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HiTeMP OUTLOOK 2018

Transforming High Temperature Minerals Processing: A multi-stakeholder perspective on pathways to high value, net-zero CO_2 products for the new economy

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HiTeMP Outlook 2018. Transforming High Temperature Minerals Processing: A multi-stakeholder perspective on pathways to high value, net-zero CO_2 products for the new economy

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This report is dedicated to Ms Ros Whysall, former CET Administrator.
Ros contributed many hours over and above the call of duty immediately before her retirement
to ensure the success of the inaugural HiTeMP forum, due to her passion for the environment.

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Executive Summary

The inaugural High Temperature Minerals Processing (HiTeMP) Forum in 2018 engaged stakeholders from industry, research and government from around the world to discuss how to transform energy-intensive high temperature processes (greater than 800 °C), particularly in iron/steel, alumina and cement/lime production. This document synthesises the key perspectives of this pathway identified at the forum.

About high temperature processes

High temperature processes are used to produce products vital to the international economy. They are driven mostly by heat – not electricity – and operate with high turnovers and low profit margins from capital intensive plant in trade-exposed markets. These features provide the sector with both unique challenges and unique opportunities, which are now arising from the emergence of new technologies and new markets.

Pathway opportunities by industry type

The pathway opportunities toward CO_2-free products will vary significantly from one industry to another, although some technologies can be transferred between industries. The HiTeMP Forum identified key pathways for the reduction process of iron/steel and the calcination processes of cement/lime & alumina, which are responsible for some 8% and 7%, respectively, of global CO_2 emissions.

Iron and Steel

The most plausible pathways to further decarbonisation are the replacement of coal-derived coke, which is needed to reduce the ore, with hydrogen and/or bio-coke from wood (Hooey, 2018) and/or carbon capture and storage/use (CCS/U). The use of hydrogen in commercial blast furnaces has already been demonstrated, offering a path to low greenhouse gas emissions, although the cost of CO_2-free hydrogen production is presently too high for commercial implementation in most parts of the world. Yet the drivers are sufficiently advanced in Sweden for company Hybrit to be planning a hydrogen-based steel production process from renewable energy, with a pre-feasibility study recently released (Hooey, 2018). The major barrier is the need to develop and demonstrate technologies that reduce the cost of production. Other challenges are the need to develop iron ore pellets to meet ironmaking requirements and to enable the steelmaking process to meet required steel grades in the new processing route.

Alumina

There are no real technical barriers to the implementation of commercially available Concentrating Solar Thermal (CST) technologies to the digestion stage of the Bayer alumina process because their temperatures are compatible. The economic viability of this path is presently being evaluated (Nathan, 2018) and, if implemented, will both achieve a significant reduction in emissions and provide the sector with experience with CST. The ongoing development and demonstration of direct use CST for the higher temperature calcination stage is proceeding in parallel. Solar fuels, such as hydrogen and syngas, generated from solar and natural gas or biomass also has potential to contribute in the mid term, with fully renewable fuels in the longer term (McNaughton, 2018). Syngas has already been used as a commercial fuel for calcination, while hydrogen has not. Further work is needed to de-risk the use of hydrogen, although no significant technical barriers are anticipated (Nathan, 2018).

Cement and Lime

In addition to its current use of “waste” to produce heat, this sector could also benefit from the development of stored, high temperature CST heat to reduce CO_2 for the energy-intensive calcination step of cement production. However, the pathway to net-zero CO_2 must also address the CO_2 released from the calcination process itself. Some 70 per cent of the CO_2 emissions derives the limestone itself in the conversion of calcium carbonate to calcium oxide. This process releases CO_2 from the limestone irrespective of the source of energy. While some substitute materials are being used as a blend to reduce net CO_2 emissions, an ongoing need for calcination is perceived for the foreseeable future (DeGaris, 2018). Hence it is likely that carbon capture and storage and/or use (CCS/U) will also be needed to decarbonise this process. One enabler for the implementation is CCS/U is oxy-fuel combustion, which is commercially available. Other emerging technologies include chemical looping combustion, which is anticipated to be a low-cost pathway to CO_2 capture in the future. Nevertheless, the temperature of calcination is also well suited to CST, and several technologies are under development for this process.

Key technologies

The key technologies with the greatest potential to achieve low cost renewable energy driven heat in the iron/steel, alumina and cement/lime industries are as follows:

- **Direct use of concentrated solar thermal (CST) heat:** Technologies are under development with a realistic expectation to supply heat at ~800 – 1000°C for AUD$10/GJ, which is thought to be competitive with present prices of natural gas, although this is yet to be demonstrated.
- **Solar fuels, such as hydrogen and syngas:** New technologies are needed to produce solar hydrogen and/or syngas at costs competitive with fossil fuels. A series of new technologies are under development seeking to meet this need.
- **Refuse derived fuels:** These fuels are well established in industries such as cement and lime, whose long residence time and potential to adsorb gas phase species enables potentially harmful products to be managed safely. They are also a potential feedstock for more valuable products, such as plastics and liquid fuels, via solar gasification and other processes.

Conclusions

Strong incentives exist to drive the transition toward net-zero CO_2 high-temperature minerals processing. New markets are already emerging in certified low-carbon products and the costs of renewable energy are falling. However, while industry is already investing to lower CO_2 intensity through increased efficiency, no technologies are yet commercially available for high temperature processing with net-zero CO_2 emissions at a competitive price.

Further government co-investment is needed to continue technology development and to demonstrate cost-effective and reliable operation at sufficient scale for the new technologies to be taken up commercially without subsidy.

A key need is a facility suitable for demonstrating new technologies at industrially realistic scales (of order 10 MW). Long term operation at sufficient scale is needed to enable new technologies to be de-risked sufficiently to justify commercial implementation.

1. Introduction

1.1 High temperature minerals processing

High temperature minerals processing industries are vital to the global economy and demand for their products is expected to continue to grow. However, the industrial sector is responsible for 32 per cent of global CO_2 emissions, of which about half is for high temperature industries and major reductions are needed over the coming decades (Figure 1). These industries require heat at temperatures above 800 °C, which cannot be achieved CO_2-free with commercially-available technology. Meeting this need is a challenge for researchers and technology providers alike.

High temperature industries operate in trade-exposed markets with low margins from capital-intensive plants. Nevertheless, investment to transform them toward net carbon zero production can be expected in response to global greenhouse gas emission targets. The relative contribution to greenhouse gas emissions from the sector is expected to double over the next 50 years to 60 per cent, as the 'easier' decarbonisation of the electricity and transportation sectors progresses (Figure 1). In addition, some 75 per cent of the energy needs for the industrial sector is in the form of heat (Philibert, 2017). Technologies to provide high temperature heat at competitive prices and with low emissions are not yet commercially available.

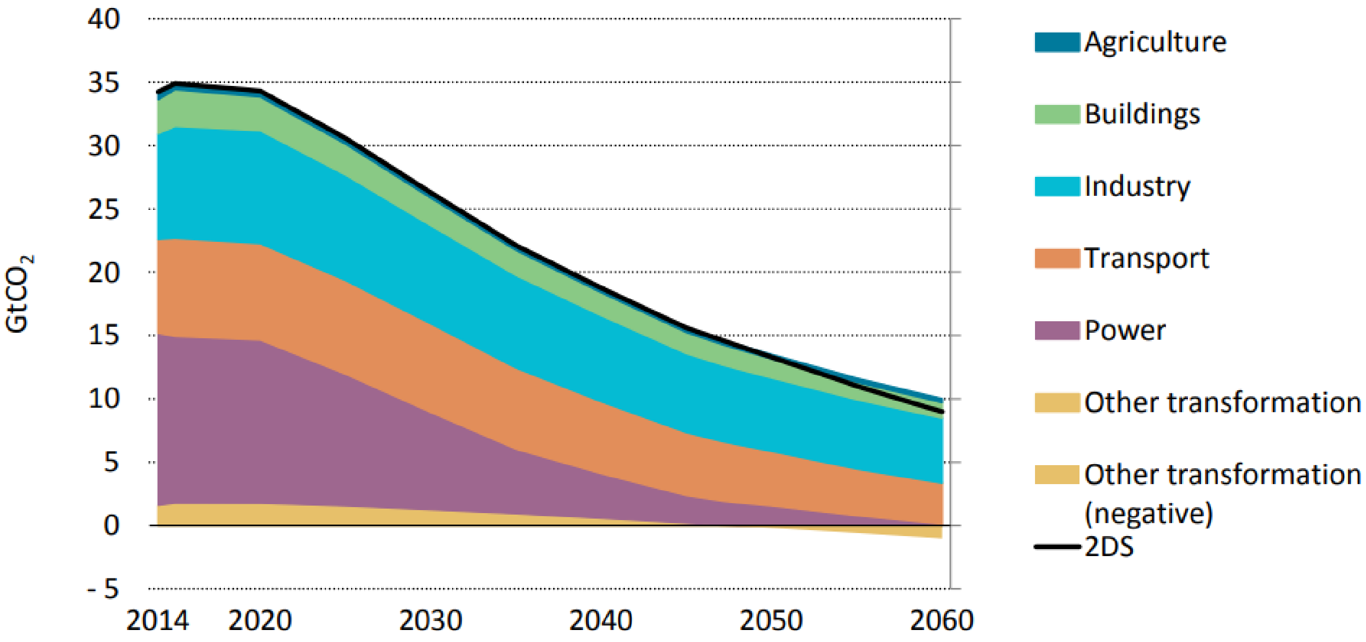


Figure 1: Anticipated trends in global CO_2 emissions from major sectors of the economy over the next 50 years (Philibert, 2017).

