HiTeMP-2 Outlook Report

The pathway to net-zero CO_2 emissions for heavy industry

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HiTeMP-2 Forum 2020

Foreword

High temperature mineral processing is a critical industry for the world's economic development but is also responsible for approximately 20 per cent of global carbon emissions.

To address climate change, visionary thinking is needed to transition high temperature mineral processing to net zero carbon emissions by 2050 at the latest.

The global HiTeMP forum led by the University of Adelaide is part of the solution – identifying opportunities to address this challenge and determining what is required to scale up pioneering and potentially disruptive technologies for metal and cement manufacturing.

HiTeMP-2 has successfully brought together international specialists from industry, research and government to examine the possibilities, barriers and enablers to bring forward carbon neutrality for high temperature mineral processing.

South Australia is an international leader in cutting-edge energy solutions, and welcomes the opportunity to host this international forum in transitioning high temperature mineral processing to carbon neutrality, on a viable, competitive footing.

I'm excited that South Australia is leading the world in integrating distributed energy with our world leading solar and batteries schemes, to transition to a modern energy system. The South Australian Government is focused on accelerating industrial-scale clean hydrogen production to export both hydrogen and low emission commodities competitively.

Just as HiTeMP is up for the challenge in charting a pathway to carbon neutrality, the South Australian Government will grow climate-smart and low emission industries, create new jobs and attract additional investment, particularly to regional areas.

The scale of the task is immense, but through collaboration between industry, research partners and government we can advance the breakthrough technologies needed to transform and grow Australia's heavy industries while simultaneously addressing global warming.

I commend the HiTeMP-2 forum for its far-sighted approach, which is consistent with South Australia's intention to support heavy industries to make the transformation to net zero emissions.

Hon Dan van Holst Pellekaan MP
Minister for Energy and Mining
Government of South Australia

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About the second HiTeMP Forum

HiTeMP-2 consolidated the HiTeMP Forum's position as a globally leading think-tank, engaging international specialists from industry, research, government, and community to chart the path for the heavy industrial sector to transition to a new, low-net-carbon future. Despite the very significant disruptions caused by the COVID-19 pandemic, overall participation increased by 70% from the first forum and successfully integrated the simultaneous streaming of virtual participants from across the world within the live meeting of delegates.

An initiative of the University of Adelaide's Centre for Energy Technology, HiTeMP-2 attracted 169 delegates from 15 countries, of which 64% participated on-line owing to travel restrictions imposed by the outbreak of COVID-19. Of these delegates, 39% were from industry, 43% from research institutions, 14% from government agencies, and 4% from non-governmental organisations. Furthermore, 90% of respondents agreed that HiTeMP-2 was highly relevant to them and that they would recommend this forum to their colleagues.

As a multi-stakeholder forum, HiTeMP-2 engaged panels of specialists with complementary backgrounds to identify for this sector drivers, opportunities, barriers, and enablers for a low-net-carbon transition. The forum synthesises key perspectives from a stakeholder group, recognising that seeking consensus on all points is unrealistic. Nevertheless, some clear findings and points of consensus did emerge, all of which are summarised in this report. Forum participants identified important opportunities for 'green' hydrogen (H_2), electrification, and the direct use of heat from concentrating solar thermal energy. Identification of these, occurred within the varying contexts of iron/steel, alumina/aluminium, and cement/lime industries, which together are the major industrial contributors to industrial greenhouse gas emissions (GHGs). HiTeMP-2 also included some discussion on other selected commodities, including copper (Cu), nickel (Ni), lithium (Li), and zinc (Zn), which constitutes an expansion in scope from the first forum.

Unlike a traditional conference, all speakers are invited, although all delegates engage in extended discussion sessions, both face-to-face and via the on-line SliDo App, for those participating virtually. Both the presentations and discussions are available for streaming from the website and the YouTube channel.

The Centre gratefully acknowledges the outstanding support from the Steering Committee, its Advisory Board, Mission Innovation via ARENA's International Engagement Program, and University of Adelaide's Institute for Mineral and Energy Resources. We are looking forward to welcoming past delegates and new participants to Adelaide in 2022 for the third event in the series!

The distribution of countries represented at HiTeMP-2.

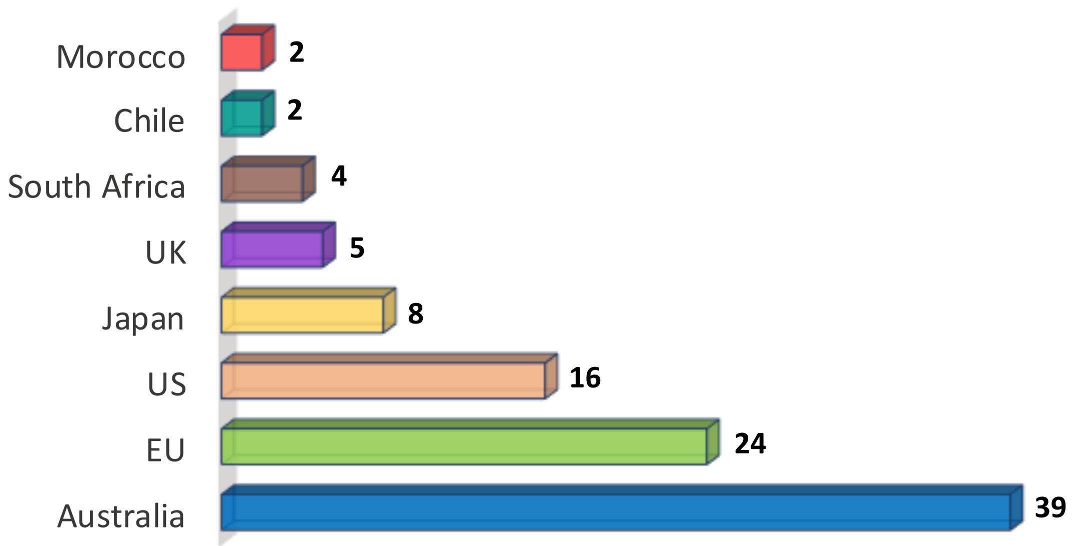


Table of the 70 organisations participating in HiTeMP-2.

Abengoa, Spain	Intercast & Forge, South Australia
Adelaide Brighton, South Australia	IP Group, United Kingdom
Advanced Mining Technology Centre, Chile	ITP Thermal, Australia
Alcoa, Australia	John Cockerill
Australian Renewable Energy Agency (ARENA)	Karlsruhe Institute of Technology, Germany
Arizona State University	Liberty OneSteel, Australia
Australian Climate Agencies	Lithium Australia
Australian National University	Maptek, South Australia
Australian Steel Institute	Metro Power, South Australia
Beyond Zero Emissions, Australia	Midrex, United States
BHP, Australia	Mintek, South Africa
BloombergNEF, Australia	Monash University, Australia
BlueScope Steel, Australia	National Energy Resources Australia (NERA)
Bruce Energy, Australia	Nippon Steel, Japan
Canterbury University, New Zealand	Norsk Hydro, Norway
Carleton University, Canada	1414 Degrees, Australia
Cement Concrete and Aggregates Australia	Outotec, Germany
Climate-KIC Australia	OZ Minerals, South Australia
CSIR, India	Polytechnique Montreal
CSIRO, Australia	South Australian Chamber of Mines and Energy (SACOME)
Decision House	Sandbag, Belgium
Deloitte, Australia	SINTEF, Norway
Department of Energy and Mining, South Australia	South32, Western Australia
Energia Potior, United Kingdom	Swiss Federal Institute of Technology
FCT Combustion, South Australia	Tenova
German Aerospace Center, DLR	The University of Adelaide
GPA Engineering, South Australia	The University of Chile
Graphite Energy, Australia	The University of Melbourne
Hatch, Australia	The University of Queensland
Helio100, South Africa	The University of South Australia
Heliogen, United States	Vast Solar, Australia
HelioHeat, Germany	Victoria University, Wellington, New Zealand
Helmholtz Institute, Freiberg, Germany	WGA, Australia
Hydrogen Economy Steering Committee, Australia	Woodside, Western Australia
Industry Capability Network, South Australia	World Economic Forum, Switzerland

Executive Summary of Key Findings

High-temperature minerals processing is on the path to the inevitable transition toward carbon-neutral production. The expectation is that the industry will need multiple decades to make the full transition, and while a range of views were expressed regarding how long this will take, most are working toward the 2050 target.

These industries are vital to the global economy, providing energy intensive materials such as steel, cement, and aluminium, but are also responsible for approximately 20% of global CO_2 emissions today and, since other sectors are expected to decarbonise more quickly, this percentage is likely to grow. The slow pace of anticipated change is due to significant challenges including: i) lack of commercially available technologies, ii) high cost of the transition, and iii) the industry's current need to maintain reliable supply and profitability when operating with low margins and high turn-overs from capital-intensive plants in trade-exposed markets. These factors make the sector 'difficult to abate'. Nevertheless, strong signals are also in place that are attracting investments to overcome the above barriers, such as i) new markets for low-net-carbon materials, ii) new technologies with potential to lower the cost of decarbonisation and iii) new global trade incentives, such as Europe's proposed carbon border adjustment mechanism that will be a part of the EU's Green Deal. The status of the drivers, barriers, opportunities and technological pathways to overcome the barriers, as identified at the second HiTeMP Forum, are as follows:

1. **Global Drivers helping to decarbonise heavy industry.** The drivers for implementing the low-net-carbon transition for the high-temperature, industrial processing sector are as follows:

   a. **Ongoing reduction in the prices of renewable energy (RE) and H_2:** The trend of falling prices in RE generation have continued since HiTeMP-1, so that these sources are projected to become dominant by 2050 [34, 4, 12]. Bloomberg predicts that the price of 'green' H_2 production will continue to fall with scale up, especially through Chinese hardware manufacturing, to the point where production costs will become competitive with "grey" H_2 from natural gas (NG) in 10—20 years. Nevertheless, Trezona projected that NG-derived "blue" H_2 will likely remain the most competitive production process for another 10 years;

   b. **Competitive advantage of embedding H_2 into 'green' products:** The high cost of transport and storage of H_2 will likely make it more competitive to embed the H_2 into energy-dense products at the source of production where possible. That is, sites with co-location of low-carbon energy and ores will favour the conversion of the mineral ores to transportable low-net-carbon products, such as 'green' iron and aluminium [34, 4, 12]. This embedding will create a competitive advantage for the production of these energy-dense, 'green' products in those countries with a coincidence of ores and low-net-carbon energy resources (i.e. renewable or abated sources);

   c. **Emerging markets and investor demand.** Investor demand for low-net-carbon products is already significant but will likely be further augmented by public-private partnerships (PPP) - the virtuous cycle [45]. Demand is growing because of the relatively modest cost of decarbonising the supply chain when compared to the final value of the finished products, together with the strengthening community demand [45]. Market signals are already emerging from companies such as Microsoft, which has announced the target that all of its products will be carbon-neutral by 2030 [43].

   d. **Employment and self-sufficiency:** It is reasonable to expect that governments will co-invest in the transition owing to the importance of the sector from an employment perspective, particularly in regional economies. High-temperature processing industries are already major regional employers, and this job-retention and job-creation driver could be expanded in those countries with a coincidence of mineral and energy resources as described above. For example, the Australian iron/steel industry alone supports 110,000 jobs, mostly in regional centres such as Wollongong, Newcastle, and Whyalla, and supports six times this number in indirect jobs [46]. The importance of these industries to regional economies underpins the expectation of local co-investment from governments. The jobs for this sector also have strong overlap in terms of labour skills compared with some of the other jobs that are disappearing, such as operation of coal-fired power stations [14].

   e. **Global and national policy initiatives** create additional drivers, such as Europe's proposed Green Deal carbon border adjustment mechanism, scheduled for introduction by 2021, and co-investments in PPPs [45, 31]. The carbon border adjustment mechanism will introduce a carbon price to address global supply chains and incentivise reductions in net carbon emissions both locally and for traded commodities [7]. Such policy instruments are underpinned by a need to ensure sustainability of local industry, to keep jobs, and to ensure the survival of manufacturing within nation states. Furthermore, while the investment necessary to decarbonise heavy industry is large (USD 0.9 Trillion), this amount is affordable as it is small relative to global GDP (0.6%). Such investments are being further supported by initiatives, such as the Industry Energy Transition Initiative and Mission Possible, and driven by the growing recognition that the heavy industry sector will need support to overcome the high barriers to its decarbonisation.

2. **What has changed since HiTeMP-1?** While many of the trends for the sector transition for heavy industry to a low-net-carbon economy identified in HiTeMP-1 (2018) have continued, new developments were identified in HiTeMP-2:

    a. **Commitment by major companies to decarbonise.** Since 2018 many more major companies in Australia and around the world such as BHP, Heidelberg Cement, and Rio Tinto, have announced commitments to be carbon-neutral by 2050. These commitments create a need for investments in technology to enable implementation of carbon-neutral strategies;

    b. **Ongoing development of low-net-carbon technologies.** The commercial readiness of low-net-carbon technologies has advanced due to ongoing investment – spanning electrification, 'green' or 'blue' H_2, concentrated solar thermal; and CO_2 capture, storage, and utilisation;

    c. **Unprecedented investment in, and commitment to, the H_2 economy.** Not only have seventeen different countries around the world already developed a strategy to use H_2 and its derivatives as a future fuel, but recent announcements have also seen concrete steps to incentivise its deployment and use. These include multi-billion dollar commitments from the EU, the USA and Saudi Arabia. Creating a thriving H_2 market will accelerate the transition and will de-risk its use either as a blend, a feedstock, or as an alternative to traditional fossil— resources.

3. **Prospective low-net-carbon energy sources and CO_2 mitigation technologies:** Due to the chemical nature of industrial commodities, the need for the high-temperature processing will continue. The prospective pathways identified for decarbonisation are as follows:

    a. **Electrification:** The ongoing reduction in the price of renewable electricity, and the growing penetration of wind and solar, is creating drivers for increasing electrification of energy-intensive processes such as steel making. Nevertheless, there are significant barriers in the short-term to its wide-scale implementation. These barriers include limited commercial availability of technologies to electrify high-temperature processes, although such technologies are under development. Furthermore, large fluctuations in the price of electricity mean that full electrification may be more expensive than hybrids, even in the long term. Hence, there is an ongoing need for the further development of new technologies both to enable and lower the cost of high penetration renewable electricity. In particular, new methods are necessary to electrify both high-temperature heating and reduction processes, and to integrate them with variable priced electricity [34].

    b. **Hydrogen:** The rapid reduction in the cost of the production of low-net-carbon hydrogen (both 'blue' and 'green'), together with the growing number of large-scale utilisation pilots (e.g., in iron/steel making) is creating strong interest in the potential role of H_2 in the low-net-carbon transition for the high-temperature process industries. Nevertheless, significant barriers remain, the biggest of which is the high cost of low-net-carbon H_2 relative to NG and coal. Risks also remain around H_2, both as a fuel and reductant. These barriers include the potential for increased NOx emissions if combusted, additional safety costs, and the need to address ore-specific reduction challenges. Other barriers and challenges include the current excessive costs for storage and distribution of hydrogen. While the perception is that none of these challenges will be show-stoppers, each will add cost and will needs for time to commercial implementation. Hence, investment is needed to overcome these barriers.

    c. **Concentrated solar thermal energy:** Recent developments in both increasing the temperature (notably through particle receivers, liquid sodium, and thermochemical energy storage technologies) and lowering the cost (including of the heliostat fields and the power block) give continued credibility to the expectation that CST energy has a growing role in decarbonising the high-temperature process industries. Cost estimates, both for commercially available steam and for emerging higher temperature stored heat, suggest that concentrated solar heat and thermal storage will be competitive within the mix of low carbon resources, particularly within the context of integrating variable RE resources. These trends justify the need for ongoing investment in the technology to overcome barriers such as the further upscaling and de-risking emerging high-temperature solar thermal technologies, the need to hybridise the technology to manage the periods of extended low solar resource (e.g. cloudy periods in winter) and the challenges of integration.

d. **CO_2 management:** The chemical nature of producing lime from carbonate ores creates a long-term need to manage CO_2, even in the event that the energy inputs to the process are fully decarbonised. However, while progress has been made in assessing the potential to adapt CO_2 capture from work developed for coal-fired power generators, further investments are necessary both to lower the cost and to de-risk the pathway for implementation. For example, the European CEMCAP program found that the cost of oxy-fuel combustion is presently too high for commercial implementation, although several technologies with potential to lower the cost of CO_2 capture are under development at pilot-scale. There was general agreement that the cost of utilisation of the captured CO_2 (e.g. by converting it to a fuel for use in the process) could be more viable than sequestration, since utilisation avoids the costs and liability of compression, transport, and storage of CO_2. However, utilisation can only achieve partial CO_2 mitigation (if the CO_2 re-emits after end-use), so achieving carbon-neutrality will require added steps also. To this end, there was particular interest in the opportunity for mineralisation of tailings since this possibility aligns well with the capability of the sector. However, further investment is similarly necessary in this pathway to better understand the full life-cycle costs and opportunities, and to develop and demonstrate the most viable options.

