheet for industrial process heat," Technology Data for Industrial Process Heat. Available from: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-industrial-process-heat. [3 October 2022].

United Nations Environment Programme and Climate and Clean Air Coalition 2021, Global methane assessment: Benefits and costs of mitigating methane emissions. Available from: https://wedocs.unep.org/bitstream/handle/20.500.11822/35913/GMA.pdf. [34 October 2022].

ter Weer, P-H 2016,"Sustaining capital of alumina refinery projects — important but unloved," in, Light Metals 2016, pp.81–83. Springer International Publishing, Cham.

World Resources Institute 2004, The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. World Business Council for Sustainable Development.

Glossary

A$	Australian dollars
ACCUs	Australian carbon credit units
AEMO	Australian Energy Market Operator
AN	ammonium nitrate
ANZSIC	Australian and New Zealand Standard Industrial Classification
ARENA	Australian Renewable Energy Agency
AusTIMES	Australian version of TIMES, The Integrated MARKAL-EFOM System
Australian Industry ETI	Australian Industry Energy Transitions Initiative
Bcm	billion cubic metres
BF-BOF	blast furnace-basic oxygen furnace
BloombergNEF	Bloomberg New Energy Finance
CAPEX	capital expenditure
CCS	carbon capture and storage
CCU	carbon capture utilisation
CCUS	carbon capture utilisation and storage
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	direct air capture
DISER	Department of Industry, Science and Resources
DRI-EAF	direct reduced iron–electric arc furnace

DRI-Melter-BOF	direct reduced iron–melter–basic oxygen furnace
EAF	electric arc furnace
ETSAP	Energy Technology Systems Analysis Project
EV	electric vehicle
FCEV	fuel cell electric vehicle
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
GWh	gigawatt hours
H_2	hydrogen
HBI	hot briquetted iron
ICE	internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISP	Integrated System Plan
kWh	kilowatt hour
kt	kilotonne
km	kilometre

LDAR	leak detection and repair
LED	light emitting diode
LNG	liquified natural gas
LULUCF	land use, land use change and forestry
LUTO	Land Use Trade-Offs
MCH	methylcyclohexane
Mha	million hectares
MRIWA	Minerals Research Institute of Western Australia
Mt	megatonne
$MtCO_2e$	megatonne of carbon dioxide equivalent
MVR	mechanical vapour recompression
MWh	megawatt hour
MWth	megawatt thermal
N_2O	nitrous oxide
NEM	National Electricity Market
NERA	National Energy Resources Australia
NG	natural gas
NDC	nationally determined contribution
NSW	New South Wales
NZE	net zero emissions

O&M	operations & maintenance
OECD	Organisation for Economic Co-operation and Development
OPEX	operating expense
PFCs	perfluorocarbons
PJ	petajoule
PPA	power purchase agreement
PV	photovoltaic
R&D	research and development
RE	renewable energy
REIP	Renewable Energy Industrial Precinct
RET	Renewable Energy Target
RFP	request for proposal
RMI	Rocky Mountain Institute
SA	South Australia
SDS	Sustainable Development Scenario
SMR	steam methane reforming
STABLE	Spatial Temporal Analysis of Balancing Levelised-Cost of Energy
SWIS	South West Interconnected System
TAS	Tasmania
TCFD	Task Force for Climate Related Financial Disclosures

TIMES	The Integrated MARKAL-EFOM System
TRL	technology readiness level
TWh	terawatt hour
VIC	Victoria
V2G	vehicle-to-grid
V2H	vehicle-to-home
VPP	virtual power plant
VRE	variable renewable energy
WA	Western Australia

FURTHER INFORMATION

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Australian Industry Energy Transitions Initiative

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