1.2 About the inaugural forum

The inaugural High Temperature Minerals Processing (HiTeMP) Forum (Sept 19-21, 2018) engaged stakeholders from around the world to address the drivers, barriers, enablers, opportunities and pathways to transform energy-intensive high temperature processes. Specifically targeted were the iron/steel industry, which is representative of reduction processes, together with alumina and cement/lime industries, which are representative of calcination processes.

The forum attracted more than 100 leaders from Australia, Japan, Germany, South Africa, USA, Sweden, Brazil and Norway, with close to equal representation from industry, research and government. More than 95 per cent of respondents agreed that the forum was highly relevant to them and recommend making the event an ongoing series.

It was not a typical conference; the forum engaged keynote speakers and panellists to answer the following questions about pathways for decarbonisation:

1. **Vision:** What would successes look like in the path to reducing carbon emissions for heavy industry in three, 10, 20 and 40 years?
2. **Drivers and Opportunities:** What prospects have strong potential for CO_2 mitigation in high temperature industrial processing using either renewable energy or any other process?
3. **Barriers:** What is preventing the uptake of renewable energy or other low-carbon processes into high temperature minerals processing?
4. **Enablers:** What role do government, researchers and industry play in facilitating the pathway to decarbonise heavy industry?
5. **Pathways:** What role do technologies that can achieve lower temperatures play in the pathway toward decarbonising high temperature processes?

The chairs then engaged the speakers and the floor to synthesise key stakeholder perspectives on these questions, the results of which are summarised in this report.

The forum attracted industrial specialists, comprising mostly Managing Directors and Operations/ Technical Managers, together with experts from universities, government laboratories and government agencies.

1.3 Purpose of this report

The forum was highly successful in attracting the right people at the right time; that is, a time when many companies, government and research agencies are looking to reduce the high energy costs and carbon emissions of high temperature processes.

2. Drivers and Opportunities

Commercial and social drivers to transform high temperature process industries are already emerging, including (a) global market pull for certified low-net-carbon metals, non-metals and hydrogen, and (b) local drivers for sustainable jobs and community pull for more renewable energy. At the same time, new technologies are emerging to meet the need, notably to directly use concentrated solar thermal energy (CST) for heat (rather than electricity), and to use alternative fuels, such as hydrogen. Direct use CST is expected to be particularly competitive in supplying heat for industrial processes because it is three times more efficient than the conversion of heat to electricity, for which there is already a market (Figure 2). Parallel investments being made to reduce the price of carbon-free hydrogen will also help to lower the cost of alternative fuels for industrial process heat.

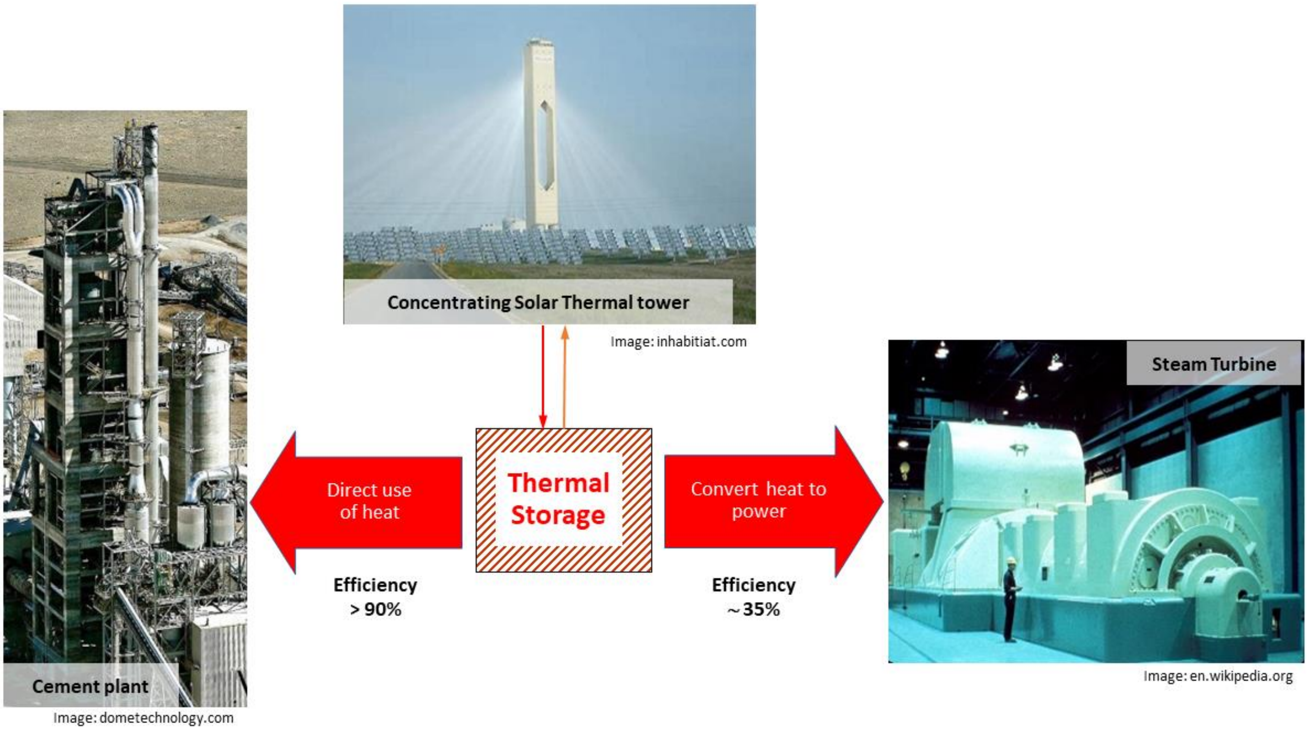


Figure 2: Stored heat from a concentrated solar thermal (CST) tower could be used directly to supply industrial heat with an efficiency of >90%, or indirectly to produce electricity with an efficiency of only ~35%. Since CST already has a market for schedulable electricity, the three-fold efficiency gain is likely to make direct use a lower cost energy source than electricity, on average, for the supply of industrial process heat from intermittent renewable energy sources (Nathan, 2018).

2.1 Market drivers

New markets for low-net-carbon metals and ceramics are emerging around the world. Some of the specific examples identified by delegates at the forum are as follows:

- Alcoa (Chatfield, 2018) and Norsk Hydro (Costa and Valstad, 2018) have introduced certified low-carbon products onto the market. For example, Hydro4.0 is certified to be 4 kg of CO_2 per kg of aluminium, verified according to ISO 14064 (Figure 3). This is a demonstration of the emerging market demand for such products.