4. **Prospective pathways for iron and steel:** Noteworthy points identified regarding pathways to decarbonising iron and steel are as follows:

a. **Slow transition of the entire industry:** The full transformation of the industry, based on what we know today, will be slow. Indeed, some delegates project that the transition may extend well beyond the 2050 target. Hence, acceleration will require significant investment in ongoing technology development, due to the following combination of challenges:

i. **Dominant incumbent technologies:** The high capital cost of the blast-furnace route, presently used for 93% of global production, provides a strong incentive to operate these plants to the end of their natural life. While it is possible to partially replace metallurgical coke with H_2, carbon (in the form of coke) is likely to remain the dominant fuel/reductant source for this technology due to a combination of technical limitations and resource constraints.

ii. **Long time-scale for new technologies:** While some new low-net-carbon technologies are available for low-net-carbon production of iron and steel from some ores, further development is necessary to accommodate the range of different ore-specific properties that occur around the world, and to integrate these new processes within global supply chains. Thus, developing bespoke solutions for each resource will be challenging. Furthermore, the large capital investment necessary for each new plant demands significant testing and demonstration to de-risk and provide confidence for investors.

iii. **Complexities and scale of established global supply chains:** As for other metals, the production of iron and steel is within a complex global supply chain. Iron making typically occurs close to the point of downstream manufacture into high value products, such as cars. This situation has come about because, without a need to mitigate CO_2, the low-cost of transport of both the iron ore and coal has favoured manufacturing of the production of iron and steel within regions with the largest markets. The large capital investments in these supply chains have driven substantial cost reductions and generated large revenues for established players. It is therefore desirable that any changes to these approaches be mutually beneficial to the key incumbent stakeholders and occur with a sound understanding of these supply chains.

b. **The start of low-net-carbon iron/steel production is imminent:** Notwithstanding the previous point, the iron/steel industry is either at, or close to, the tipping point that will begin the investment toward establishing the commercial implementation of low-net-carbon production of iron and steel for the following reasons:

i. **Sufficient drivers:** There are already strong drivers for a market to emerge for low-net-carbon steel in regions such as Europe and Japan, which import both iron ore and fuels, while also having only moderate resources of RE. These drivers include the European carbon border adjust mechanism, scheduled to begin in 2021, the Japanese plan for a H_2 economy, and the willingness of customers prepared to pay the 1-3% added cost from decarbonising, relative to the value of final products, such as automobiles.

ii. **Available technology:** Technologies to produce low-net-carbon iron with a substantial fraction of H_2 as a fuel and reductant (e.g. via directly reduced iron, DRI) are now commercially available and are on the path to using only H_2.

iii. **Rapidly falling costs of 'green' H_2 production:** The cost of 'green' H_2 is falling rapidly and, while further reductions in cost and increases in scale are necessary before we can anticipate its wide-spread use in production of iron is expected to occur at a local cost of ~ USD 1.30 (AUD 2.00). This cost is close to the long-term projected cost for 'green' H_2 production from renewable electricity, although international transport and storage of H_2 will add ~ 40% to the total cost.

iv. **Potential advantages of international supply chains:** A market for 'green' steel in regions such as Europe or Japan will create a strong economic driver to reduce iron ore to iron at locations with a coincidence of excellent RE and iron ore due to (i) the lower cost of H_2 production (by 10—50%), (ii) the avoided costs of transport and storage of H_2 (~40%) and (iii) the lower shipping costs for iron over iron ore (by 10—20%). The combined benefit of these factors constitutes an advantage of 200—370% for the conversion of ore to iron with H_2 at the source relative to shipping both the ore and the H_2 to a third location. This advantage is likely to be sufficient to overcome any compensating disadvantages, such as higher costs of construction and operation in countries of iron production. That is, the modification to traditional supply chains, including the additional complexities that arise from shipping a reactive (iron) versus inert (iron-ore) cargo, would result in a net benefit for all parties.

5. **Prospective pathways for alumina and aluminium:** Aluminium is already a front runner in the establishment of low-net-carbon products, with a certified product on the market, (AL4.0 - 4.0 tonnes of CO_2 per tonne of aluminium) being supplied by companies such as Norsk Hydro and Alcoa. These are among a growing body of companies who have committed to further efficiency advances. The market for low-net-carbon products is expected to grow due to stated commitments by major companies, such as Microsoft and Apple, who want to procure carbon-zero products by 2030. Nevertheless, significant barriers remain for the entire industry to decarbonise by 2050. The key points identified regarding expected transition pathways for aluminium are as follows:

   a. **The path to flexible aluminium production:** While electricity is already used to power aluminium smelting, which is the most energy-intensive stage of aluminium production, this electrification is presently only undertaken for sites representing around 25% of global production, typically with good access to large sources of hydro-electricity[1]. Hence, production of certified 4.0 aluminium is only practical for a small fraction of global aluminium production. Indeed, the global average carbon intensity is approximately four times higher than these certified products, due to their reliance on grids supplied predominantly from fossil-fuels. However, to the extent that renewable electricity supplies can be firmed, aluminium smelting from sites without access to hydro electricity, also have potential to operate with increased proportions of firmed variable renewable electricity[2]. Nevertheless, a further barrier to the extent to which these other smelters can be supplied with variable RE is the constraint that current smelters were designed to operate at steady state, so that they have historically had very limited capacity to turn down. Despite this barrier, progress has been made, with some smelters now beginning to provide increased demand management services to the grid[3,4]. Furthermore, other recent technologies, such as that being provided by EnPot (see pg. 25-26), may have the potential to accommodate a much more flexible load, and hence a greater share of RE. Notwithstanding this progress, investment is needed to overcome remaining barriers, such as the need for sufficient demonstration at scale to de-risk these new approaches sufficiently to justify the large investments needed for their roll-out.

   b. **The path to low-net-carbon alumina production:** The production of alumina, an intermediate product between bauxite and aluminium, is yet to begin the transition for its energy to be supplied with low-net-carbon sources due to the lack of commercially viable or demonstrated solutions. Identified critical steps for this pathway are as follows:

      i. **Low-net-carbon steam production** will likely begin implementation during the next five to ten years as the necessary technology is up-scaled and adapted from other applications where they are already commercial for different conditions. While no technology breakthroughs are necessary, further investment in technology development is nevertheless still needed because no system is commercially available that meets the cost, scale, and reliability requirements for wide-scale implementation by the industry.

      ii. **Low-net-carbon calcination** is expected to be introduced over the next 10 to 20 years as the technology under development is progressively up-scaled, refined, and demonstrated. No technology is presently available at a scale sufficiently close to market for implementation in the next 10 years. For example, while hydrogen could technically be used to replace NG relatively easily, at least ten years is needed before it will become cost competitive without a subsidy. Hence, ongoing investment in new calcination technology is necessary to accelerate the transition for the sector.

[1] https://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/#histogram
[2] https://aluminium.org.au/wp-content/uploads/2020/10/201019-Aluminum-P2025-Market-Design.pdf
[3] https://www.afr.com/companies/energy/sydney-greyness-eases-power-fears-but-peak-still-ahead-20210106-p56s1b
[4] https://esb-post2025-market-design.aemc.gov.au/32572/1608712640-energy-synapse-demand-response-in-the-nem-final-report-14-dec-2020.pdf

6. **Prospective pathways for Cement and Lime:** The transition of the cement and lime sectors of the industry have many similarities, but also significant differences. Consideration together is warranted because lime is the dominant component of an intermediate stage in the cement-making process, while also being an independent product that is an important industrial chemical in the production of materials such as iron, alumina and paper. Also, lime is usually manufactured close to the mining site, while cement clinker is traded. The key elements in the transition to carbon-neutral production for these products are as follows:

    a. **The wide-scale deployment of blended cement,** which comprises ~ substitution of fractions of cement clinker (derived from limestone) with calcined clays. This results in a reduction by some 40% in net CO_2 emissions. Unlike coal ash, clays are available throughout the world so that no significant technical barriers prevent its implementation. Instead, the barriers to wide-scale deployment are those of regulation, policy and the need for new business models to change established industry practice. Nevertheless, there are also opportunities for new technology developments to accelerate the roll-out, for example by allowing use of a wider range of clays.

    b. **The further development, demonstration, and deployment of Carbon Capture, Utilisation, and Storage (CCUS),** that is, the capture, utilise, and/or store underground the CO_2 released from the production of lime and cement clinker from limestone. The management of this CO_2 is particularly important for cement and lime because approximately 75% of the CO_2 from the process is derived from limestone itself, rather than from the combustion of fossil fuels. Significant investments in this pathway have already begun, both in retrofit and new-build configurations, but further investments are needed to lower the cost and/or to increase the value. Some of these investments are planned such as commercial scale demonstrations in the next five years, which would put the sector on track for wide-scale deployment by 2050.

    c. **The further development and deployment of alternative fuel utilisation** is considered to remain an important component of increasing the sustainability of this industry, even though the combustion of fuel is responsible for only ~ 25% of the CO_2, owing to the ideal nature of the cement making process described above. Alternative fuels are an important aspect of the broader circular economy principals, since they enable energy to be recovered from by-products of other processes and avoid landfill. The major barriers to the further deployment of such fuels are mostly associated with establishing their supply chains. Nevertheless, there is also a need for some of the fuel-specific technology development that results from the need to safely and effectively manage the pollutants derived from their combustion.

7. **Prospective pathways for other metals:** Decarbonisation of other metals such as Cu, Li, lithium, lead (Pb), and Zn, was confirmed as being highly synergistic with the processes described above, although each has some unique challenges. The key elements in the pathway are as follows:

    a. **Common challenges:** Decarbonising other metals processing can leverage strongly from the developments being undertaken for iron/steel, cement/lime and alumina/aluminium, since these processes are typically smaller in scale but involve the similar challenges of:

        i. **Integration of variable RE sources.** This applies for processes such as electrowinning and electric smelting.

        ii. **adoption of H_2** and its derivatives as alternative fuels for heating, reduction, and/or as a feedstock or as a reductant; and

        iii. **capture and utilisation of CO_2,** either as means to mitigate CO_2 from existing plants with a long life or for the processing of carbonate ores.

    b. **Greater relative importance of the upstream (non-thermal) processes:** The CO_2 produced from the manufacture of other metals such as Cu, are mostly derived upstream from the high-temperature processing step. That is, the emissions from the mining and upstream minerals processing tend to dominate. The lifecycle emissions therefore suggest that a higher priority should be placed on reducing emissions from upstream processes for these metals, allowing time to leverage developments in the other industries, such as iron/steel, cement/lime and alumina/aluminium.

    c. **Greater need for increased recovery of minor elements from other mines:** Further investment is also warranted in technologies to increase the recovery of minor and trace elements from those ores that are already mined, but generally left in the tailings of current mining operations. Recovering these minor and trace elements is likely to be an effective pathway for both implementation of circular economy principles and reducing CO_2 emissions from the production of these metals.

1 Global drivers to decarbonise heavy Industry

Since the release of the HiTeMP-1 report, we have witnessed the continued strengthening of drivers to decarbonise energy intensive process industries. Many major companies have since announced commitments to decarbonise by 2050, creating a market for low-net-carbon products and processes. This trend is driven by falling costs in the supply of renewable and other low carbon forms of energy carriers, the relatively low cost of decarbonising relative to the cost of the finished product, and the strong evidence that the market is willing to bear this small increase. Added to these trends is the growing expectation from employees, customers, communities, and shareholders that large corporates should not only take action, but should lead, in the transition. Lastly is the growing development of supportive governmental policies to facilitate such a transition.

1.1 Ongoing demand for the products of the heavy industrial sector

The need to decarbonise the heavy industry sector is fuelled by the ongoing demand from society for the products it produces, together with the need to mitigate CO_2 emissions. Figure 1 shows that demand for energy-intensive products is projected to deep increasing, with a 40% increase in demand for cement projected to 2050. This is driven particularly by the growth in living standards non-industrialised and third world countries. Hence, low-net-carbon technologies are needed, not only to deal with existing emissions, but also from new installations. Similarly, demand for iron/steel, alumina/aluminium, and other metals is driven by ongoing growth in both global population and the standards of living.

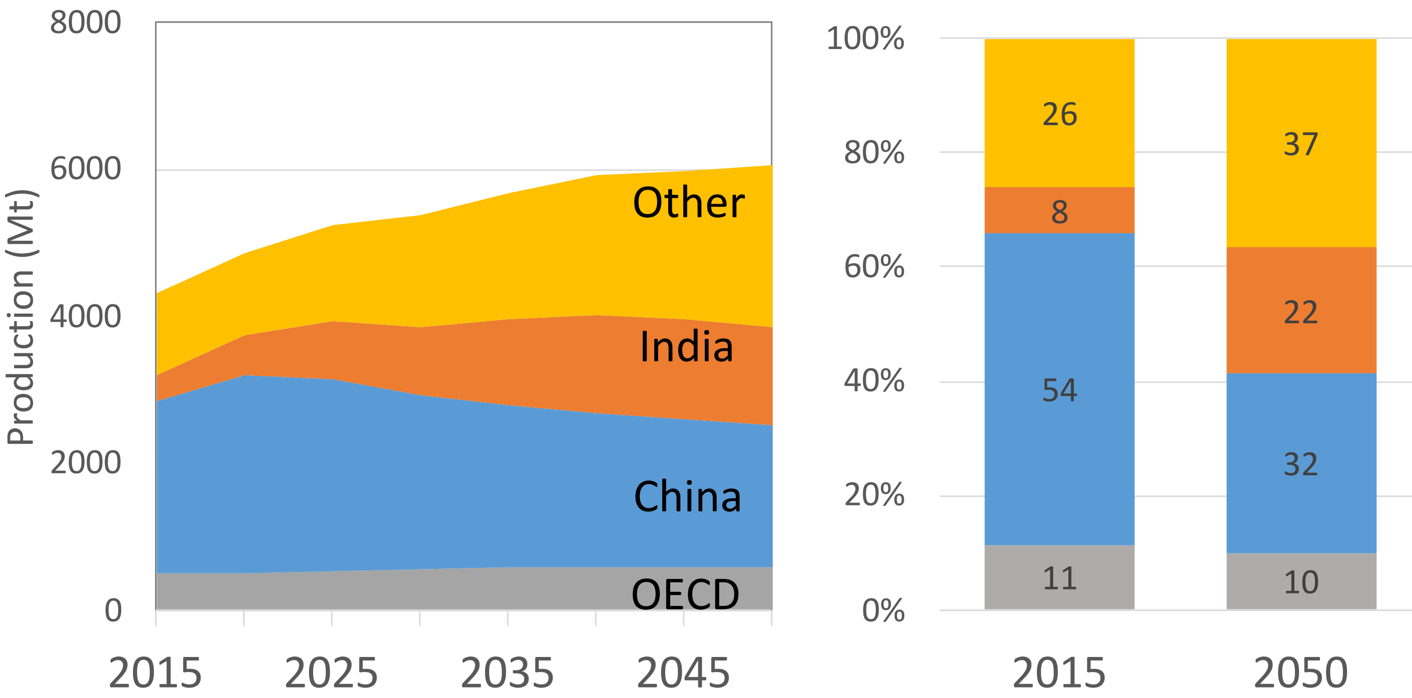
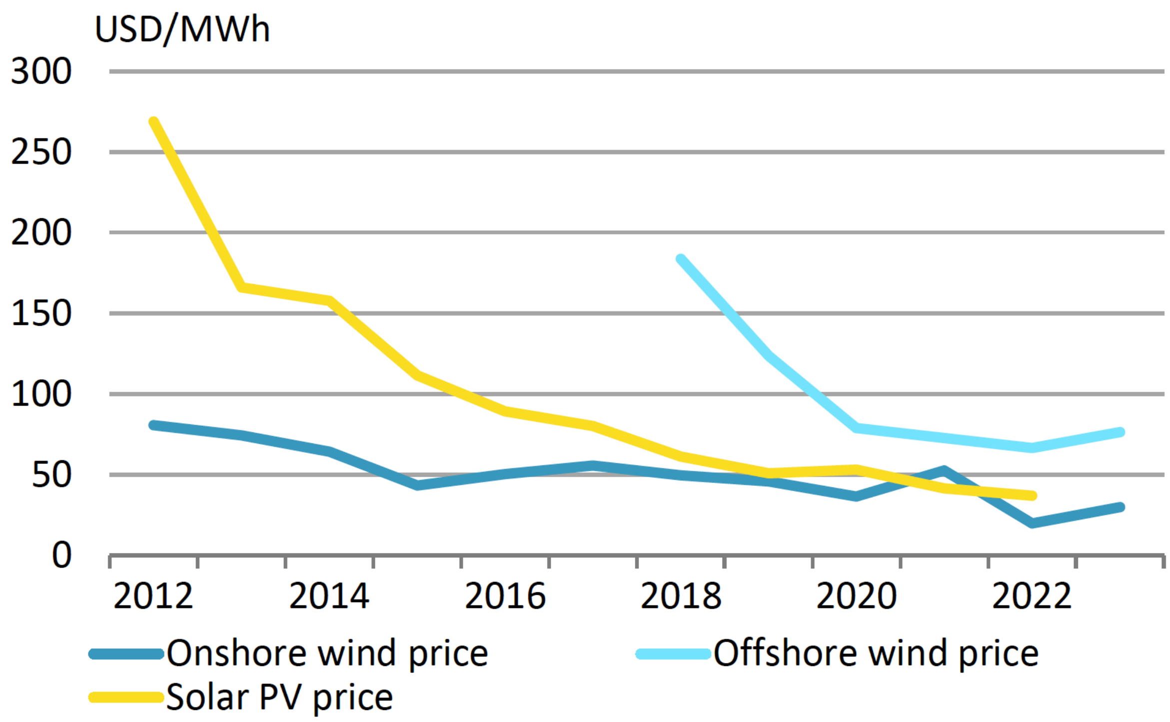


Figure 1: The projected growth in demand for cement and its distribution globally. Source Karen Scrivener, EPFL [41].

1.2 Ongoing reduction in the prices of RE and 'green' H_2

The downward trend for of renewable electricity generation costs has also continued since HiTeMP-1, as shown in Figure 2. This trend is making renewable electricity become an increasingly important component of electrical grids and a growing enabler for in the low-net-carbon transition. In parallel with these trends, the development of other technologies to mitigate CO_2 emissions in the industrial sector are also progressing. These technologies include the conversion of NG to 'blue' H_2 using carbon capture and storage (CCS) and the progressive development of high-temperature concentrated solar thermal energy technologies. These alternative pathways are largely complementary owing to their differences in scale and in their capacity to leverage alternative types of infrastructure and regional opportunities. Collectively, renewables, H_2, and CCS are driving investment based on the expectation that these alternatives will become the dominant forms of primary and secondary resources within the timeline of the heavy industry transition.



Source: IEA, *Renewables 2017* [17]

Figure 2: The globally average auction price for three forms of electricity from renewable wind and solar PV energy [17].

The projected long-term cost of H_2 production from 'green' electricity, which is an important reference in the emerging forms of low-net-carbon H_2, is projected to reach prices of < USD 1.60/kg (< USD 12/GJ) by 2050 in regions with particularly strong coincidence of wind and solar resources, as Figure 3 shows. This cost is competitive with that of producing metallurgical coke from coal for iron making (USD 8—12) and, while it is higher than the current costs of fossil fuels without CO_2 pricing (typically USD 2—12 / GJ), it is nevertheless competitive within the mix of other complementary emerging forms of low-net-carbon energy. This is true especially given that the costs and/or availability of other forms of RE resources will likely fluctuate with the resource availability. Furthermore, as is discussed below, the added costs of decarbonising are small relative to the cost of the final product.

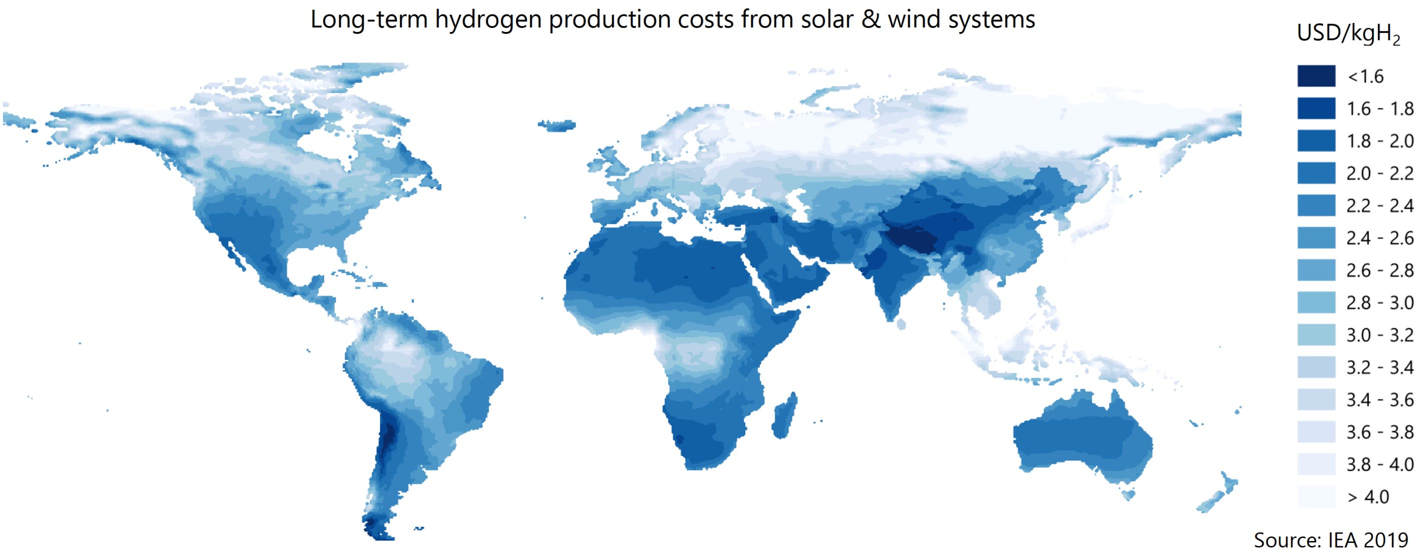


Figure 3: The projected long-term cost of production of 'green' H_2 from renewable wind and solar PV energy. Source IEA 2019, The Future of Hydrogen [16].

1.3 Competitive advantage of embedding 'green' H_2 into products

Figure 3 also shows that the long-term cost of producing 'green' H_2 varies greatly from region to region around the globe from a low of < USD 1.6/kg to a high of > USD USUS4.0/kg. However, unlike widely traded fossil fuels, which are cheap to transport and store, for hydrogen-based fuels the cost of transport, storage, and recovery (e.g., from a chemical carrier, such as ammonia (NH_3) or a liquid organic) is currently high. Avoiding these added costs means it will be more cost effective to use H_2 within energy-intensive processes if possible, such as at locations where low-cost H_2 can be produced coincident with the ores. Such co-production is likely to be cheaper than the transport of both the ore and the alternative fuel to a third country, as typically occurs today (transport of both).

That is, the process of decarbonising the supply chains in of industrial materials such as iron/steel, cement, and aluminium, will favour the production of the energy-intensive products at those locations with both RE and mineral resources.

Figure 4 provides more details of this trend and compares the estimated landed costs in Europe of locally produced versus imported hydrogen or NH_3 (the key vector for transportation). Also presented is the case of production via NG with no CO_2 emissions, e.g., via CCS or cracking NG to solid carbon and H_2.

This 'blue' production process shows, firstly, that the cost of imported low-carbon H_2 will be 10% lower than the locally produced product approximately and, secondly, that the combined cost of transport, storage, and de-hydrogenation (i.e. recovery) of the hydrogen based fuel is approximately 40% that of the final product. Worth noting is that these data are based on the growing consensus that NH_3 is going to be the preferred carrier [34]. Furthermore, while the cost of international production of 'green' H_2 with the commercially available technologies is comparable with H_2 from NG with steam-methane reforming and CCS, the carbon footprint will also be lower, making it likely to be a preferred route in many cases. It is reasonable to expect that this option would create a competitive advantage to countries such as Australia, South Africa, and Chile with both mineral and RE resources for the local upgrading of ores to higher value products such as iron.

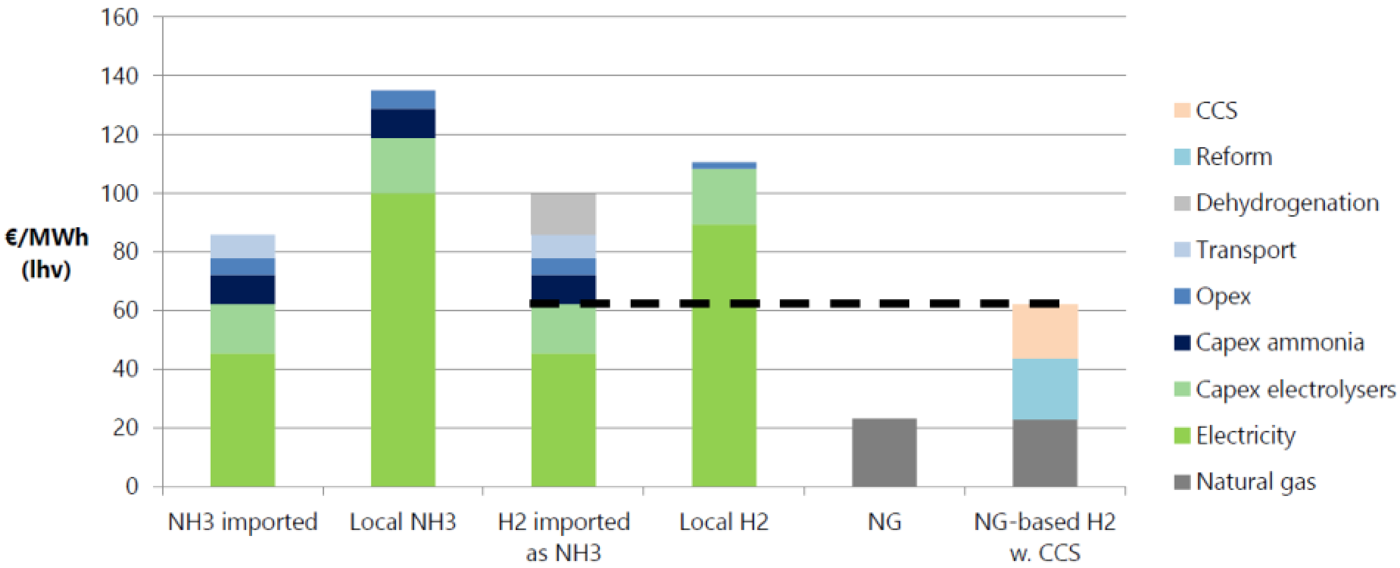


Figure 4: The projected cost of key sources of energy in Europe, namely of 'green' NH_3 and H_2, both imported and produced locally, compared with current prices of NG and 'blue' H_2 produced from NG with CCS. The dashed line compares the production-only cost of 'green' H_2, produced offshore, with that of 'blue' H_2. Note that the 'green' H_2 retains a competitive advantage owing to a lower net CO_2 emission. Source Cedric Philibert [34].

1.4 Emerging markets and investor demand

Although the cost of producing low-net-carbon materials (such as steel, cement, and ethylene) is projected to be greater than current practice by 20%—100% (without allowing for technology breakthroughs), this added cost is a far smaller increase of 1%—3% to the final product (such as a car, a building, or a plastic bottle) as Figure 5 shows. This negligible extent of increase in the final product, together with growing public demand for action on climate change, is increasing the proportion of customers willing to pay the small premium necessary to decarbonise these products. Indeed, markets are already emerging for these higher value products. Microsoft has pledged to be carbon-neutral by 2030 and Amazon by 2040 [43]. These emerging markets are creating demand driver for industry to develop low-embedded-carbon products.

Aluminium remains at the forefront of this transition with companies such as Alcoa and Norsk Hydro offering a certified low-net-carbon product as reported in HiTeMP-. The expectation is that other products, such as iron/steel and cement will follow to decarbonise fully as technology becomes available commercially.

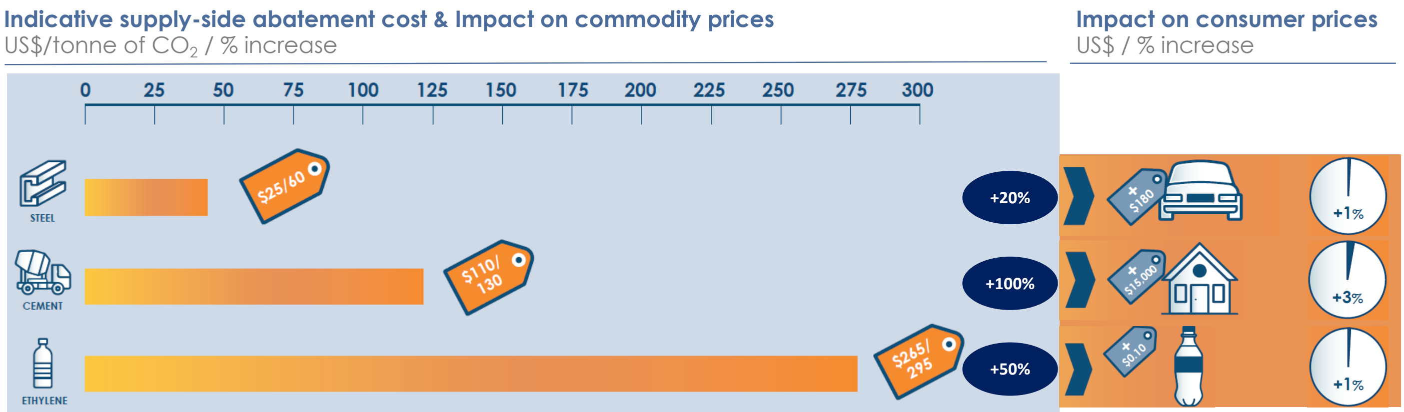


Figure 5: The estimated percentage increase in the cost of decarbonising a) the production of steel, concrete and ethylene, and b) on the final manufactured products of an automobile, a building and a plastic product. Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018) [10].

Since HiTeMP-1, investor demand for decarbonisation has increased, as can be seen in recent announcements by companies such as BHP, RioTinto and Arcelor Mittal to become carbon-neutral by 2050 [45]. This call for further investment will likely continue because the level of investment projected to be required, while large, is still small compared with the scale of global GDP. The Bund Summit (2019) reported that, while an investment of USD0.9 trillion is necessary to decarbonise the economy over the period 2020—2050, this amount is still only 0.6% of global GDP over the same period [45].

Furthermore, since investments in new infrastructure will be necessary during this period, the added incremental investment decarbonise the sector is ~ 25% of what would be spent anyway [45]. Together these points demonstrate the financial viability of the transition.

1.5 Global and national policy initiatives

A series of policy initiatives and PPPs have also been established to drive the investment necessary to decarbonise the high-temperature minerals processing sector (an estimated USD US0.9 T9T to 2050). Europe is establishing the Carbon Border Tax under the European Green Deal, scheduled to be introduced by 2021 to address the global nature of the supply chains for manufactured goods [7], and China is set to have a similar carbon pricing mechanism in 2021. These policy instruments are designed to ensure that industry will not be disadvantaged by investing in technologies to lower carbon intensity but will also have a flow-on effect by driving investments within their trading partners to compete in the same markets.

Public-Private Partnerships, PPPs, are being established to harness the investment necessary to enable the heavy industry, low-net-carbon transition. These PPPs include the Mission Possible Platform, convened by the World Economic Forum in collaboration with the Energy Transitions Commission, with action platforms in steel, cement, and aluminium [43, 31]. These PPPs are aiming to build coalitions to raise the financial investments necessary to implement the low-net-carbon transition for the sector.

Chile, South Africa and Australia are investing in the pathway to support the low-net-carbon transition for their mining and minerals processing sectors in recognition of the competitive advantage of the coincidence of outstanding mineral and RE resources. Chile's CORFO recently announced the creation of the Institute of Clean Technologies to foster the renewable production of high value products from its two major mineral resources, namely Cu and lithium [19]. Similarly, the priorities of Australia's RE Agency, ARENA, are aligned with decarbonising high-temperature industries, with its three priorities being the integration of RE into the grid, the production of 'green' H_2 and lowering the emissions of the industrial sector [27]. After the Forum, Australia also announced the AUD 2B Technology Investment Roadmap, which is also well-aligned with this challenge.

2 Prospective low-net-carbon energy sources heavy Industry

The forum reaffirmed the view identified in HiTeMP-1 that a mix of energy resources will be necessary to decarbonise the sector. Figure 6 illustrates this perspective with a typical result from one of the scenario-based assessments. This scenario anticipates that the dominant energy sources for high-temperature processes in a carbon-neutral economy will be electrification, fossil fuels with CCS and 'green' H_2. The forum also presented work from the concentrated solar thermal sector, which identified its potential to also contribute to the sources of low-net-carbon energy.