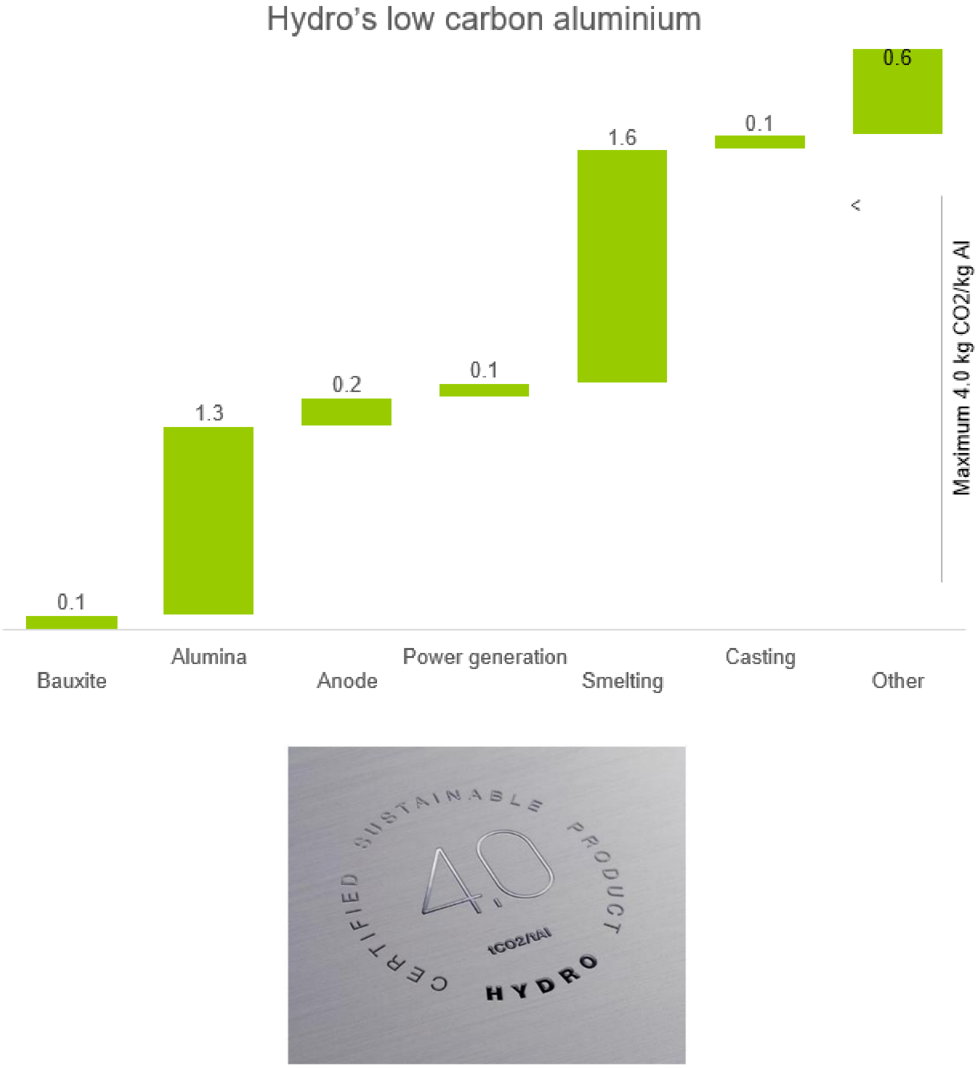


Figure 3: The certified low-carbon alumina product of Norsk Hydro (Costa and Valstad, 2018).

- BMW has both a target and a plan to achieve net-zero CO_2 by 2020 for its production plants. BMW is also seeking to decarbonise its supply chain, in expectation of growing demand for low-carbon products.
- Japan's plan to convert its economy to operate from hydrogen, produced with net-zero CO_2 emissions, will also help drive investment in the high temperature processing sector. New technology is needed to meet the Japanese target to reduce the cost of hydrogen production by a factor of five, from ¥100/Nm^3 today to ¥30/Nm^3 by 2030 and ¥20/Nm^3 by 2050 (Onazaki, 2018). New technology is similarly needed for carbon-zero high temperature processing to be economically attractive. Both of these will require investment. One of the potential pathways to low-cost hydrogen production is via CST energy at high temperatures (Sattler, 2018; Stechel, 2018). Therefore, low-cost hydrogen is also a driver for high temperature concentrated solar thermal energy technologies. The Japanese plan is also driving investment in Australia (and elsewhere) for the production of CO_2-free hydrogen, as supported by the South Australian and national Hydrogen Roadmaps (Finkel, 2018).
- Technologies that can meet the energy needs on-site will offer companies the potential to isolate themselves from the adverse effects of price volatility, to which they are presently subjected when purchasing conventional sources of fuel and power. This possibility was agreed at the forum to be a significant potential benefit.

2.2 Technology drivers

New technologies are emerging with the potential to meet the need for low net-carbon energy sources in high temperature industrial processes. This includes CMI Solar's commercial solar thermal technology that can supply temperatures of up to 850 °C (Agneti, 2018). With sufficient investment to upscale, new technologies could be cost-competitive with conventional energy sources in the next one to two decades. Specific examples identified by delegates at the forum are as follows:

- **Solar syngas:** CSIRO and DLR have each demonstrated technologies to reform natural gas with steam to produce solar syngas, to yield an upgraded fuel with a 20-30 per cent solar share (Figure 4). Pacific Renewable Fuels, in collaboration with Sandia National Laboratories, has demonstrated the mixed reforming of natural gas (with steam and/or CO_2), together with tri-reforming (also adding some oxygen to the mix), with a similar solar share. Further work is being undertaken to evaluate how to integrate a variable solar resource into a steady-state downstream process.

Figure 4: Pilot-scale demonstration of CSIRO's solar steam reforming of natural gas to upgrade it to syngas (McNaughton, 2018). A related technology has been demonstrated at DLR by an INDIREF project funded by the federal state of North Rhine-Westphalia, Germany.

- **Solar air heating:** DLR, the University of Adelaide, CSIRO and Sandia National Laboratories (in collaboration with Arizona State University (ASU), Georgia Institute of Technology, and King Saudi University) have several air heating technologies under development with potential to achieve temperatures in the range 700-1000 °C in the near term, and up to 1200 °C in the longer term. A volumetric air receiver being demonstrated at pilot-scale is shown in Figure 5, while several particle-based solar heating technologies are also under development that offer potential for thermal energy storage. Work is also in progress at the University of Adelaide to evaluate how to integrate air heating technologies into the Bayer alumina process. CMI Solar is offering technology to supply hot air with CST commercially to temperatures of up to 850 °C (Agneti, 2018).

Figure 5: The demonstration of a solar thermal open volumetric air receiver (7.5 MW_{th}), heating air to 750 °C using DLR's Solar Tower in Jülich, Germany (Sattler, 2018).

- **Commercially available hydrogen production technology:** Both AGIG and H2U have targets to produce H_2 at AUD$3/kg in Australia using commercial PV and electrolysis technology. This price will be competitive enough to access selected existing markets. However, it is three times the price of natural gas in Australia on a $/GJ basis (which is currently ~AUD$10/GJ), so substantial further reductions are needed before it is competitive as an industrial energy source (Figure 6). However, the price of CST heat is estimated to already be competitive with the cost of natural gas in Australia, although these estimates are not yet based on fully costed technologies that include integration with a process (see Figure 6 and McNaughton, 2018).

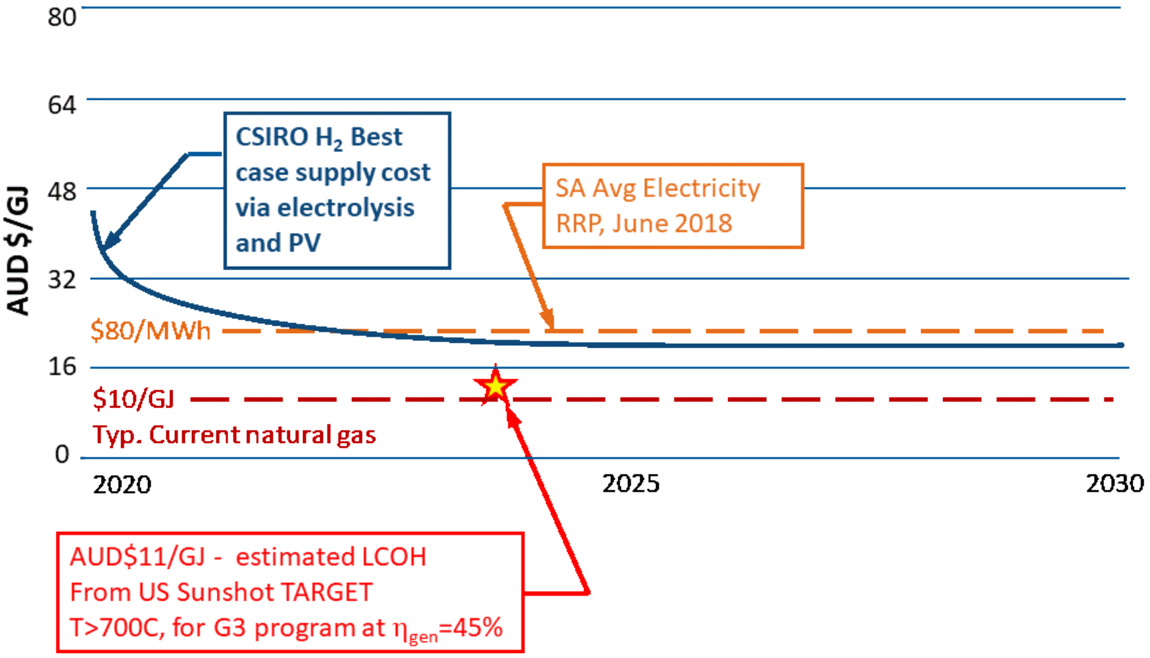


Figure 6: A comparison of the best-case estimated future cost of hydrogen (CSIRO roadmap), with current typical prices of natural gas and electricity in Australia and with the cost of heat estimated from the USA Sunshot targets for several current pilot-scale demonstration programs in the USA (Nathan, 2018).