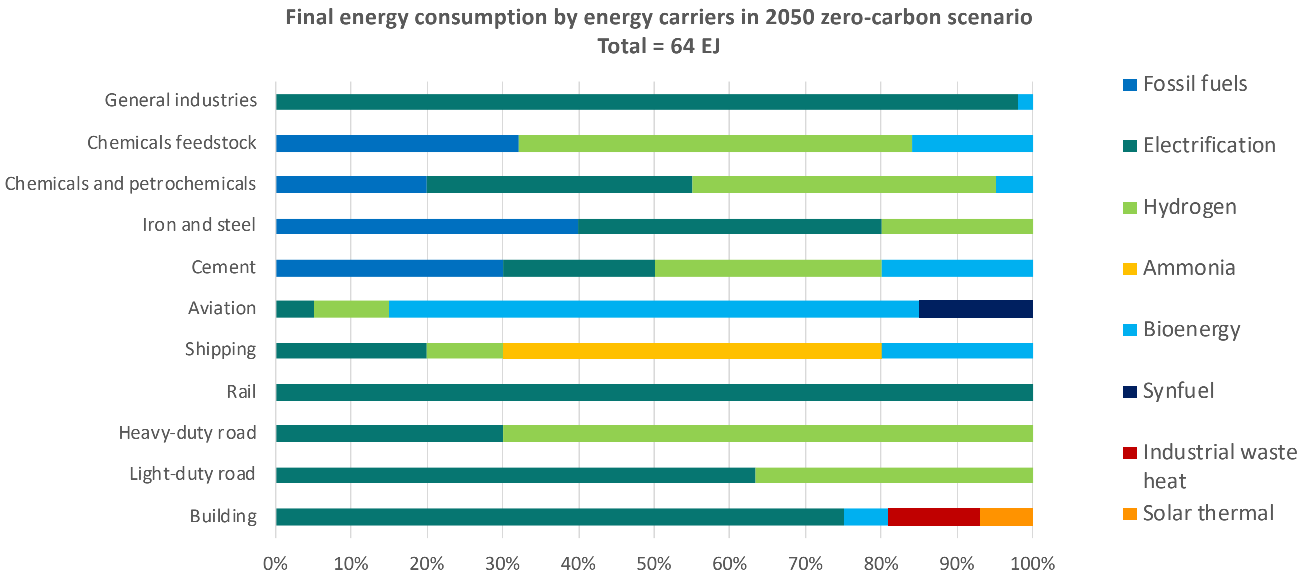


Figure 6: A scenario-based projection of a plausible mix of energy sources by 2050 to achieve a carbon-neutral economy, totalling 64EJ. Source: Robert Trezona, IP Group [45].

It is also important to note that the majority (typically 75%) of the energy needs for the present high-temperature industrial processes are in the form of heat and chemical feedstock, rather than electricity (Figure 7). Furthermore, the majority of these processes require heat at > 800°C and some at temperatures of > 1400°C, although processes such as alumina manufacturing also require significant energy at lower temperatures of ~200°C [22]. In addition, the timescale for the development, upscaling and wide-scale roll-out of any entirely new process technology can be expected to be 20—30 years out. Hence, the low-net-carbon transition for the sector must address the pathway to the supply of low-net-carbon heat and industrial chemical feedstock at sufficiently competitive prices.

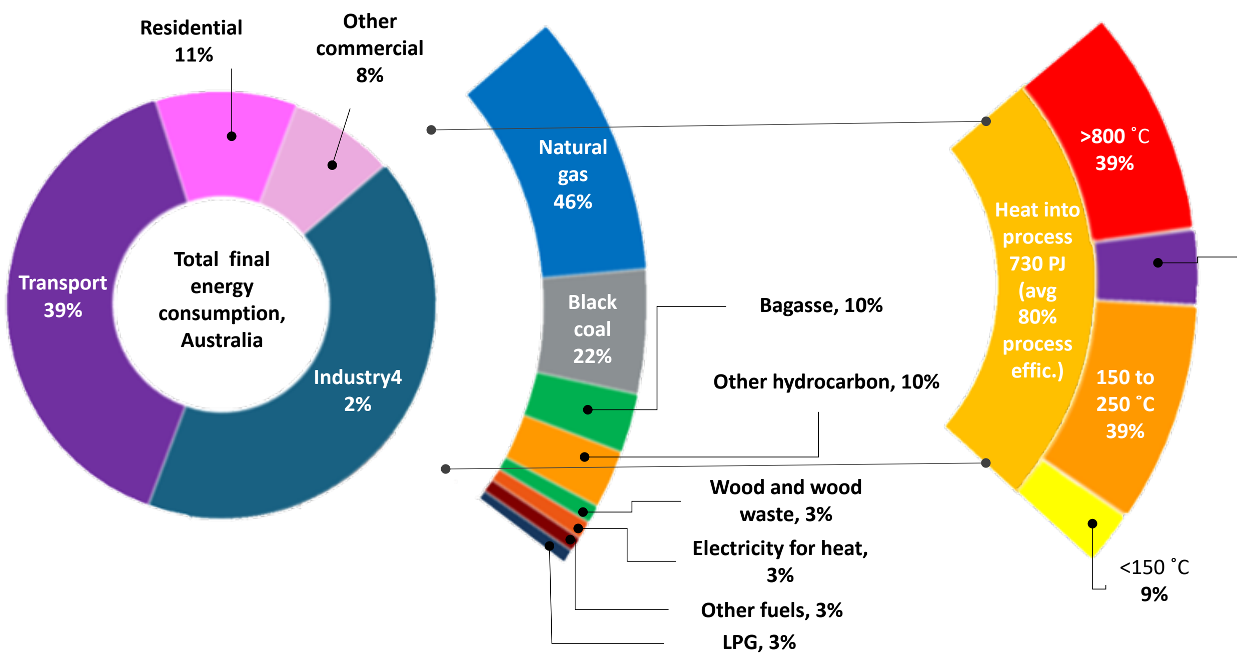


Figure 7: The relative demand for heat and electricity in the high-temperature process industries in Australia, together with the temperatures at which they are required. Source: Lovegrove, K., et al [23].

2.1 The role of electrification

The expectation that electrification of high-temperature heat will play a growing role is driven, in part, by the ongoing trajectory of reducing costs of RE generation (Figure 2), and in part by the ongoing investment in new technologies including those for electrification, such as electrowinning [34]. Several electrical heating technologies are also available commercially, including heat pumps and resistive heating, although these have not yet been demonstrated at the scale required for large industrial processes.

Notwithstanding these opportunities, significant barriers remain to the implementation of electrification, particularly for high-temperature processes in the short-to-medium term. Figure 8 compares the levelised cost of heat for a series of energy sources, calculated for a series of typical scenarios [22]. While energy produced with heat pumps can be competitive with fossil fuel combustion, resistive heating tends to be more expensive by a factor of two to three. Furthermore, heat pump (and associated) technologies are presently only available to temperatures of ~200°C, although DLR and others are investigating opportunities to increase this temperature range [37]. Hence, while heat-pump and related vapour compression technology is applicable to the low-temperature needs of heavy industry (notably for the first stage of alumina production), it is not applicable to the majority of high-temperature processes. Also, while H_2 can be used to deliver high temperatures via electrical energy (i.e. by electrolysis), it would then typically be more expensive than electrical energy since it would be produced from electricity and requires the added costs of storage and transport. These considerations imply that the full electrification of these processes is unlikely to be viable without significant further technology developments, although partial electrification is likely to play a growing role during intermittent periods of relatively low-price electricity dispatch. Moreover, in addition to the price barrier, further development and demonstration of these processes would still be necessary to establish reliable operation in high-temperature, dusty environments, owing to the absence of technology demonstrations of these processes within the sector operating environment.

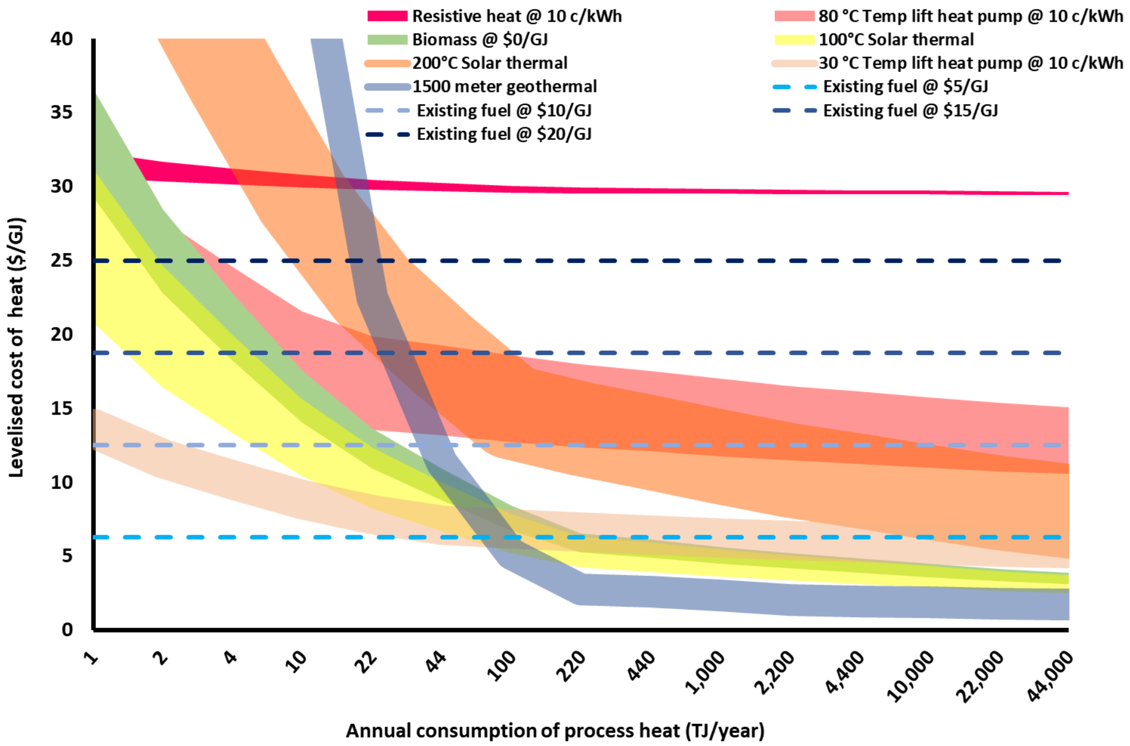


Figure 8: A comparison of the levelised cost of producing heat (in AUD) via a series of alternative energy types of low-net-carbon heat relative to current costs of fossil fuels. Source: Bader, R., et al [3].

2.2 The role of H_2

With 95% of the present global production of H_2 being from steam-methane-reforming of NG (SMR), it is evident that commercial H_2 is necessarily more expensive than NG on an energy basis, typically by a factor of 60–100%. Similarly, the cost of producing H_2 from coal gasification is greater than that of using coal. Thus, H_2 is presently used primarily as a chemical feedstock in refineries or NH_3 production, and not as a secondary energy source. Decarbonising SMR-derived H_2 is possible with CCS, although this production of 'blue' H_2 further increases the cost to an estimated USD US1.50–1.82 (AUD USD1.60–$2.00/kg, which corresponds to USD US10.56–12.80/GJ (AUD 16.30 – 19.72/GJ). That is, decarbonised NG (renewable NG or synthetic NG) is approximately twice the cost of NG as a conventional energy source. The Finkel COAG report estimates that the best-case scenario for the production of 'green' H_2 from electrolysis is AUD 2.50–3.30/kg (USD 1.62–2.02) by 2025, which is 25% higher than the anticipated cost of the 'blue' equivalent derived from SMR-CCS in the same timeframe. This estimate is consistent with the long-term production cost of USD 1.60/kg reported above (Figure 2).

This projected cost of production is similar to the long-term Japanese target cost for H_2 delivered to Japan of ¥20/Nm3. Hence the production cost required to meet this target is in the range USD US1.00 – 1.30 /kg and AUD 1.50–2.00/kg depending on the exchange rates and the added costs for transportation [26]. On the other hand, the tipping point at which the cost of H_2 production in Australia is expected to become economic relative to metallurgical coke for the production of iron and steel is at the upper end of this range, at ~ AUD 2.00/kg (USD US1.30), as Figure 9 shows. Nevertheless, while this cost target is significantly better than direct competition with NG for heat, further reductions in the cost of H_2 production will still be necessary beyond those currently projected for the industry to achieve this target without a new market mechanism, such as a premium or a carbon tax.

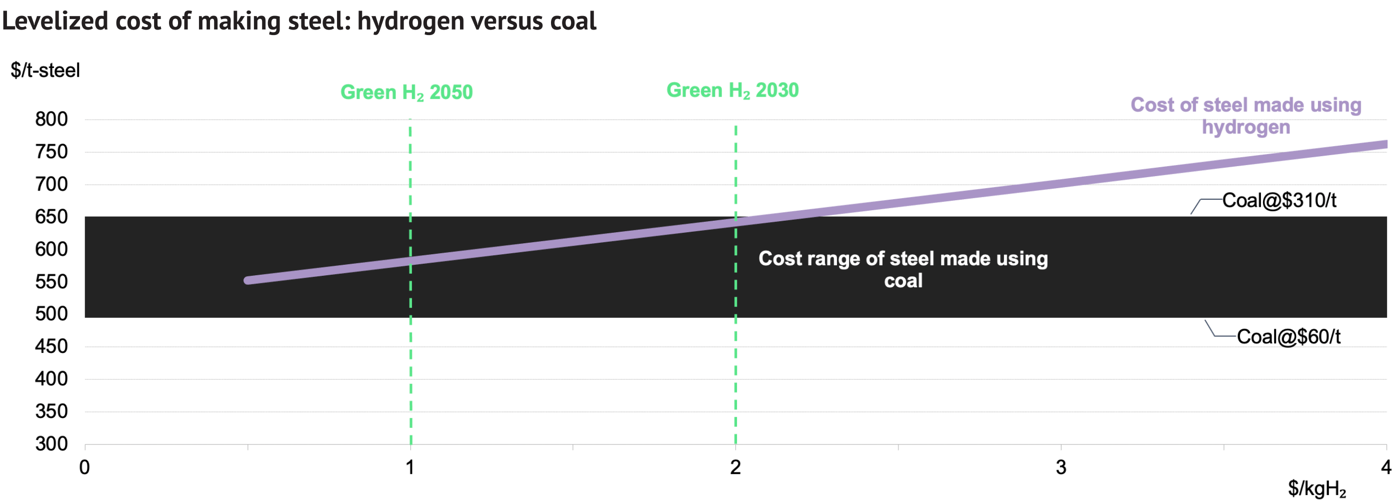


Figure 9: A comparison of the cost of steel making (in AUD) via coal and H_2, showing that H_2 begins to become economic at AUD 2.0 per kg, $2kg. Source: Bloomberg-NEF.

The opportunities that would be unlocked through further reductions in the cost of 'green' H_2 production is driving substantial investments in the development of new technology, e.g. through the international Mission Innovation Converting Sunlight challenge, whose support for the HiTeMP forum is also gratefully acknowledged. Figure 10 shows three of the classes of technology for photon-induced water splitting, namely the commercial route of solar-PV electricity used to drive electrolysis, together with solar photo-catalysis and the photo electro-chemical route, both of which are under development. Other routes include high-temperature solar thermochemical water splitting and a hybrid between solar-thermochemical and electrolysis, termed the Hydrogen-Sulphur cycle [9, 7]. The further development of 'blue' H_2 are also under development, notably that based on the pyrolysis, or 'cracking' of NG to solid carbon and H_2 [43]. Together the ongoing investment in this range of new technologies give confidence that further cost reductions are realistic within the 2050 transition timeline expected for the sector.

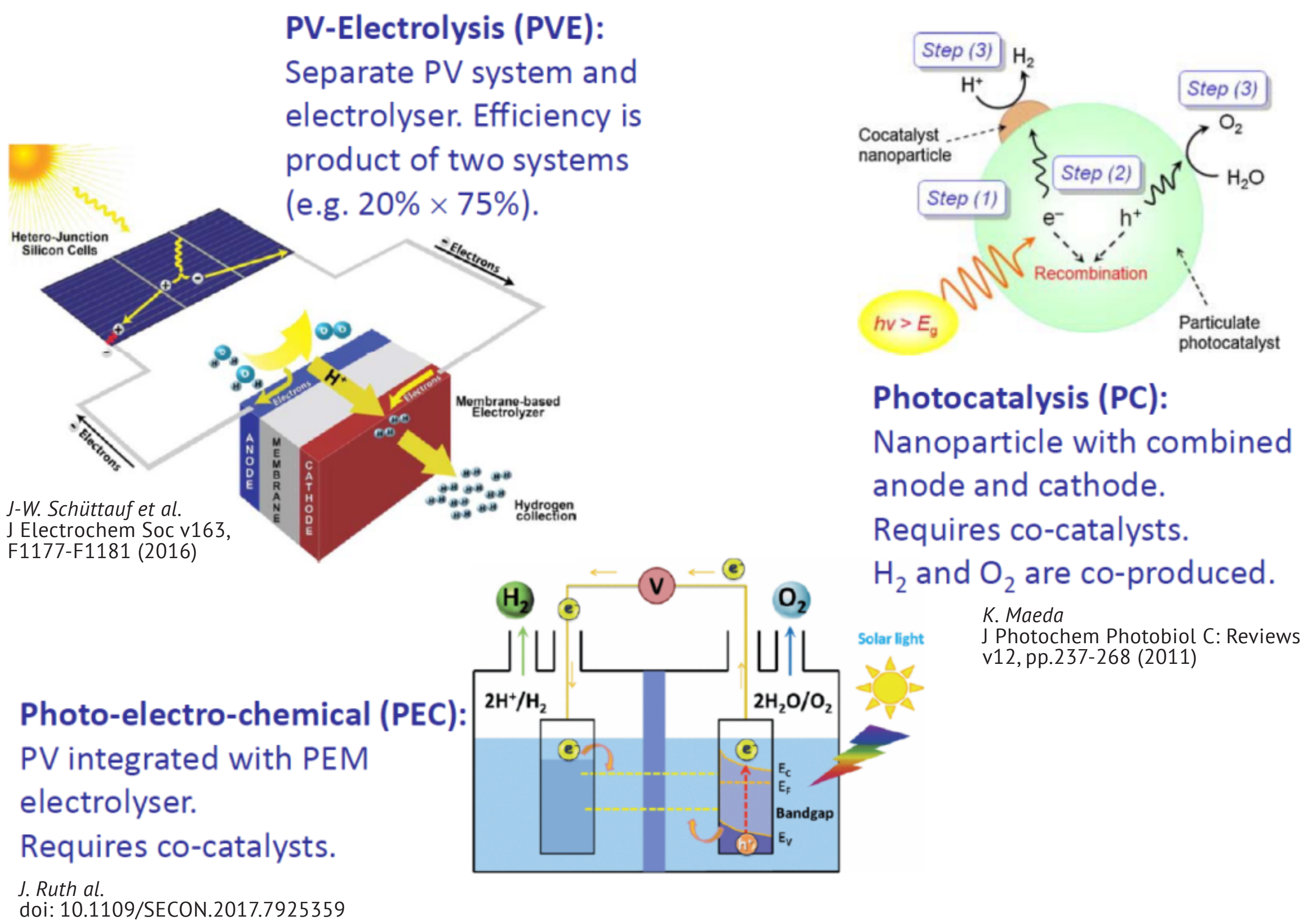


Figure 10: Three of the alternative routes for hydrogen production from solar energy, namely a) Solar photo-voltaic with electrolysis, which is commercially available; b) solar photo-catalysis, which is under development, and c) photo electro-chemical, which is also under development [26].

2.3 The role of concentrated solar thermal energy

The key driver for ongoing development of concentrated solar thermal energy (CST) for high-temperature industrial processes is the potential to achieve a relatively low-cost source of stored, renewable heat by avoiding the highly inefficient process of converting the heat to electrical power, while also capitalising on the much lower cost of storing heat than electricity. The potential significance of this opportunity is illustrated in Figure 11, which compares the internal rate of return for CST configured to produce steam for process heat (and calculated at two years allowing for emerging cost reductions, namely 2018 and 2023) in comparison with the most cost-effective electrical alterative, that of mechanical vapour recompression (MVR) system [22]. The basis for this data is a solar resource typical of alumina plants south east of Perth and the IRR for the MVR system is presented as a function of the cost of electricity. It can be seen that, on average, the relative cost of these two sources of energy depend on the future cost of electricity, the availability of the solar resource and access to land, all of which have many site-specific factors. However, it is also evident that the two sources of energy are broadly complementary because of the fluctuations in the price and availability of the solar and wind resources. For example, the price of electricity in the Australian National Energy Market (NEM) fluctuates with the availability of wind and solar resources from negative prices to up to AUD 13,000/MWh. On the other hand, the low-cost of stored heat offered by solar thermal implies that it is likely to be a cost-effective alternative during those periods when the electricity prices exceed a threshold. Notwithstanding this potential, further investment is necessary to demonstrate and de-risk these technologies at the scale and reliability required for industrial process heat, such as for alumina plants.

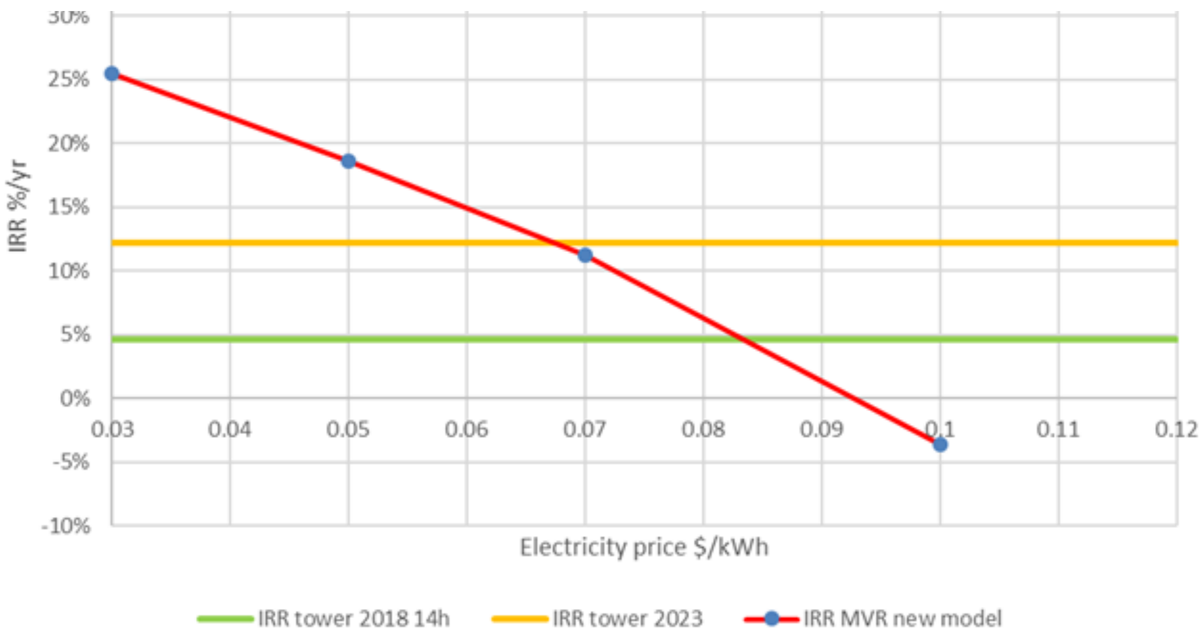


Figure 11: A comparison of the projected levelised cost of stored solar thermal steam for application as process heat at approximately 200°C with that of mechanical vapour recompression (MVR) as a function of the assumed electricity price. Neither technology is currently demonstrated for process heat under conditions required for alumina production, despite being commercially available at other conditions. Source: ITP Thermal, Lovegrove, K., et al, [22].

New developments in the CST are also emerging with strong potential both to further lower the cost and to increase the temperature at which heat can be collected and stored through a series of programs being undertaken around the world [44]. For example, Heliogen have recently demonstrated a concentrating system with both a 26% reduction in the cost of radiation delivered to the tower and an increase in concentration to enable temperatures of order 1000°C to be achieved [40]. Similarly, Helioheat has demonstrated the supply of stored heat at temperatures of ~900°C at 2.5MWth and are presently upscaling the technology with target temperatures of ~1500°C. The projected internal rates of return suggest that the supply of stored heat at these higher temperatures will also be economically competitive within the mix of low-net-carbon sources (Figure 12). These projections, combined with the need for new energy sources, suggest that the added investment to upscale these technologies for the sector can be justified. The remaining barriers include the ongoing need to upscale and de-risk the emerging high-temperature solar thermal technology, the need to hybridise the technology to manage the periods of extended low solar resource (e.g. cloudy periods in winter) and the challenges of integration.

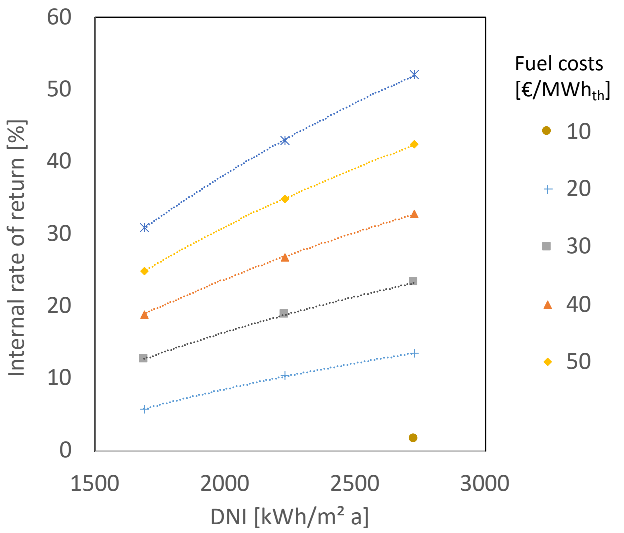


Figure 12: The estimated internal rate of return (left) of stored solar thermal heat at temperatures of ~1000°C for a particle-based receiver system under development by Helioheat. Image of DLR's Centrec facility at the Jülich Solar Tower, used with permission. Source: (left to right): HelioHeat; DLR [2].

Economically attractive opportunities for the use of this technology to provide process heat have been identified through a joint study by Mintek and DLR for a Zn plant [15]. The process requires hot air at 800°C to pre-heat the ore to 600°C, which is presently supplied by the combustion of diesel fuel. Figure 13 shows that current estimates find that the Helioheat technology is competitive not only with diesel, but also with grid electricity. These niche opportunities are necessary to drive the commercialisation and up-scaling of the technology and thereby, in turn, drive the virtuous cycle of cost reductions by deployment [24].

Other developments are also occurring in the CSP industry to lower costs of power generation, which will contribute to the high-temperature process industries both through access to lower cost power and to spin off benefits for lower cost heat. One of these developments is the novel sodium-based technology of Vast Solar, which is targeting AUD50/MWh for stored electricity [50]. This company is presently constructing a 50MW plant in Mount Isa. Similarly, Abengoa is driving cost reduction in the CSP industry through economies of scale, technology refinement, manufacturing developments and highly refined performance predictions [38].

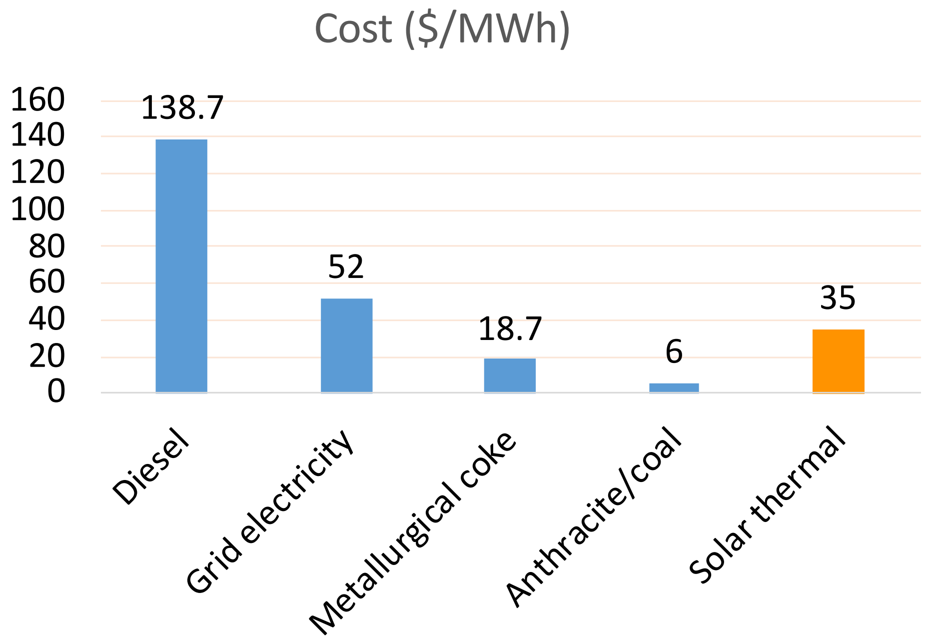


Figure 13: The estimated levelised cost of heat for the supply of hot air at 800°C, calculated without any carbon price, to a Zinc pre-heat furnace in South Africa using the Helioheat technology compared with other options [15]. Source: Mintek.

2.4 The role of CO_2 management

The high-temperature process industries are different from the electricity generation sector in that even the complete replacement of all energy sources with low-net-carbon sources would not eliminate the need to manage CO_2. Added mitigation stems from the long-term projected demand for products such as cement [41], for lime as an industrial chemical, and for the processing of other carbonate ores. There was broad agreement that the cost of utilising the captured CO_2 (e.g. by converting to a fuel) could be significantly lower than that of sequestration, since utilisation avoids the costs of compression, transport, and storage. However, many types of utilisation can only achieve partial CO_2 mitigation, notably those for which CO_2 is eventually emitted to the atmosphere on end-use. For such approaches, additional steps are needed to achieve net-zero operation. These include mineral carbonation, offsets and direct air capture (DAC) of CO_2. The heavy industry sector may be able to leverage from other investments in DAC and related technologies arising from the need to address the projected overshoot in anthropogenic emissions. Figure 14 shows the persistent increase in atmospheric CO_2 concentration that are driving such investments [43].

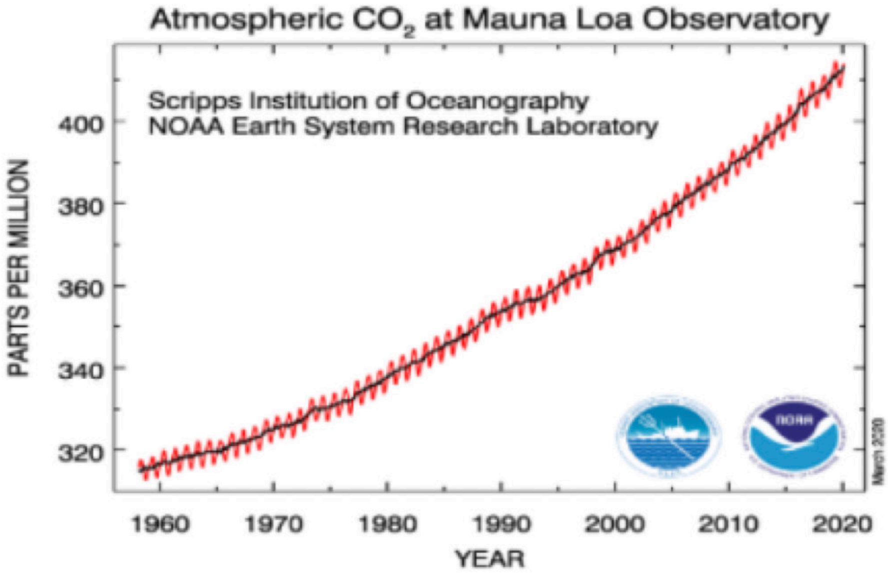


Figure 14: The ongoing rise in atmospheric CO_2 emissions, based on data from Mauna Loa observatory. Source: Scripps Institute of Oceanography.

The two approaches to mitigating atmospheric CO_2 emissions considered at HiTeMP-2 are the use of mine-site tailings and DAC. Mineral Carbonation International [28] is developing one pathway that converts tailings (and other feedstock) into building materials. The opportunity for mineralisation of tailings particularly well aligns with the capability of the sector (see Figure 15). While DAC is presently one of the more expensive options for CO_2 capture, not only are costs reducing but it also has unique capabilities that are likely to keep it within the mix, much as electrical grids dispatch power from a mix of generators with different costs and availabilities. Some of its compensating advantages are the ability to avoid the cost of transport, the less harsh conditions for the capture material compared with flue gas and the capacity to directly remove CO_2 from the atmosphere. Furthermore, the energy required to capture the CO_2 from the air is typically less than 10% of that required to convert it to a fuel [43]. Hence, several companies are developing technology for this pathway, including Carbon Engineering, ClimateWorks, Global Thermostat, and Silicon Kingdom Holdings. These options are expected to contribute to the pathway to net zero emissions, although more development and investment will be necessary to achieve commercial scale implementation and further drive down the cost. Fundamentals suggest that costs under USD 100 per metric ton are achievable [43].

Figure 15: Technology is under development to accelerate the carbonation of the mine residues in mine-site tailings, which typically settle in tailings dams (left) but can be extracted and configured to accelerate their reaction with, and capture of, atmospheric CO_2 [28]. Source: Adobe Stock Image

3 Prospective pathways for iron and steel

3.1 Progress and status

A key development since HiTeMP-1 has been the broad commitment by the iron and steel industry to decarbonise. In Australia, Bluescope has now committed to a 1% year-on-year reduction for its existing blast furnace [51] while Liberty GFG has recently announced a target to produce carbon—neutral steel by 2030. There has also been a growth in understanding of how the transition to low-net-carbon iron and steel can realistically be implemented. For example, the Midrex technology is a commercially proven path to produce Direct Reduced Iron (DRI) using NG as the fuel at half the CO_2 intensity of the conventional blast-furnace route (Figure 17). Furthermore, the use of H_2 in this process is already commercially proven because the NG is converted to syngas (by reforming) before being introduced into the shaft furnace. Hence, H_2 can already be used with up to 3:1 displacement of NG (with a pro-rata reduction in CO_2 intensity). In addition, short-term operation with H_2 has also been demonstrated during short-term trials, as shown in Figure 18 [8]. Other DRI technology providers are also in the market and other processes are under development to implement H_2 reduction, including the Hybrit technology reviewed in HiTeMP 1 [30]. Hence, some technology is already available to displace fossil fuels with H_2 for some ores. However, significant further development is still necessary to fully decarbonise iron and steel manufacture for all ores, and to develop an effective replacement for ironmaking blast furnaces as they come to the end of their lives.