- **Next generation hydrogen production technology:** The recent CSIRO roadmap (produced with an international team of experts) predicts a best-case reduction in the cost of H_2 by producing it in Australia using commercial PV and electrolysis technology at AUD$2 per kg by 2025. This production cost will further increase market penetration over the present state-of-the-art, but it will still be twice the price of natural gas on a $/GJ basis (Figure 6), and even more expensive than coal. This implies that next-generation technologies with a lower cost of production than electrolysis will need to be developed before hydrogen can be competitive as an industrial fuel. Such alternative technologies are already under development, including by the DLR, CSIRO, University of Adelaide, Australian National University, and Sandia/ASU (Stechel, 2018).

- **High temperature solar thermal technologies:** A series of complementary technologies is under development around the world to achieve stored heat at temperatures significantly higher than the 580 °C of commercial molten salt technology, typically targeting temperatures of ~700 °C. The target application is electricity generation and the target temperature is lower than that needed for cement, iron and alumina, but these temperatures are relevant for some industrial processes and the programs will have synergistic benefits for the development of solar receivers and thermal storage systems at even higher temperatures. For example, the US Department of Energy (DoE) is providing US$72m to support the development of Generation Three concentrating solar thermal power (CSP) technologies in a process where three technologies will be down-selected to one. The equivalent levelised cost of heat (LCOH) of these programs closely matches the current price of natural gas in Australia, namely ~AUD$10/GJ. One of these programs is a global consortium led by Sandia National Laboratories, also involving the Australian Solar Thermal Research Initiative (ASTRI), employing particles that have potential to be extended to even higher temperatures of ~1000 °C, with further development. The use of CST heat to directly process minerals at temperatures of order 1000 °C has been demonstrated at laboratory scale (Figure 7). However, further development and demonstration is needed to identify the pathways to achieve these higher temperatures cost-effectively in operating plants.

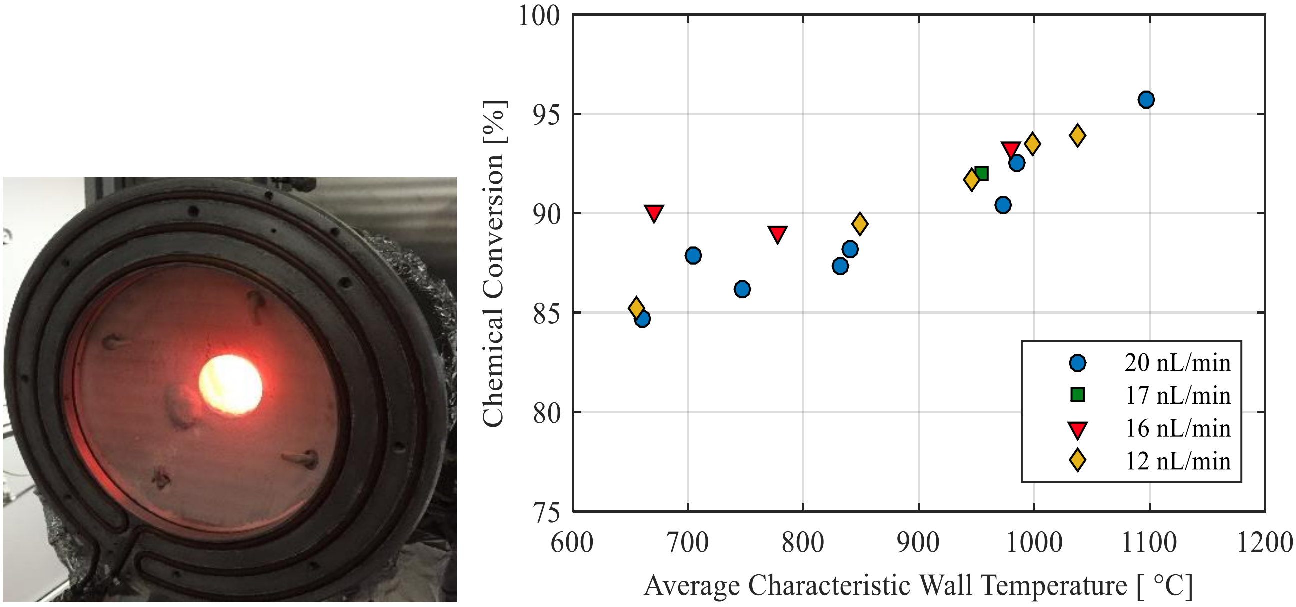


Figure 7: The demonstration of the calcination of alumina with CST radiation in a 6 kW vortex receiver in a joint project by the University of Adelaide and ETH Zurich (Davis et al., 2017).

2.3 Social and environmental drivers

A wide range of social benefits will stem from the transformation of the heavy industrial sector, which may justify additional public investment to leverage commercial investment. Society and the environment stand to benefit strongly from the reduction of global CO_2 emissions, since these are key drivers of climate change (Peters, 2016). General acceptance of the need for this has led to the global commitment to the Conference of the Parties (CoP) 21 Paris Agreement (UNFCCC, 2015), which agreed to a target of keeping global temperature rise to well below 2 °C and preferably below 1.5 °C. Significant investment is anticipated to meet this challenge. For example, the Group of Seven (G7) set a target of 100 per cent decarbonisation within 100 years, together with US$100b per year of investment in low carbon actions in developed countries alone (Sattler, 2018). Complete decarbonsation requires lowering net CO_2 emissions not only from the electricity sector, but also from industrial processes and transport (Figure 1).

Despite the agreed need to lower global CO_2 emissions, the global community is not yet on track to meet the target of less than 2 °C global temperature rise, let alone 1.5 °C. To put this into perspective, the atmosphere currently contains ~3100 Giga tonnes (Gt) of CO_2, whereas pre-industrial it was ~ 2200 $GtCO_2$. A concentration of beyond ~3500 $GtCO_2$ (> 450 ppmv) is considered to present risks to the climate that are too great (Stechel, 2018). Moreover, the proven fossil reserves, if all burned, would contribute an additional ~2800 Gt CO_2 emissions, of which approximately 45 per cent will remain in the atmosphere, with the remaining 55 per cent being absorbed by the biosphere (~35 per cent) and the oceans (~25 per cent). Contrast that with the estimated cumulative budget left to meet the target, which is only ~900 $GtCO_2$. Hence, to stay within budget would require ~4.25 per cent year over year (yoy) decrease in net emissions across all sectors, which corresponds to a:

- 34 per cent decrease in 10 years
- 56.5 per cent reduction in 20 years
- 81 per cent reduction in 40 years.

Most commentators agree there is significant likelihood that the world will exceed the concentration target commensurate with staying well below 2 °C. On this basis, it will be necessary to achieve CO_2 negative emissions in the latter half of the century – that is, it will be necessary to remove CO_2 from the atmosphere (Stechel, 2018). In order to achieve negative emissions, several entities around the world are exploring carbon dioxide removal (CDR) technologies, including direct air capture of CO_2, with either storage or recycle of the captured CO_2 (De Richter, 2013; Keith, 2018). The mining and minerals processing sectors could also play a role in sequestering captured CO_2 emissions, which can be chemically bound in residues such as slags (Stolerov, 2005).

While it has proven to be politically difficult to implement a price on carbon in many jurisdictions, the price of renewable energy is continuing to fall rapidly to become cost competitive in an increasing number of markets without subsidy (Figure 8). This is generating a wide range of new business opportunities (Ellis, 2018), which are becoming the social drivers for change that are reinforcing the environmental drivers. For high temperature process industries, the growing trend of increasingly competitive renewable energy relative to fossil fuel sources has potential to not only reduce production costs in the long term, but also to generate new opportunities for more value-adding processing for countries rich in both natural and renewable resources, such as Australia, Chile and Morocco.