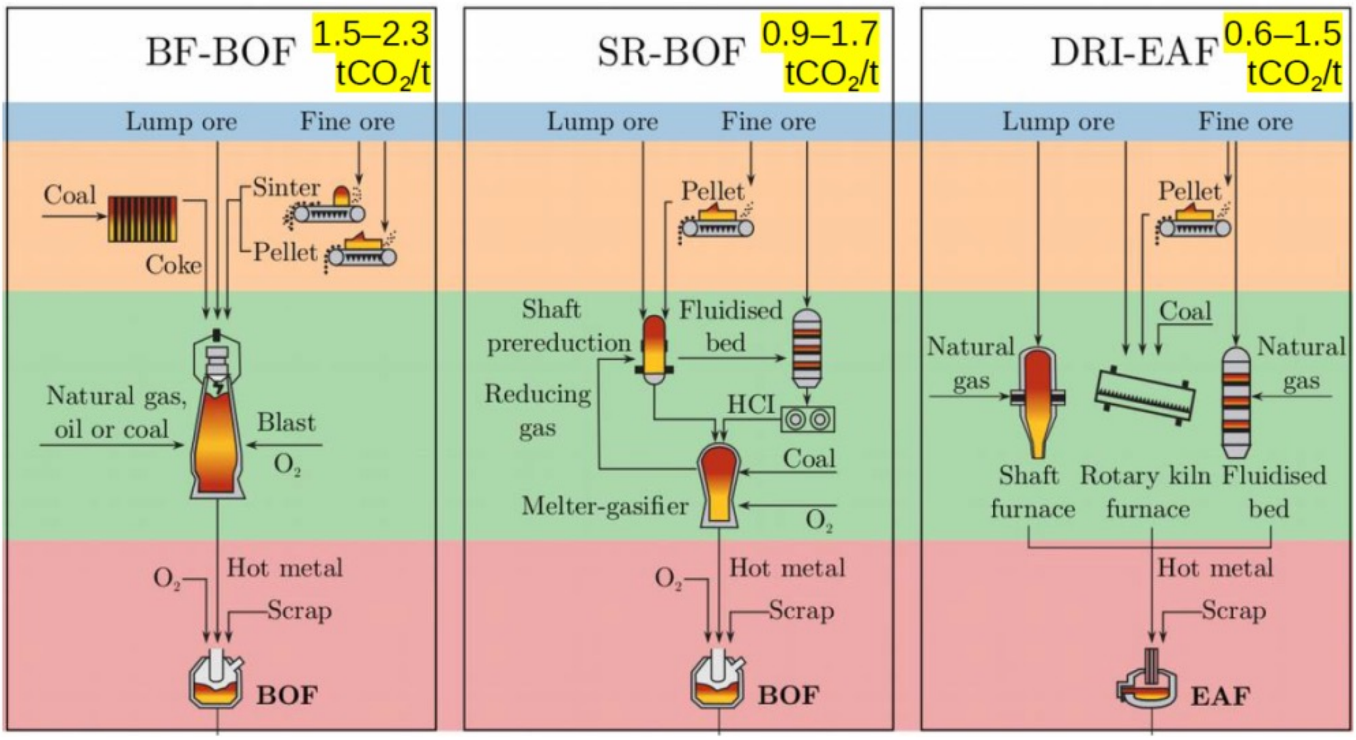


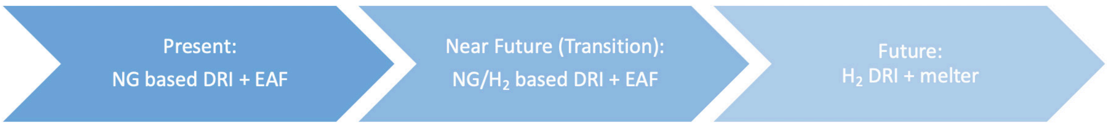
Figure 17: The range of CO_2 intensities of the commercially available routes of Blast Furnace-Basic Oxygen Furnace (BF-BOF), Shaft Reduction-BOF and Direct Reduced Iron-Electric Arc Furnace (DIR-EAF) and also showing the common role of iron pellets (and sinter) in these processes [35]. Source: Rahbari, Venkataraman & Pye, Australian National University.

3.2 Timeline and challenges

A range of perspectives were presented about the timeline for the transition to full decarbonisation. On the one hand, some steel manufacturers put the timeline as being between 2050 – 2100 assuming business as usual with no legislative requirements, new market premiums and/requirement or carbon taxes. However, others noted that a number of plausible scenarios, such as the introduction of a premium for low-carbon automobiles, could trigger a more rapid transition. Indeed, early movers, such as Liberty GFG are targeting to begin low-net-carbon steel manufacture by 2030. Nevertheless, the impediments to a rapid transition are as follows:

- **Technology transition:** The dominant pathway for ironmaking is via the blast furnace, comprising 93% of global production of new iron [35]. This technology cannot realistically be fully decarbonised, due to its heavy reliance on coke as the reductant, which can only be partially replaced by H_2 and biomass. The diffusion around the world of the best available blast furnace technology today would lead to a 21% reduction in emissions from this sector to 2100, while the roll-out of the innovation technologies currently under development in the COURSE 50 program would result in only an additional 5% reduction [33]. Hence, the decarbonisation of this sector requires the replacement of blast furnaces with new low-net-carbon technologies, such as Direct Reduced Iron (DRI) and Electric Arc Furnaces (EAF). However, the large capital investment tied up in these plants, together with their long life, means that there is strong incentive to run them to the end of their life. Not only will this replacement be slow if current plant is to be operated to the end of its life, but the replacement requires the roll out of technologies that are not yet fully commercial. Hence, additional incentives will be necessary to accelerate the complete roll-out of the low-net-carbon technologies, such as DRI/EAF.

- **Cost and availability of H_2:** Substantial reductions in the cost and investment to increase the availability of 'green' and 'blue' H_2 will be necessary to facilitate this pathway to achieve scale and become viable. The cost of carbon-neutral ('blue' or 'green') H_2 needs to be reduced by a factor of four from the current USD 4.2/kg (DOE) to the necessary ~USD 1.0/kg [8]. Furthermore, the operation of just one Midrex plant of 2 MtDRI/yr on 'green' H_2 would require 130 of the largest commercially available 20 MW PEM electrolysers currently under construction in Europe to supply the necessary 13.5 metric tons of H_2 per hr [8]. Similarly, the conversion of all of Australia's iron ore to iron via carbon free electricity would require 150 TWh/yr, which corresponds to a seven-fold expansion of Australia's national grid [35].
- **Supply chain challenges:** Iron and steel are produced via global supply chains in which both the ore and the coal are typically shipped to countries such as China, Korea and Japan to supply their downstream manufacturing processes for products such as automobiles. Hence, the best way to attract the investment to change the established trading pathways is to identify opportunities that are mutually beneficial to both trading parties. The shipping of both iron ore and iron products, such as iron pellets from certain ores, is safe and reliable. However, the technology is not available to make these products for all ores, particularly given that ship transportation brings stringent requirements for strength, while iron is also a flammable material. Hence, while commercial solutions are available for some ores, further investment is necessary to develop those tradable, low-net-carbon iron products that will be considered to be mutually desirable for all trading partners.
- **Ore-specific challenges:** Each technology implementation has ore-specific challenges that must be addressed in the development and implementation of any new technology pathway. These challenges stem both from the type of, and the impurities in, the ore. Pellet requirements are also typically higher for DRI processes than for blast furnaces and need to be optimised for each ore.



		MIDREX NG™	MIDREX NG™ w/ H2	MIDREX H2™
Reducing Gas	H_2	55%	Gradual conversion from 55% to 100%	90% - 100%
	CO	35%	Balance	0% - 10% (if carburization is required)
	Others	10% (CO_2, H_2O, CH_4, N_2)	<10% (CO_2, H_2O, CH_4, N_2)	Mostly H_2O and N_2 CH_4 only for DRI carbon (melting requirement)
	H_2/CO	1.5	From 1.5 to ∞	∞
Reformer		Yes	Yes: steam addition may be required	No: only heater needed
Carbon in DRI	(%)	1.0 – 4.0	1.0 – 4.0	0 Up to 4.0 if required for melting
CO2 emissions	(t/t)	1.1	Decreasing as %H_2 increases	Mostly from heater – can be zero or negative
Technology Readiness Level (TRL)		9	7-8	6
References		>90 modules, 1B tons produced	Strong Interest	AM Hamburg Demonstration plant

Figure 18: The manufacturer's reported performance data, including of CO_2 emissions intensity, for the current Midrex process employing natural gas (NG), the proposed transition technology employing both NG and H_2 and the future process employing only H_2 [8]. Source: Midrex Technologies Inc.

3.3 Opportunities and pathways

There is strong potential to achieve a mutually beneficial pathway to produce low-net-carbon, energy-intensive products for those countries with a coincidence of mineral and low-net-carbon energy resources, such as solar radiation and wind. In particular, the potential to upgrade iron ore to low-net-carbon iron products, such as pellets or DRI, seems to be highly prospective. This path has the potential to both lower the cost of decarbonising the supply chains of the large iron and steel making nations such as China, Japan and Korea (while maintaining their steel industries), and to provide additional export revenue to countries such as Australia, South Africa and Brazil. The potential benefits are as follows:

- **Lower cost of H_2 production:** Given that the cost of electricity is the biggest single component in the cost of 'green' H_2 production via electricity, access to a better RE resource will lower the cost of H_2 production via 'green' electricity for steel makers with only modest RE resources. For example, the cost of H_2 production has been estimated to be 30% lower in the Australian Pilbara than in Eastern China and 10% lower than inland China [35]. Similarly, ACIL Allen estimated that the cost advantage relative to production in Australia relative to Norway and Japan could range between 10% and 50% [1].
- **Avoided costs of H_2 transport and storage:** As noted above, the direct use of H_2 at the site of production avoids the high-cost transport, storage and de-hydrogenation (for case of NH_3 as the H_2 carrier), which together comprise ~ 40% of the cost of a transported H_2 product [34].
- **Lower costs of shipping:** There is an opportunity to reduce the cost of traded ore by some 9—20% by reducing the shipping costs, since converting iron ore to iron results in a 36% reduction in the weight and shipping typically represents ~ 26% of the export cost for Australia's low-cost iron ore exporters, as shown in Figure 19 [6].

Value driver for embedding H_2 into low-net-carbon iron

The combined benefit of converting iron ore to iron with H_2 at the source relative to shipping both the ore and the H_2 to a third location totals 200—370% based on the factors identified above. This benefit is likely to be sufficient to overcome any compensating disadvantages, such as higher costs of construction and operation in countries of iron production. This difference is likely to drive changes to the nature of the global supply chains to favour increased processing at those countries with a confluence of mineral resources and low-net-carbon energy resources.

Where realistic, the approach of embedding H_2 into energy dense products prior to shipping will also be much more cost effective than the transport of both the ore and the H_2.

Both the production of low-net-carbon iron pellets and DRI seem to be particularly prospective for the decarbonisation pathway [8]. The industry can use iron pellets in both blast furnaces and some DRI processes, such as the Midrex DRI process. Hence, existing steel making processes can use 'green' iron pellets. On the other hand, DRI is mostly used with electric arc furnaces although it can, and has, been used in BF-BOF processes and as a scrap supplement [8] so that it is compatible with both present and future low-net-carbon steel making processes. These opportunities are significant enough to justify further investment to begin to overcome the challenges identified above.

Potential for co-investment: The conversion of iron ore to iron or steel is likely to stimulate co-investment by the host nation, because it would increase the value of the product by a factor of three to six, depending on the product. For example, Garnaut has estimated that converting Australia's iron ore to steel would generate an additional AUD 200B per annum in revenue [12].

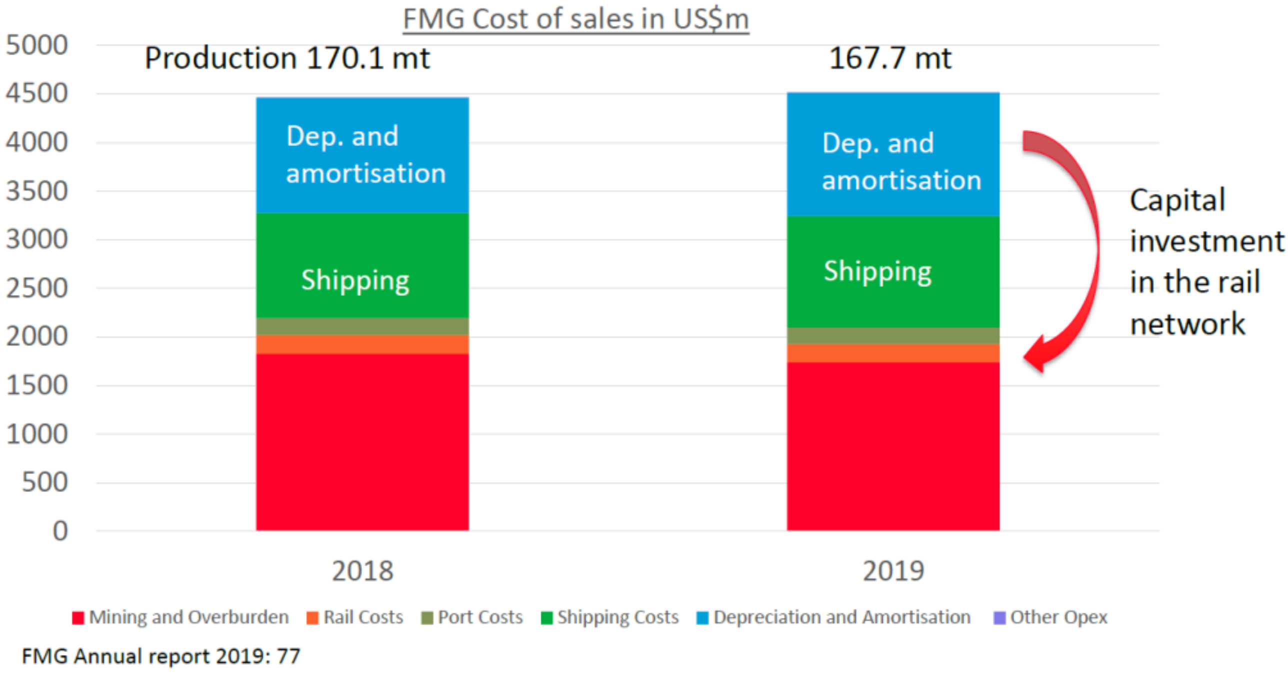


Figure 19: The importance of shipping in the cost of iron ore exports, shown here for the case of FMG, which is the world's lowest cost bulk exporter [6]. Source: FMG Annual Report 2019:77.

4 Prospective pathways for alumina and aluminium

4.1 Progress and status

Consistent with HiTeMP-1, aluminium (Al) remains the front-runner as the only certified low-net-carbon metal on the market, namely the 4.0 kg CO_2 per kgAl certification standard. As noted above, this certification standard is having an important influence on entire global markets in facilitating the introduction of a premium for certified low-carbon products. However, the availability of this product was not driven by these market measures, but rather by the historical requirement for cheap and abundant electricity that led to the construction of smelters close to hydro-electric plants in Europe, North America, and South America (Figure 20). Given that approximately two-thirds of the energy in the aluminium production process comes in the form of electricity for the smelting process (Figure 21), the access to hydroelectricity makes these particular processes ~80—85% renewable. However, the same is not true in general throughout the industry, with the fraction of RE in other countries varying from zero to 50%. Since those nations that use coal are also the biggest producers, the large majority of aluminium is still approximately four times that of the low-net-carbon-intensity producers at ~ 15.5 kg CO_2 per kgAl. Progress has also been made in the development of non-carbon-based anodes to avoid the production of CO_2 as these anodes are consumed in the reaction, with low-net-carbon alternatives now being commercially available [39]. Nevertheless, despite the progress, further developments are necessary to fully decarbonise aluminium production.

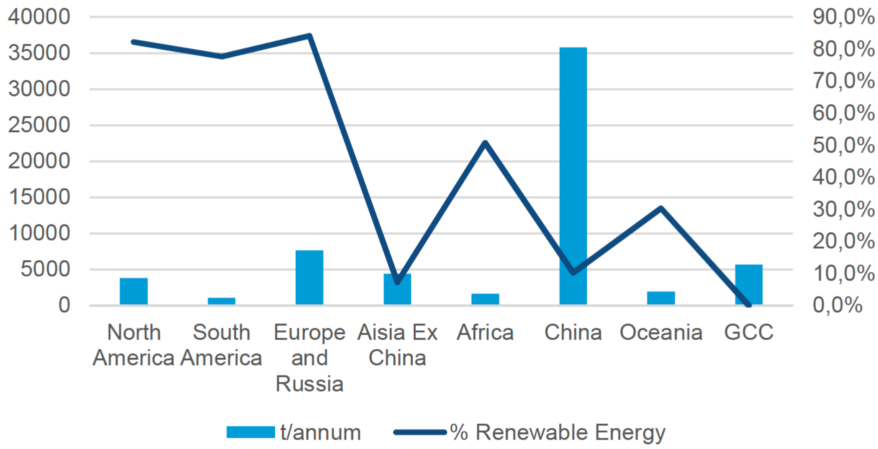


Figure 20: The range of both nationally averaged production rate and the percentage of RE penetration in the energy-intensive smelting stage of aluminium production [39]. Source: Outotec.