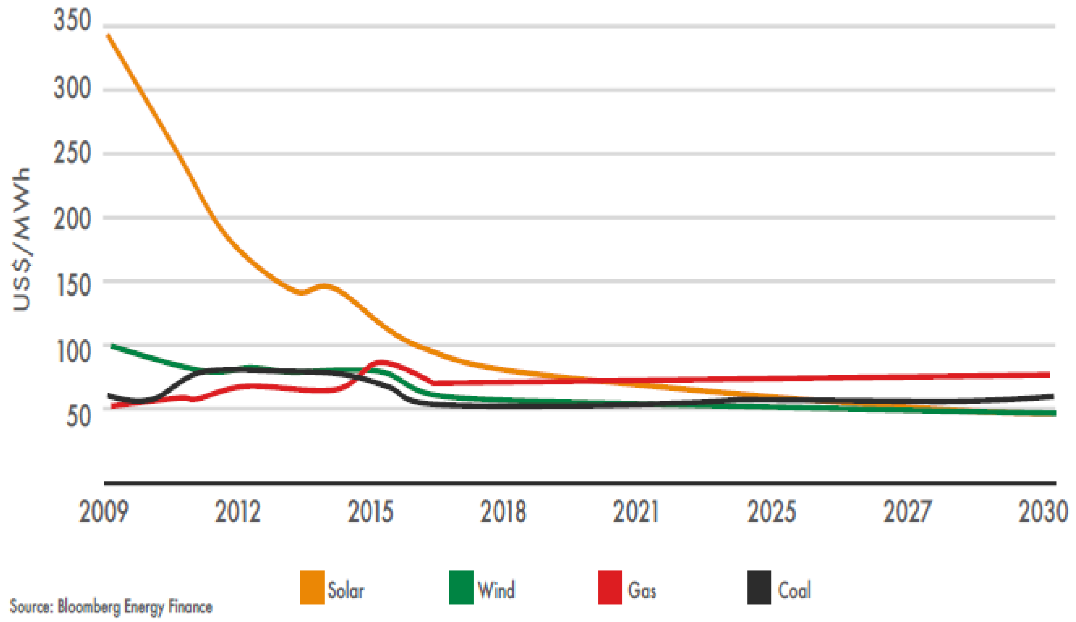


Figure 8: The cost of solar and wind power is continuing to fall, while the cost of gas and coal is rising (Bloomberg New Energy Finance, 2017; Ellis, 2018).

The social and environmental drivers identified at the forum of particular relevance to the heavy industry sector include the following:

- **Jobs for the new economy.** Both to ensure industry remains competitive in the new market and, potentially, to increase the market share of value-add by increasing the viability of value-add production with renewable heat, power and fuels.
- **Community acceptance and social impact.** The strong acceptance for the use of renewable and clean energy continues to drive change.
- **Long term energy security particularly for liquid fuels.** The local supply of renewable fuels, such as hydrogen and drop-in diesel/kerosene from local renewable resources will decrease reliance on imports, increasing energy security.
- **Hydrogen as a potential new source of energy export.** The Japanese target to transition to a renewable hydrogen economy by 2040 is a strong driver for Australia to export its abundant solar resource in the form of embedded energy in hydrogen and other exportable products. Similar drivers are present for other countries with a combination of both natural and renewable resources.
- **Mining and minerals processing in space.** Investment opportunities are emerging to meet this potential long-term need, since any mining and minerals processing in space would need to be done with renewable energy.

3. Barriers

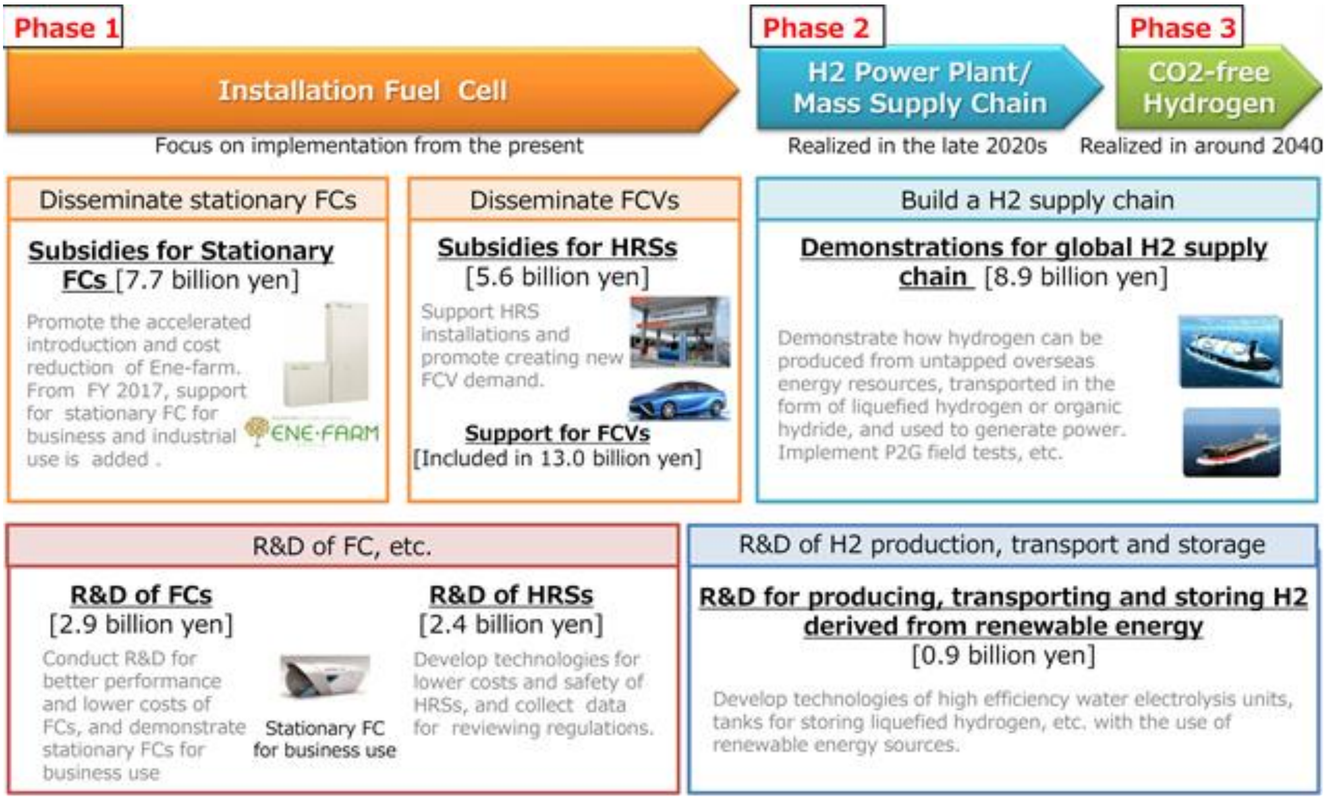
The key barriers to implementing new technology for high temperature process heat identified at the forum are as follows:

- The risk-averse nature of the sector. This results from operating in trade-exposed markets with high turn-over, low margins and capital-intensive plants.
- Technologies are not yet available at commercial scale to deliver high temperature process heat or fuel at sufficiently low cost and the anticipated cost reductions from the roll-out of commercial technologies such as electrolysis and solar PV, will also not meet the cost targets.
- While new technologies are under development with potential to achieve high temperature process heat at competitive costs, no large-scale facility is available to demonstrate them. A facility is needed to mitigate commercial risks by demonstrating reliable operation for extended periods at sufficient scale, firm up predictions of cost and ensure reliable production can be maintained.
- The high cost of capital.
- The lack of a policy framework for CO_2 mitigation and industrial transformation.

4. Enablers

The key enablers for new technology for high temperature process heat identified at the forum are as follows:

- **Government co-investment:** This is needed to bridge the gap between commercial investment criteria and the higher costs and risk for new technologies. The driver for co-investment is the broader social and environmental pull.
- **Capability of the research community:** The community has established a range of new technologies with potential to meet the needs of the sector, together with well-established international partnerships to enable cost-share.
- **Potential for international cost-share:** This can be achieved by harnessing complementary drivers and expertise from different countries. For example, countries rich in mineral and renewable resources can benefit from exporting value-added products, countries with downstream processing or manufacturing can benefit from accessing high value sustainable products at lower cost, and countries supplying the new sustainable-energy technology can benefit from participating in the industrial transformation.
- **Growing investment in hydrogen technology:** Hydrogen is one of the low-carbon fuels with potential to play a role in decarbonising heavy industry. Japan is Australia's largest energy trading partner and is notable for leading the push to hydrogen. The Japanese Basic Hydrogen Strategy aims to establish a supply-chain for CO_2-free hydrogen by 2040 (Figure 9). The supply of net-zero hydrogen is expected to come mostly from imports, with Australia identified as a target supplier. This plan is a clear example of international co-investment because countries such as Australia, rich in renewable resources, can benefit by exporting hydrogen to Japan.



Subsidies for Stationary FCs [7.7 billion yen]

Promote the accelerated introduction and cost reduction of Ene-farm. From FY 2017, support for stationary FC for business and industrial use is added.

Subsidies for HRSs [5.6 billion yen]

Support HRS installations and promote creating new FCV demand.

Support for FCVs [Included in 13.0 billion yen]

Demonstrations for global H2 supply chain [8.9 billion yen]

Demonstrate how hydrogen can be produced from untapped overseas energy resources, transported in the form of liquefied hydrogen or organic hydride, and used to generate power. Implement P2G field tests, etc.

R&D of FCs [2.9 billion yen]

Conduct R&D for better performance and lower costs of FCs, and demonstrate stationary FCs for business use

R&D of HRSs [2.4 billion yen]

Develop technologies for lower costs and safety of HRSs, and collect data for reviewing regulations.

R&D for producing, transporting and storing H2 derived from renewable energy [0.9 billion yen]

Develop technologies of high efficiency water electrolysis units, tanks for storing liquefied hydrogen, etc. with the use of renewable energy sources.

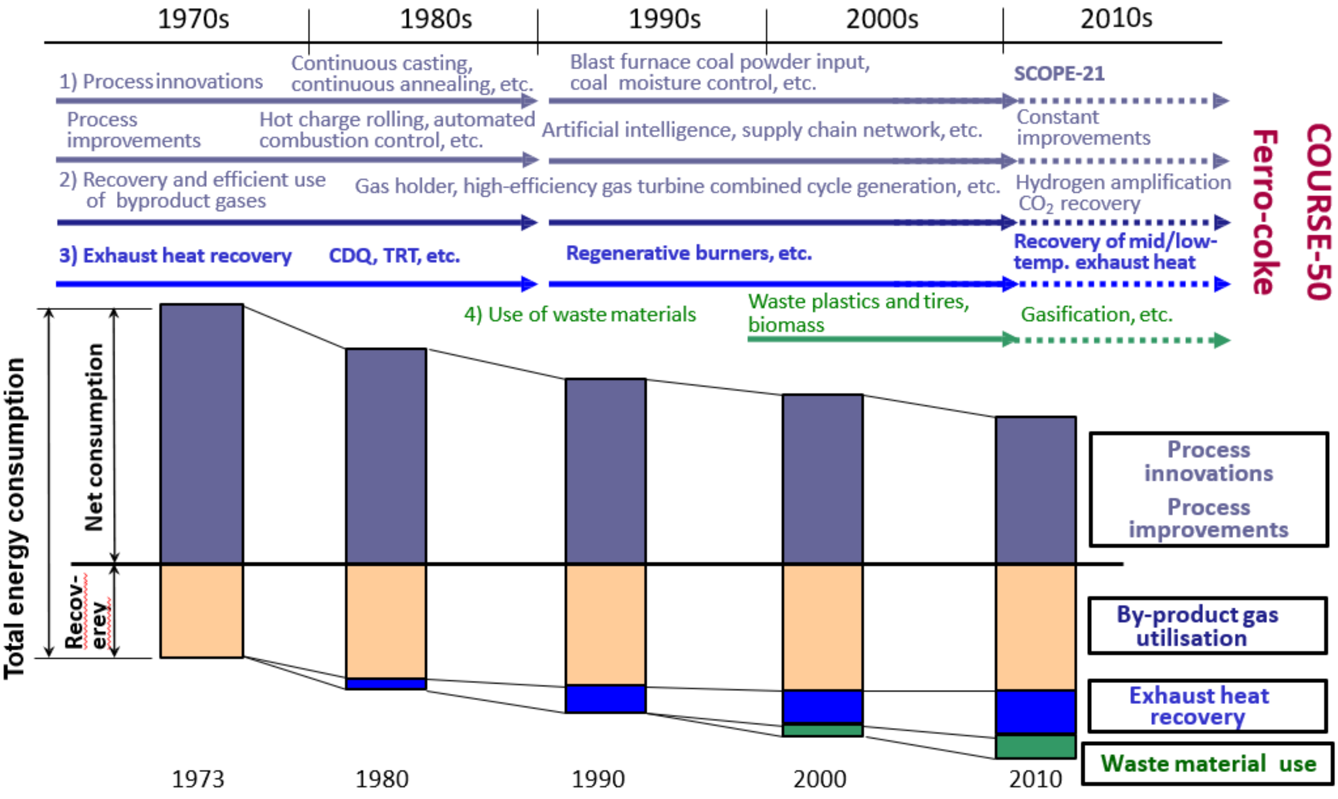
Figure 9: The Japanese plan to establish a hydrogen economy by 2040, mostly from the import of CO_2-free hydrogen (Onozaki, 2018).

5. Pathways

Pathways to reduce the net CO_2 intensity from high temperature process industries are necessarily diverse, due to the differences in temperatures and technology in each industrial process. These differences are further compounded by differences in the properties of ore, in the combination of renewable and non-renewable resources available at each site, and by other regional differences in infrastructure and geo-political environment.+ For this reason, anticipated pathways have been identified for the three industrial sectors most represented at the inaugural HiTeMP Forum: iron/steel, alumina and cement/lime.

5.1 Iron and Steel

Steel is the most widely used structural material in the world for applications spanning road, rail air and sea transport, buildings, appliances and many more. Global demand is also expected to rise by another 30 per cent to 2050 to an estimated 2.2B tpa (Suenaga, 2018). However, the production of iron and steel is also estimated to be responsible for some 8 per cent of global CO_2 emissions (Philibert, 2017), produced mostly from blast-furnaces that operate at temperatures of up to ~1300 °C (although some more recent direct reduction technologies operate at lower temperatures of approximately 850 °C). This sector has already made big steps to progressively lower greenhouse gas emissions, particularly in Japan, where emissions intensity has reduced by more than 30 per cent since the 1970s and a further 40 per cent reduction is planned to 2030 (Figure 10).



Source: JISF (Japan Iron and Steel Federation)

Figure 10: Progress by the Japanese steel industry in reducing energy consumption, and hence CO_2 emissions, since 1973 (Suenaga, 2018).

The key technology pathways under development around the world to reduce net CO_2 intensity of iron and steel production are:

- **Efficiency:** While increases in efficiency are not enough to meet future CO_2-free production, they are an important first step to lowering greenhouse gas emissions and can be done with commercially-available equipment. All the steel companies represented at the forum (BlueScope, Liberty OneSteel, Nippon Steel and Hybrit presented by Swerea MEFOS) have processes to continually increase efficiency as part of the pathway to lower net-carbon intensity. The best practice blast furnaces are now already highly efficient. However, emissions intensity varies greatly from country to country and plant to plant, depending on local policy drivers and plant differences. For example, the average emissions intensity of steel production in India is some four times higher than that of Japan (Suenaga, 2018). Nevertheless, there is a good understanding of what is needed to bring all steel-making plants to their maximum efficiency, and great potential to do so. The key barrier is the lack of a policy framework to induce investment.

- **Hydrogen:** The reduction of iron ore with hydrogen is a technology under development with agreed strong potential to all achieve CO_2-free production. Big steps are already under way to achieve this, both through modification of conventional blast furnace and by production of DRI using hydrogen. The COURSE 50 project in Japan aims to achieve a 30 per cent reduction of CO_2 emissions, of which hydrogen accounts for 10 per cent and the rest comes from the separation of CO_2 from off-gas in the blast furnace. As a member of this consortium, Nippon Steel has been verifying the effectiveness of hydrogen in CO_2 reduction via test operations in a 12 m^3 experimental blast furnace. The Swedish consortium company, Hybrit, is in the process of building a pilot-scale plant to demonstrate >90 per cent CO_2 reduction by using H_2 to produce DRI followed by EAF steelmaking. (Hooey, 2018). At the forum, the general consensus was that no fundamental barrier exists to change from blast furnace to direct reduction, although research and testing are needed to address the impact of ore grade on H_2-based DRI production as well as downstream steel production.. The main barrier to the widespread use of this process is the cost of hydrogen, although this will vary from place to place depending on conditions. In Australia, its predicted cost of production by 2025 using PV and electrolysis, even after allowing for best-case technology development scenarios, will be double the price of natural gas on an energy basis (Bruce et al., 2018).

- **Biomass and Plastics:** There is strong potential to displace some of the coke, which is presently produced mostly from coal, with coke derived from biomass and waste. Indeed, the utilisation of up to 30 per cent bio-char in blast furnaces has been demonstrated. Key limitations for wood-based substitution are resource availability and cost, while for plastics there are alternative availability constraints with additional limitations due to the presence of inorganic species such as chlorine.

5.2Alumina

An intermediate between bauxite and aluminium, alumina (Al_2O_3) is also a ceramic product in its own right. As with the other commodities, demand for alumina and its derivative aluminium, is continuing to grow, owing to aluminium’s high strength-to-weight ratio, resistance to corrosion and suitability for casting. Aluminium is widely used in the aerospace, automotive, building and food industries and beyond. The production of alumina is Australia’s most significant high temperature industrial process, with more than four times the tonnage produced relative to steel. Alumina is produced via the Bayer process, which is already highly efficient. It is a two stage process, the first being a low temperature digestion stage at ~200 °C using steam heating, and the second a high temperature calcination process that occurs at ~1000 °C, generally using natural gas.

The key technology pathways under development to lower the net CO_2 intensity of alumina production identified at the forum are:

- **Efficiency:** All the alumina companies represented at the forum (Norsk, Alcoa and South32) continuously pursue increases in efficiency to reduce net carbon intensity. Across the world, in the alumina industry in general, more efficient production capacity (with the shutting down of older plants) has led to a 17 per cent decrease in net energy intensity between 2012 and 2017. While ongoing efficiency gains are important, they can only be expected to make a small contribution to further CO_2 reductions in this industry.