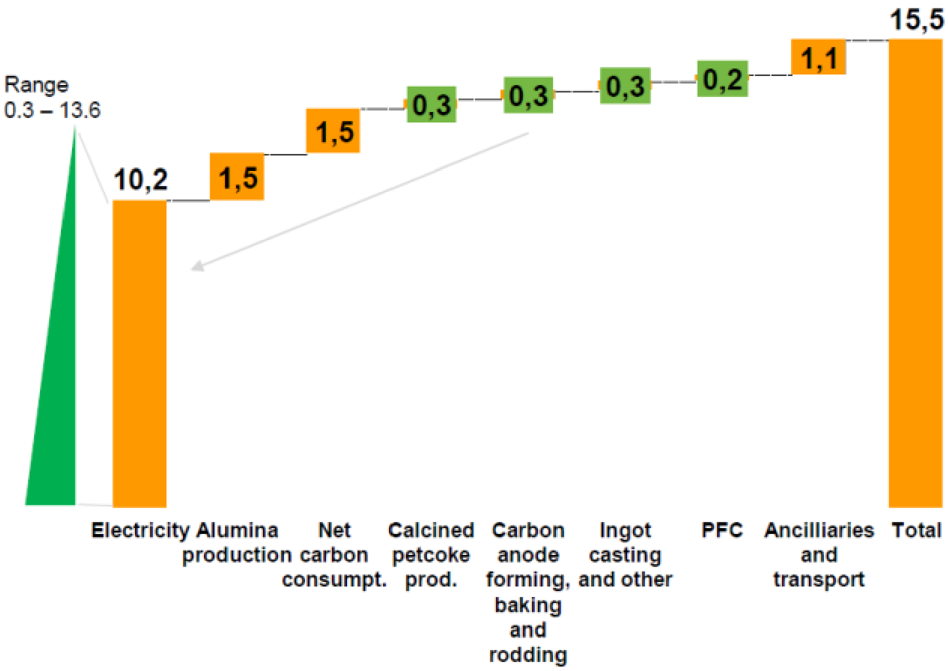


Figure 21: The average breakdown of net CO_2 emissions intensity as a function of the various steps in the aluminium production process. Source: Outotec [39].

4.2 Timeline and challenges

Despite the progress noted above, significant technology advances are still necessary to achieve carbon-neutral production through the full aluminium production process. The advances needed are as follows:

- **Integration of variable energy sources:** New developments are necessary to integrate variable RE sources into aluminium smelting to achieve cost-effective operation with renewable electrical sources other than hydroelectric. This necessity arises because present smelters were designed to operate at steady state during the period of base-load generators and are also very large energy consumers, while electricity supply is increasingly being driven by variable renewable resources. Hence, further developments are necessary, both for the smelters and the grid, which will generate new opportunities for early movers who can develop better ways to integrate variable energy resources into aluminium smelting.
- **Low-net-carbon production of alumina:** New or improved technology, and especially scale-up and demonstration opportunities, are necessary to decarbonise the alumina processes, since none are commercially viable today. This claim applies to both the low-temperature steam production and high-temperature calcination, although the technology options to produce low pressure/temperature steam for the Bayer process are relatively simple and advanced compared to technologies for high temperature processes.

For these reasons, most delegates judged that the aluminium industry is capable of carbon-neutral operation by 2050.

4.3 Opportunities and pathways

The following opportunities were identified with potential to meet the above challenges:

- Technology is now commercially available to begin to electrify the steam production for the digestion stage of alumina production. Norsk Hydro are beginning this transition with a plan to use immersed electrode steam boilers and high-temperature heat pumps [47]. Effective storage solutions to integrate variable renewable energy (VRE) sources will play an important role in enabling electrification of heat processes where constant heat flux is required.
- The EnPot technology of Energia Potior is a new development that may enable aluminium smelter pots to be configured to provide a controllable load by turning the electrical demand up or down by up to 30%, as Figure 22 illustrates [25]. This flexibility increases the viability of operation with variable RE.
- A new technology is under development at the University of Adelaide with potential to lower net CO_2 emissions from calcination [29]. This technology is being developed for retrofit to current processes to operate with hydrogen and/or electrification or, in a greenfield application, also with CST. Nevertheless, the technical maturity is relatively low (presently at TRL-3), so that, even if successful, it will likely take 10—20 years to become available commercially.

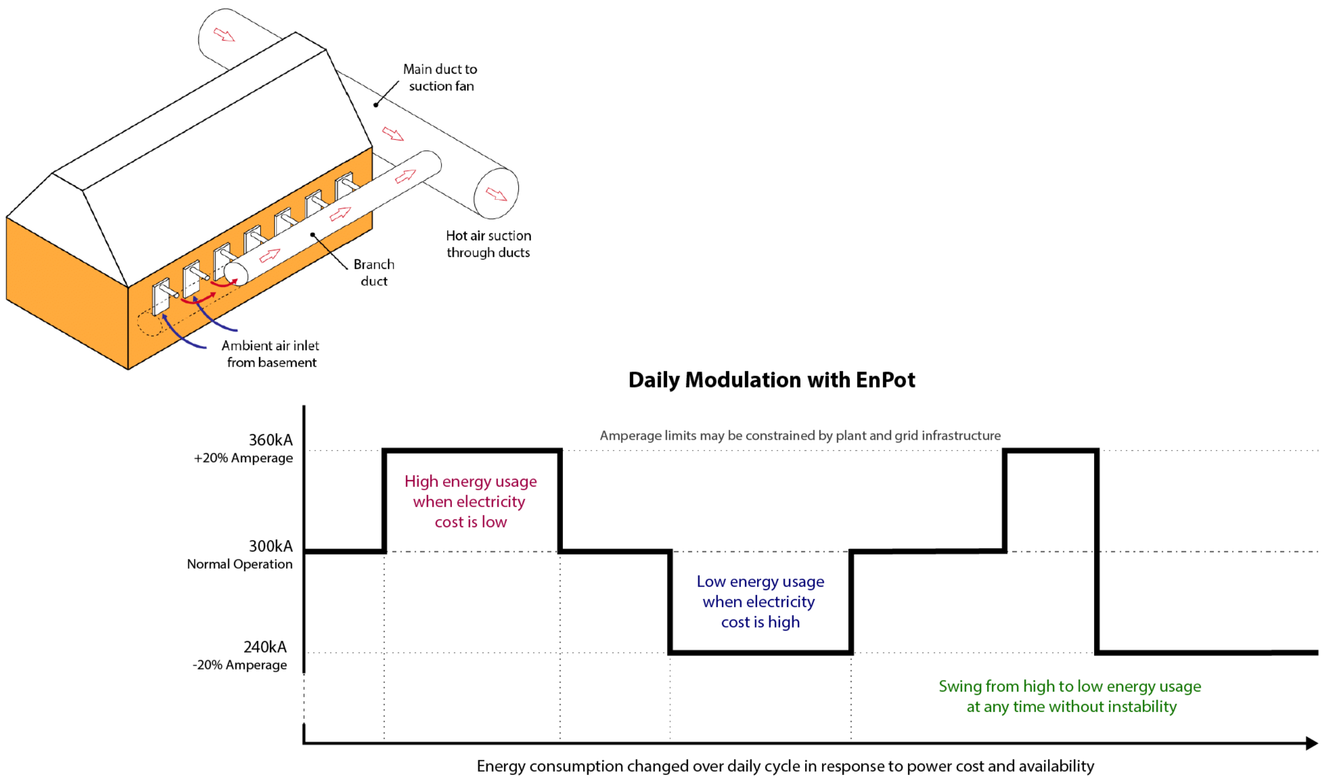


Figure 22: The EnPot technology, which offers the potential to turn the electrical demand from aluminium smelter pots up or down by up to ± 30% in response to the availability of variable energy resources [25]. Source: Energia Potior.

5 Prospective pathways for cement and lime

5.1 Progress and status

The cement and lime industry is in a strong position to achieve substantial reductions in CO_2 emissions in the next 5—10 years and is on the path to carbon-neutral operation by 2050. Nevertheless, significant barriers remain to be overcome to complete the transition. Key prospective pathways are as follows:

- New cement blends: The partial substitution of cement clinker with calcined clays at fractions of up to 50% has been shown to enable a reduction in net CO_2 emissions by up to 40%, while still meeting the necessary strength requirements as Figure 23 shows [41]. The technology to implement the substitution is available commercially and suitable clays are widely distributed, so that no fundamental technology barriers need to be overcome to begin to incorporate calcined clays into commercial cement. Instead, the main barriers to the roll-out of this technology are within the regulatory framework and building codes, both of which have been developed for conventional cement, together with embedded industry practice. Nevertheless, further developments in the technologies of clay calcination are also desirable to lower cost and increase market penetration.

- Alternative fuels: The cement/lime industry is also continuing to increase the fraction of alternative low-carbon fuels as a substitute for carbon-intensive fossil fuels. For example, all Australian cement producers are now using at least some alternative fuels, with Adelaide Brighton's Birkenhead plant having already implemented 30% substitution and developed plans for 45% [21]. Alternative low-carbon fuels remains an important component of the path toward sustainability for the industry because it contributes to waste mitigation and to the circular economy, even though its contribution to CO_2 mitigation for cement is more modest with only ~ 30% of the total CO_2 being derived from combustion and the remainder being derived from the limestone itself [30]. The main barriers to further increases in alternative fuel substitution are those of social acceptance, the adaptation or retrofits of the technology, and the availability of alternative fuels in sufficient quantities, due to associated supply-chain challenges.

- Carbon capture, utilisation, and storage of CO_2: There has been progress in advancing towards implementation of the CCUS pathway from the cement clinkering process. The European CEMCAP program has identified oxy-fuel combustion as the most promising pathway of the five options they tested and evaluated (Figure 24). Oxy-fuel technology has now been demonstrated to a technology readiness level 6 (TRLTRL-6) and the partners are now developing plans for upscaling and demonstration at TRL-8 in an EU Horizon 2020 project at Heidelberg Cement plant Lixhe, Belgium.

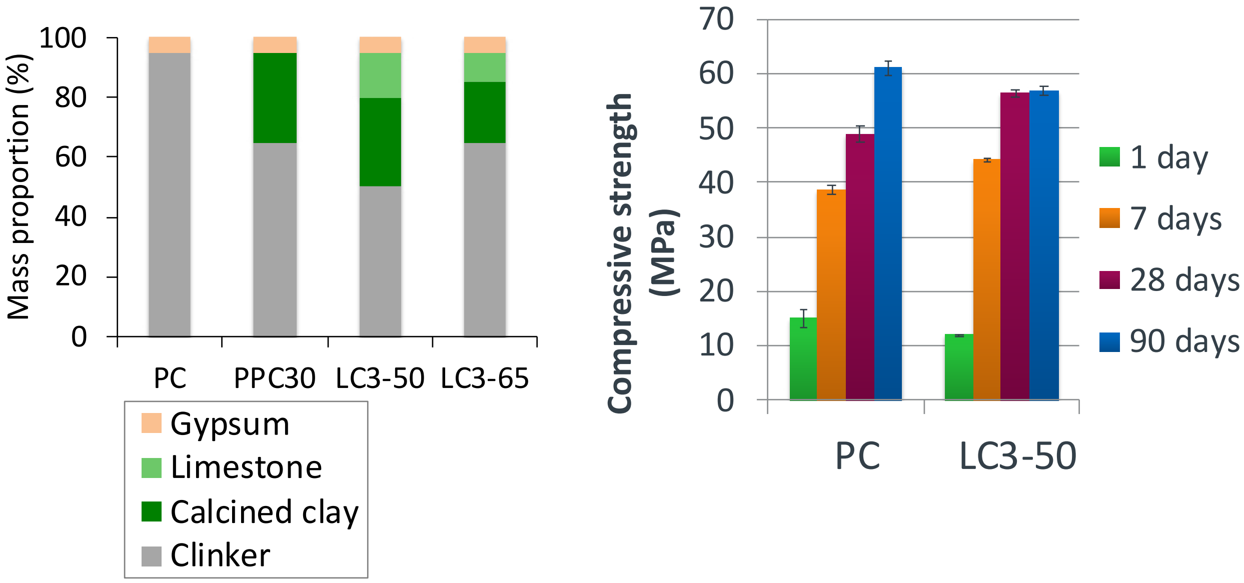


Figure 23: The composition (left) of various alternative blends of cementitious material, spanning Low-net-Carbon (LC) blends against the reference of Portland Cement (PC), together with their compressive strength (right). Note that the LC3 blended cement has 40% lower net CO_2 emissions [41]. Source: Karen Scrivener, EPFL.

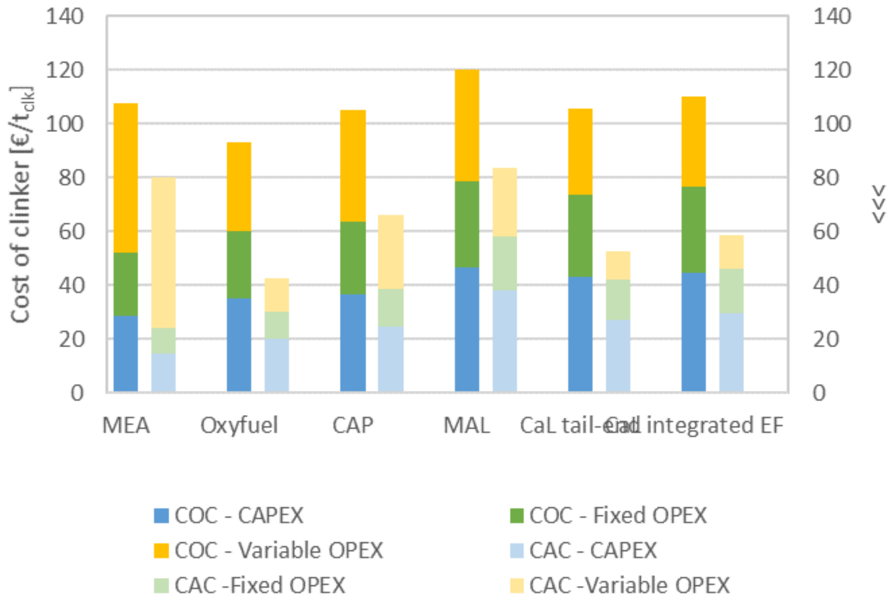


Figure 24: The relative cost-effectiveness of the alternative CO_2 capture pathways for cement clinker production investigated under the CEMCAP program. Source: Gardarsdottir, S.O., et al [11].

5.2 Timeline and challenges

Despite the progress noted above, significant challenges remain to be overcome before carbon-neutral production across the full cement/lime production process can be achieved.

The general barriers to more rapid decarbonisation identified for the cement/lime industry are as follows:

- The lack of a sufficient market premium for low-net-carbon products and/or regulation to justify the industrial investment to change to low-net-carbon/sustainable operations;
- The lack of a clear certification process for quantifying carbon footprint;
- The lack of sufficient measures for business success to reflect a priority on low-net-carbon production
- Resistance to change in established business practices in a risk-averse industry.

The identified specific barriers to the deployment of low-net-carbon blended cements, which are now commercially available are as follows:

- Building codes that direct design and new products to meet national standards.
- Building practises and cultural acceptance of transitioning to low-net-carbon materials.
- Establishing supply chains and adapting or installing additional plants to support calcination of clays.
- Community and customer acceptance of the change to the use of non-traditional materials.

The specific identified barriers to the wider roll-out of the use of alternative fuels, which are also commercially available, are as follows:

- Plant operations – training operators to control a more complex processes than traditional manufacturing;
- Plant design to allow non-traditional technologies to be adapted into existing plant, where equipment life may be 40 years;
- Finding suitable sources of alternative fuels in sufficient quantities;
- Community acceptance of change in use of non-traditional materials;
- Burner technology to support a variety of alternative fuels with regional or local sources.

5.3 Opportunities and pathways

The opportunities to overcome the barriers are as follows:

- **New business models for low-net-carbon products:** The opportunity to develop new business models based on market premiums for low-net-carbon products, such as LC3;
- **Synergistic business developments with H_2:** Provide a market for the oxygen (O_2) co-produced with H_2 and use this O_2 either for O_2 enrichment in kiln firing and/or for oxy-fuel combustion for CCUS;
- **Re-purposing old plants for clay calcination:** Re-purposing old or under-utilised rotary kilns, which were built for lime or cement production, to produce calcined clays.
- **Better harnessing community and shareholder values:** Provide a vehicle to give enhanced returns to communities and investors seeking CO_2 mitigation.
- **PPPs to increase and employment:** Expanded production of clays and increased utilisation of local resource recovery will increase local employment and local manufacturing, providing a vehicle to garner increased public support.
- **New industrial partnerships:** Connect lime suppliers with industrial customers, such as in the steel, alumina, agriculture, and glass industries, to help them decarbonise their supply chains.

Five-year pathways: Proposed plausible pathways to implement CO_2 mitigation in the next five years are as follows:

- **Green' Buildings:** Ensure building certification and star-rating processes recognise the benefits of blended cements with calcined clays and the use of alternative fuels.
- **Industry targets:** Set targets for:
  - 50% substitution with calcined clays to substitute for clinker in cement and convert or establish lime kilns to calcine clays
  - 50% use of alternative fuels
- **Policy and regulation:** Change policy and regulations to encourage low-net-carbon processing.
- **Carbon capture, utilisation, and storage:** Demonstrate CCUS at commercial scale and refine the value proposition for utilisation and/or storage options.

6 Prospective pathways for other metals

6.1 Progress and status

The low-net-carbon transition is driving a projected six-fold growth in the demand for those metals employed in renewable electricity generation and distribution technology, such as Cu, Ni, Li, and cobalt (Co). The processes needed to produce each of these metals must also be decarbonised, even though their present contribution to global CO_2 emissions is much less than that of iron, aluminium, and cement. Hence, the HiTeMP forum sought to identify synergies between the production of new-energy metals and the decarbonising endeavours described above.

To this end, the key points identified are as follows:

1. There is strong synergy between processes needed to decarbonise these other metals and those to decarbonise iron/steel, cement/lime, and alumina/aluminium. That is, the decarbonising of these processes will typically also involve one or all the following steps:
    a. Conversion of an existing electrical process (e.g. an electric arc furnace or electrowinning process) to operate with variable renewable electricity.
    b. Replacement of a fossil fuel source with an alternative fuel source, such as H_2.
    c. Capture and conversion for utilisation of CO_2, particularly that derived from the processing of any carbonate ores.
2. Many of the rare and specialist metals exist in low concentrations as secondary or tertiary products within the primary target ore that is mined at any location. Typically, only a fraction of these elements is recovered in most mines, with the residual being dumped in tailings, as shown in Figure 25. Given that the energy for mining is significant and sometimes the dominant contributor to GHGs in the production of mined metals, it seems that further investment into methods that could significantly recover additional elements from current mining operations [36].

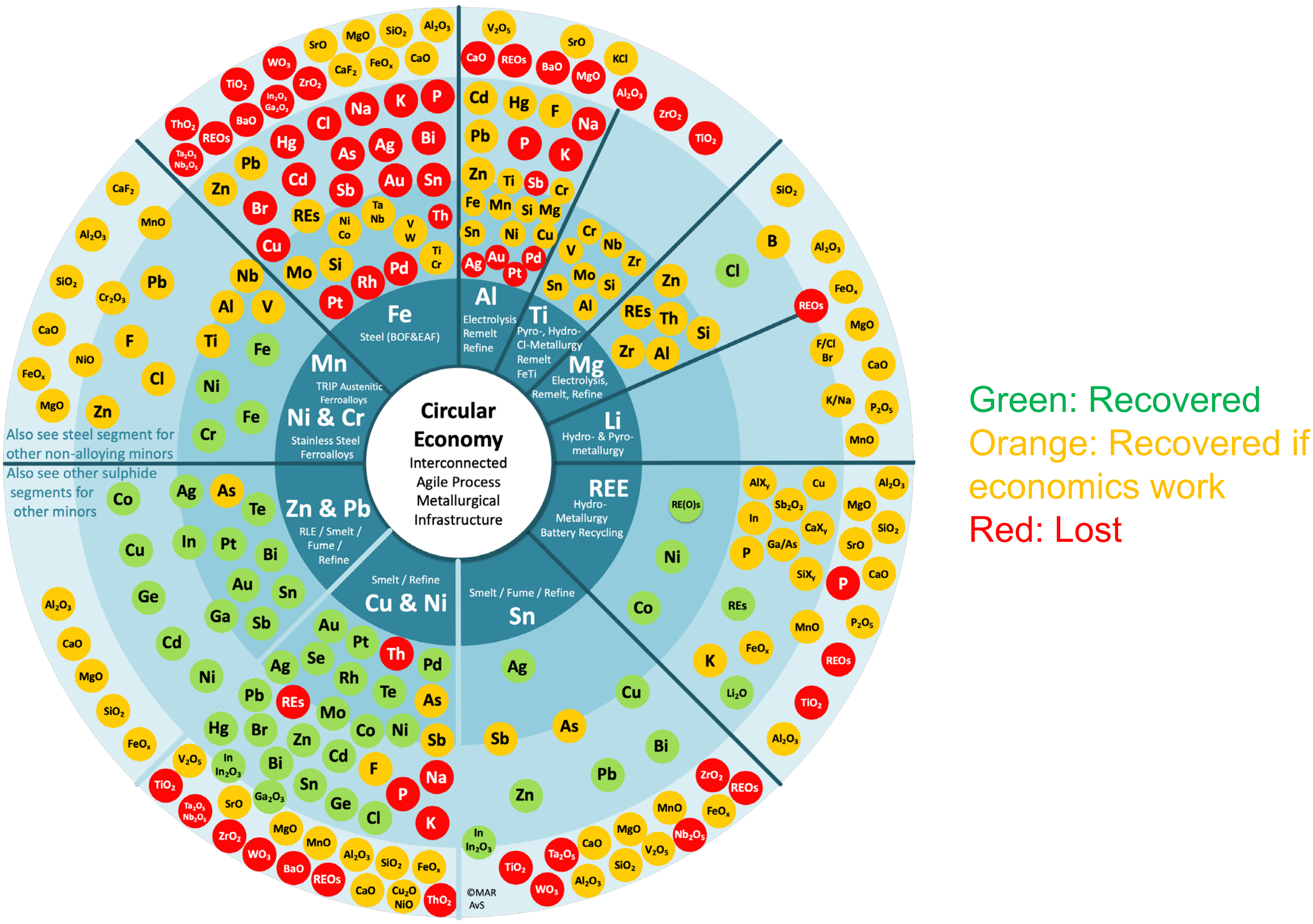


Figure 25: The distribution of secondary, tertiary, and trace elements typically mined with the primary products shown in the inner wheel. Typically, a significant fraction, and often the majority, of the elements are not recovered [36]. Source: SMS Group Düsseldorf Germany.

A range of processing options are available for most metals, as Table 1 illustrates well for the case of Cu. Overall Cu contributes less than 0.5% to global CO_2 emissions, less than 10% that of iron and steel, although it has a similar embodied carbon footprint [49]. The CO_2 intensity of the pyro-metallurgical route (~3.25 kg CO_2 per kg Cu) is only approximately half that of the hydro-metallurgical route (~6 kg CO_2 per kg Cu), with the pyro-met route being used for sulphide ores and hydro-met route for oxide ores. The pyro-metallurgy route is synergistic with H_2 production since it also requires O_2 for the smelting process. Overall, there are nine different technology pathways for the high-temperature processing (including various flash processes, the Isa-smelt and Mitsubishi processes), but all can potentially be decarbonised by access to renewable electricity, H_2, and O_2 at sufficiently competitive prices. Nevertheless, as with the other high-temperature processes, these transformations are pre-commercial and require overcoming a number of barriers, such as the capability to manage variability in energy resources [49].

It is important to put the CO_2 emissions from the high-temperature processing for Cu within the context of those generated from mining and minerals processing. Although presented as embodied energy rather than CO_2 emissions, it can nevertheless be seen from Figure 26 that the CO_2 emissions from the high-temperature processing of Cu are much smaller than their upstream counterparts. This comparison suggests that, for these and related processes, investments to reduce emissions from the upstream have potential to give a greater impact on net CO_2 emissions than for the downstream, high-temperature processing.

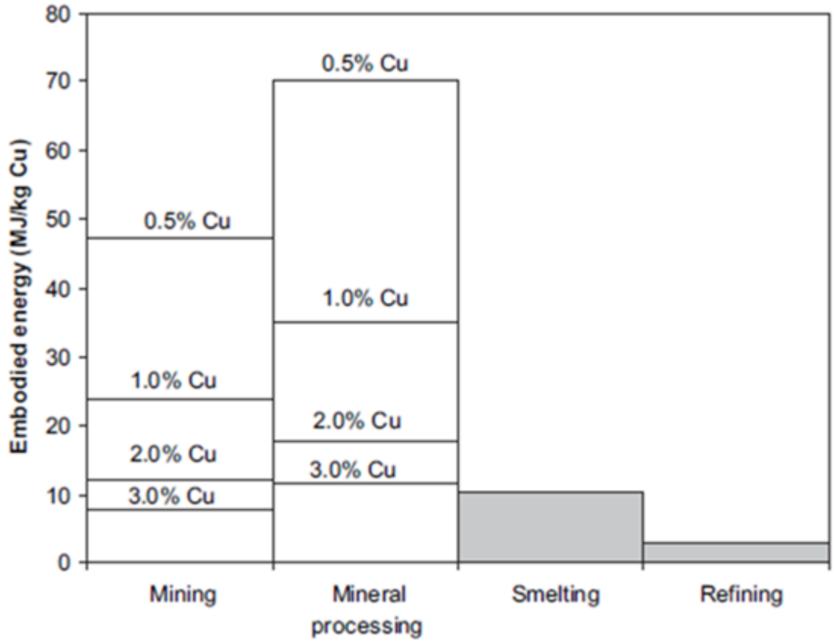


Figure 26: The distribution of secondary, tertiary, and trace elements typically mined with the primary products shown in the inner wheel. Typically, a significant fraction, and often the majority, of the elements are not recovered [36]. Source: Norgate, T., et al [32].

6.2 Timeline and challenges

The key barriers identified to the low-net-carbon transition of other metals, such as Cu, Ni, and Zn are as follows:

- **The absence of an economic incentive** such as a low-net-carbon premium or a carbon tax. Such incentives are important drivers for investment to begin the transformation process.
- **The use of low-cost fuels for the smelting processes.** Unlike blast furnaces, which rely on coke (an expensive form of fuel), processes such as Cu smelting can access lower cost fuels, such as NG. Therefore, to be affordable, significant reductions in the cost of H_2 are necessary to replace coke and NG;
- **The need for increased capacity factors to manage variable energy sources** for those electrical processing technologies to enable reliable operation to be maintained when harnessing variable RE sources.

6.3 Opportunities and pathways

The opportunities to overcome the barriers are as follows:

- **New business models for low-net-carbon products:** The opportunity is to develop new business models for low-net-carbon products, particularly those associated with the RE industries;
- **Synergistic business developments with H_2:** The opportunity is to capitalise on the need for both H_2 and O_2 in some processes, such as pyro-metallurgical Cu production;
- **Better harness community and multi-stakeholder values:** The opportunity is to provide a vehicle to generate enhanced returns to communities and investors seeking CO_2 mitigation.
- **PPPs to increase employment and resilience:** The opportunity presented from local resource recovery is to increase local employment and local manufacturing, providing a vehicle to garner increased public support. This may require public-private partnerships (PPP);
- **New industrial partnerships** between regional industries in the supply chain. One potential opportunity is to share the cost of decarbonising lime from lime manufacturers with their industrial customers for lime, such as in the steel, alumina, agriculture, and glass industries. Another potential opportunity is to make better use of slag from the steel industry for the cement industry.

Five-year pathways: Plausible proposed pathways to foster next steps in the transition for CO_2 mitigation in the next five years are as follows:

- **'Green' premiums:** To provide a value for low-net-carbon products employed in the RE sector;
- **Policy and regulation:** To change policy and regulations, which in turn would encourage low-net-carbon processing.

7 Conclusions

The transition has begun

The transition toward low-net-carbon production of the energy-intensive and 'difficult to abate' products from the high-temperature processing of minerals has begun and appears to be on-track to attract the large investments needed to complete substantial decarbonisation by 2050. Nevertheless, some industries judge that the full transition will be on-going until 2100 without further investments beyond those already anticipated. Furthermore, whilst the timeline needed to complete this transition is long, the forum has identified a confluence of drivers, enablers and tipping points that are deemed to justify the ongoing investments needed to progressively accelerate this transition. With each successive wave of deployment, cross learnings from different industries in the sector are expected to have a cascading effect to continue to lower costs and broaden the market, thereby justifying the further investments needed to complete the transition.

A market for low-net-carbon products is emerging

Sufficient elements are in place to justify the establishment of a strong market for premium-priced, low-net-carbon products. Indeed, some certified low-net-carbon products are already available, notably for low-net-carbon aluminium [30], while large companies, such as Microsoft, Amazon, and Apple, have announced plans to be carbon-neutral by 2030 [43]. Going a step further, Microsoft has pledged carbon-negative to recover legacy emissions by 2050. This kind of pledge is the next frontier [43]. Furthermore, the cost of decarbonising the sector is typically only a few percent of the final price of the product and there is good evidence that a significant fraction of the market will be prepared to pay this premium [45]. Carbon taxes, such as the European-based carbon border tax scheduled to begin in 2021, will complement and augment these premium-based market measures.

Stronger driver for trade in 'green' iron than H_2

The price-point at which it becomes economic to trade 'green' iron is likely to be significantly higher than that of 'green' H_2. Indeed, the transport of low-net-carbon iron may even become economic at CSIRO's projected cost of H_2 production in Australia of AUD 2.29—2.79 by 2025 [5]. (Note that the projected cost of 'blue' H_2 via SMR with CCS is similar to that of 'green' H_2 [5]). This economic argument arises because of the (likely) cost effectiveness of the import of low-net-carbon iron over that of importing both the H_2 and iron ore for countries in Europe and Japan who have a stated commitment to produce low-net-carbon steel. The trade in 'green' iron/steel for these countries has the combined advantages of a lower cost in the remote production of 'green' H_2 (10—50%), the avoided costs of transport and storage of H_2 (~40%) and lower costs of shipping of iron than shipping the ore (10 — 20%). The combined benefit of these factors totals 200—370%. This benefit is likely to be sufficient to more than overcome any compensating disadvantages, such as higher costs of construction and operation in countries of iron production.

Furthermore, only a modest reduction of 28 ± 12% of 'green' H_2 production is necessary beyond the CSIRO projection of AUD 2.29—2.79 by 2025 [5] to reach the AUD 2.00/kg threshold at which H_2 is projected to begin to displace coke by cost alone for the production of iron with no subsidy [4]. This option is at least as attractive as the production cost required to meet the long-term Japanese target cost for H_2 delivered to Japan of ¥20/Nm^3, which corresponds to USD US1.00 — 1.30/kg and AUD 1.50—2.00 depending on the exchange rates and the additional costs for transportation and storage [26]. That is, the iron and steel industry appears to be closer to a tipping point that could trigger a large investment in the establishment of new supply chains in 'green' and 'blue' H_2 than other uses for H_2. Furthermore, significant investment is likely to occur in countries that have both outstanding RE and iron ore resources, such as Australia and South Africa. Such investment would serve to drive the cost of H_2 production down and open other markets creating a virtuous cycle.

Key technical challenges

HiTeMP 2 Forum has identified the following key technical challenges that need to be overcome in order to implement the low-net-carbon transformation of the high-temperature processes:

1. Variable Energy Integration: Further investment is necessary to develop the technology and further experience is necessary to integrate variable RE resources into industrial processes, which presently operate almost entirely at steady state. For those processes already operating from electricity, such as electric arc furnaces, the transition to renewable electricity requires a capability to operate as a flexible load and/or cost-effective storage. For other

processes driven by combustion, complete substitution with renewable electricity is still a decade or more away. However, new technology is expected to be necessary to enable switching between different fuel and other energy sources, including electricity, in response to fluctuations in price or availability.

2. Lowering the cost of high-temperature process heat delivered at large scale: Further investment is necessary to reduce the cost of high-temperature process heat and for integration into the process, particularly at temperatures higher than those available from heat pumps (~200°C). This investment necessity arises because it is typically not economical to produce heat from either the average price of renewable electricity or from 'green' or 'blue' H_2. These processes typically use lower-cost fuels than the metallurgical coke used as a feedstock, so have a lower price point. The plausible sources of heat for which further investment is necessary include electrification (during intermittent periods of low-cost), H_2 and concentrated solar thermal heat, together with their hybrids.
3. Adapting processes to operate on H_2 and its derivatives, such as NH^3: This adaptation is needed for processes such as the manufacture of iron and steel, which need some carbon for the steel, and even for combustion to ensure that the heat transfer is maintained and other emissions, such as NO_x, are avoided.
4. Reducing the cost of CO_2 capture and utilisation (CCU): For those processes that use carbonate ores, CCU is likely to be part of the lowest cost route to carbon-neutral operation. However, CCU can also contribute during the transition period to facilitate the mitigation of CO_2 emissions from existing processes that operate with fossil fuels, while technology is being developed and demonstrated to replace fossil fuels with low-net-carbon alternatives.

Non-technical challenges

The additional non-technical challenges to be overcome to implement the low-net-carbon transformation of the high-temperature processes have been identified to be as follows:

1. Regulatory, policy and industry-change barriers: These barriers need to be over-come for the implementation of most changes within an industry and to enable operation with new technology. A clear example identified in HiTeMP-2 are those barriers to the deployment of low-net-carbon blended cement such as LC^3, which displaces half of the traditional cement clinker with calcined clays. The LC^3 cement is now a proven path to achieve a 40% reduction in CO_2 emissions so that the main need is the establishment of new supply chains, new policy, new industry standards, and the change to established practices for implementation. Nevertheless, technology advances in this area are still desirable to enable accelerated deployment and penetration.
2. Lack of suitable business models: New business models are necessary to drive the investment in, and deployment of, these new technologies. Clear examples were identified in HiTeMP-2, such as low-net-carbon steam production from electrification and/or solar thermal.

Opportunities

The opportunities to overcome these challenges are summarised in the key findings.

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