- **Fuel substitution:** Most alumina plants use natural gas as the fuel of choice for calcination, although heavy fuel oil continues to be used in some places. Coal is also used, either directly for steam raising, or indirectly via syngas for calcination. There has already been niche uptake of renewable energy sources. For example, South32 uses biomass as a part-replacement for coal in steam raising. There seems to be no technical barrier to the use of hydrogen, although the presently high cost means that little work is being done to explore its use commercially.

- **Concentrating solar thermal:** A consortium (Adelaide, CSIRO, Alcoa, Hatch, ITP and UNSW) is taking a three-pronged approach to identify a realistic path to achieve a 50 per cent solar share in the commercial Bayer alumina process, based primarily on a cost target of displacing natural gas at AUD$10/GJ (Nathan, 2018). Each of the three stages is considered to have good potential to meet the target, albeit with some support needed for first-of-a-kind development and demonstration:
  a) Integration of commercially-available CST to produce steam for the digestion process at approximately 180 °C. The project is comparing the relative potential of various types of solar concentrating technology (e.g. trough and tower) and alternative options to manage the variability of the solar resource. The preferred class of technology identified for this project is a combined heat and solar tower-based plant, owing to the need for thermal storage to achieve a high enough solar share for the targets. This is best met with molten salt using already available technology.
  b) Integration of CST heat to reform natural gas to syngas, which upgrades the fuel with some 20 per cent solar energy, depending on the conditions (McNaughton, 2018). The project is seeking to achieve the above cost target and to develop the best approach with which to manage the variability of the solar resource within the steady-state and continuous Bayer process. Solar syngas could potentially be supplied both to the digestion and calcination stages of the process.
  c) Introduction of CST directly into the high temperature calcination process, which presently operates at 1000 °C. The project is exploring options as to how to integrate the high temperature energy cost-effectively, given the constraints of the existing plant, so that it can continue to operate continuously. The presently preferred approach is targeting the heating of air to displace some 40 per cent of the combustion in the process.

  The forum also suggested the potential to employ CST for the pre-calcining of bauxite prior to digestion to remove organics, which occurs at 400-500 °C. If plausible, this could be a useful development pathway to the high temperature hydrate calcination.

5.3Cement/Lime

Cement and lime play a very important role for society, not only as a building product, but also as an intermediate in many industrial processes. Demand for cement and lime is continuing to grow, particularly to support the building sector. However, it accounts for 5.5 Mt and 2.8 Mt of CO_2 emissions annually (DeGaris, 2018), and is also estimated to be responsible for some 7 per cent of global greenhouse gas emissions (Philibert, 2017). The operating temperature for the process is ~850 °C for calcination and ~1450 °C for clinkering. This sector has already implemented substantial measures to lower its carbon intensity, particularly in Europe but also in other OECD countries, achieved mostly from the use of alternative fuels such as those derived from "waste", many of which are classified as low carbon fuels (Parham, 2018). One enabler for the use of waste fuels is the inherent suitability of cement to adsorb elements that are difficult to dispose of by other methods, such as chlorine. The main barrier to increased penetration of these alternative fuels is their availability, since significant investment is required to establish their supply chains. The temperature of calcination is also well suited to CST, so that several technologies are also under development for this process (Figure 11).

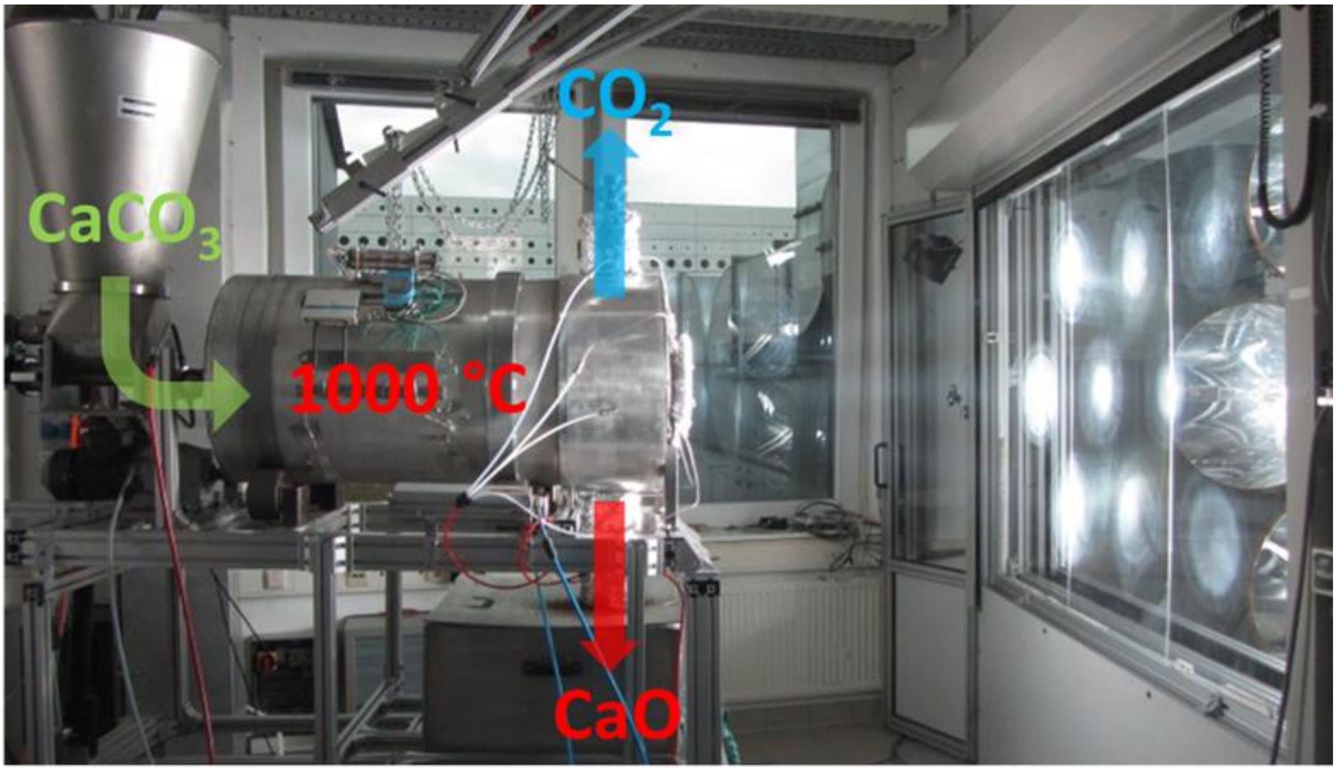


Figure 11: A solar heated rotary kiln that is under development for cement and phosphate production, with potential to both avoid combustion-generated CO_2 emissions and achieve inherent CO2 capture. DLR solar simulator, Cologne, Germany (Sattler, 2018).

The key technology pathways under development around the world to reduce net CO_2 intensity of cement/lime production are:

- **Alternative fuels:** The cement/lime industry is well advanced in developing and implementing technologies to use alternative fuels classified as low net-carbon, such as plastics and refuse-derived fuels. Some countries, such as Germany, have achieved almost complete conversion to alternative fuels while others, such as Vietnam, are continuing to use low-grade coals almost exclusively (Parham, 2018). The key barrier to using alternative fuels is the difficulty in establishing reliable supply and the need for policy drivers to overcome barriers from cost and risk.

- **Alternative feedstock:** The sector has established pathways to replace some of the limestone feedstock with alternatives, such as fly-ash, which avoid the calcination process. These can significantly reduce net CO_2 emissions, although fly-ash from coal-fired power stations is a limited resource that is not sustainable in the long term. Also, since no alternative is in sight that can completely substitute limestone, the calcination of limestone is expected to continue to be needed for the foreseeable future.

- **Concentrated solar thermal:** A number of projects around the world are seeking to develop methods to use CST for the high temperature calcination process, either intermittently or after storage. While the temperature of calcination, at around 850 °C, is compatible with CST, further work is needed to identify practical approaches to integrate the variable resource within a continuous process and within the constraints of an operating plant. This challenge is similar to that of alumina calcination.

- **CO_2 capture:** Net-zero CO_2 production must address the release of CO_2 from the calcination process itself. That is, the combustion-generated emissions comprise only 30 per cent of the total CO_2, with the majority (approximately 70 per cent) released from the conversion of calcium carbonate to calcium oxide (DeGaris, 2018). The most logical way to address this seems to be via carbon capture and storage and/or use (CCS/U). One of the commercially available approaches to achieve CO_2 capture in cement processing is oxy-fuel combustion, which is a low-cost method to CO_2 capture, albeit requiring an upfront air separation step. Any further use of the CO_2, such as to convert it to another fuel or in enhanced gas recovery, would need to demonstrate CO_2 reduction in the short term and path to net-zero carbon emissions in the long term, either with the process itself or within a broader framework of mitigation.

6. Synthesised Perspectives of General Relevance to the Sector

This section identifies outcomes from the forum that could be applied broadly.

6.1 Vision: What would success look like?

- Technology will be successful when it is being used to generate revenue by companies and is both reliable and cost-competitive with alternative options.
- Success for a region can be based on progress relative to the Paris Agreement, with the long term objective of a balanced carbon budget (i.e. where net CO_2 sinks match or exceed net CO_2 sources).
- Success for a sector is definable in the context of achieving net-neutral carbon emissions. This does not preclude the use of some hydrocarbons. For example, hydrocarbons produced from low to neutral net-carbon pathways and/or in combination with CCS/U can contribute to a balanced CO_2 budget.

6.2 Barriers

- **Awareness:** Lack of industry awareness or acceptance of the available technologies.
- **Risk:** New technologies require de-risking by demonstration and pilot scale operations. The minerals processing sector is risk-averse, owing to its need to compete in a trade-exposed market with capital-intensive plants that must deliver high-throughputs at low margins. Any loss of production can therefore have a significant impact on profitability. New technology also brings perceived safety risks. For example, the wide flammability limits of hydrogen will likely increase the risk of working in confined spaces. However, these barriers can typically be much lower in a retrofit context than in a greenfield site. This is because a retrofit can typically be configured either to testing only a small section of the process and/or enabling the new component to be bypassed if needed to revert to original operation. This allows demonstration with much less capital investment than for a full plant, together with a low risk to production.
- **Cost of capital:** New technologies typically have a high up-front cost and Australia has a particularly high cost of capital. In addition, costs are higher for first-of-a-kind technologies and then predictably decrease with industry learning through deployment and experience. Hence, there is a need for government co-investment and/or loan guarantees to reduce financial risk of commercial projects.
- **Coordination:** There is a need for increased coordination between researchers, developers and end-users, which can be difficult to achieve due to differing time scales and objectives.

6.3 Enablers

- **Government support and funding/co-funding:** This is needed to bridge the gap between commercial investment criteria for a company and the higher costs that accompany implementation of new technologies to meet the broader societal objectives.
- **Policies supporting decarbonisation:** Industry will comply with any regulation and policy, but needs a stable regulatory/policy environment to make the appropriate investments. Germany has had such an environment in this field, while Australia has not.
- **Demonstration:** New technologies need to be demonstrated at sufficiently large scale to de-risk investment in them. However, while a series of pilot-scale testing facilities is available, no demonstration-scale facility is available with which to prove reliable operation at a large enough

scale to de-risk a commercial installation. Hence, there is a need for a demonstration-scale facility to de-risk technologies with strong potential to lower the cost of both solar fuels production and direct use high temperature solar heat in an industrial process.

- **International collaboration:** This is an enabler because it offers the potential for global cost-sharing in technology development, harnessing the complementary drivers from different countries or regions. Technologies that perform high temperature minerals processing with renewable energy at costs that are competitive with fossil fuels will benefit the global community. They will offer countries with a combination of strong mineral and renewable energy resources, such as Australia and Chile, not only the potential to lower the cost of production and access new low-carbon markets, but also to increase the amount of value-added processing of mineral resources in their country. At the same time, countries with downstream manufacturing to high value end-products, such as Japan, Korea, India, China, Europe and USA, can benefit from the cost-effective supply of carbon-free materials such as iron, steel and aluminium. Countries with technology providers can also benefit from participating in the global industry transformation.
- **Long-term vision from government and/or industry:** This is considered to be driven mostly by society's expectation for action in response to climate change and, where present, will underpin the investment needed to transform a sector that is capital intensive. That is, it will help to overcome the barrier of the higher up-front costs that are needed to achieve a long-term more sustainable sector.
- **Community expectation:** There is already strong community expectation of the need to transform the sector toward sustainable operation. This, however, can be further fostered by increased engagement between the research sector and the community/public.

6.4 Pathways

- Implementing the direct use of CST into low temperature processes (such as to generate solar steam) will help facilitate the path to high temperature processing by familiarising the industry with the technology and enabling operating systems to be established. It will also help to lower the cost of the technology by increasing market penetration. For example, the cost of heliostats will decrease with the number of installations in common with all manufacturing processes.
- Demonstrating new technologies as retrofits to existing plants is an important part of the pathway, since it offers potential to reduce the risk of lost production. Careful design of a retrofit will enable operation to revert to the original configuration, if needed, to continue production. In addition, such a pathway typically reduces the risk of capital investment, since it can also utilise existing infrastructure. It also avoids all the processes and costs needed to establish a new site.
- Modular systems can be a pathway for some technologies, since it can be easier to replicate (number up) than to upscale (size up). On the other hand, thermal systems typically benefit from increased scale, which can achieve greater efficiency, so that standardised system components can be an alternative.
- Collaboration between stakeholders, such as universities, government agencies, developers of the energy systems and end users, must be part of any pathway chosen.

7. Industry-Specific Outcomes

In this section, industry specific *opportunities* identified at the forum are shown in Table 4.1. Industry specific *pathways* are shown in Table 4.2. The *barriers* and *enablers* and shown Table 4.3 and 4.4, respectively. The relative merit of these alternatives was not discussed, but it is obvious that significant opportunities are available.

Table 4.1: Industry-specific opportunities identified at the forum.

Process	Renewable energy opportunities	Other opportunities

Calcination (alumina and cement)	• Calcination using CST
	• Calcination using hydrogen
	• Renewable electricity (e.g. PV) to generate heat, such as electric technologies for calcining – dielectric heating and resistive heating. See: http://bze.org.au/electrifying-industry-2018/ However, specific technologies are yet to be developed.
	• Solar fuels, syngas
	• Pre-calcination – for some types of bauxite
		• Oxy-fuel firing to enable cost effective CO_2 capture
		• Cement
		  • Clinker-free cements
		  • Clinker substitutes such as BF slag
		  • Reduced use of concrete in built environment
		• Bauxite pre-treatment and limestone pre-calcining at quarry

Iron and steel production	• Bio gas and charcoal
	• Hydrogen reduction
	  • Enrichment
	  • 100% hydrogen
	• Electric arc furnaces, powered by renewables
		• Recycled steel
		• By-product gas utilisation
		• Exhaust heat recovery
		• Waste material use e.g. plastic, tyres

All	• Alternative fuels (e.g. RDF, biomass)	• Process optimisation • Carbon capture and storage or use (CCS/U) • Trading or otherwise cost-sharing with CO_2 negative emissions generated elsewhere

Table 4.2: Industry-specific pathways for anticipated successful implementation with indicative timelines.

Process	3 years	10 years	20 years	40 years
Alumina production	• Commercial scale demonstration of CST for combined heat and power (CHP) for Bayer digestion process • Pilot projects adding CST, hydrogen, etc. in calcination - development of portfolio of options	• Wider CST for CHP deployment for Bayer digestion process – no subsidy needed • Demonstration scale hybrid (e.g. 20MWth) projects incorporating CST and/or hydrogen in calcination • Retrofitting • Develop regulation	• Commercial plants (subsidy free, retrofit), incorporating CST and/or hydrogen in calcination • New greenfield sites (If CST cost is competitive)	• Alumina production 100% carbon neutral
Cement and lime production	• Pilot of CCS/U – to solar fuels • R&D of solar fuels • Global drivers - market and/or policy based • Look at other NG networks for demonstration to reduce risk • Oxy-fuel firing to concentrate CO_2	• Wide deployment of alternative fuels • Demonstration of CCS/U for solar fuels and products • R&D of next gen solar fuels • Demonstration of increased lime-stone substitution	• Commercial plants (subsidy free) with CCS/U – to solar fuels • Demonstration of improved gen solar fuels • High penetration of limestone substitutes	• Deployment of next gen solar fuels technologies
Iron and steel production	• Begin implementing known process improvements • R&D program for hydrogen reduction of Australian iron ore and low-cost production integrated with steel processes • Develop pathway for large-scale charcoal industry • Increase heat recovery from blast furnace slag	• Complete implementation of known process improvements in existing plants • Feasibility studies and pilot projects for hydrogen reduction of Australian iron ore and related production technologies	• Demonstration projects for hydrogen reduction of Australian iron ore • New steel plants in Australia based on hydrogen reduction	• Substantial share of Australian iron ore processed domestically using renewable energy • Large steel export industry (e.g. to India) • $35-50b extra revenue

Table 4.3: Categories of barriers to successful implementation.

Category	Barriers
Technology risk, cost and development	• Valley of death (at 2-3 phases of development) - difficulty funding pilot and demonstration projects • High cost of new technologies • Unproven technologies • Capital blowouts • Capital intensive industries with low margins – need to ensure high availability when incorporating new technologies • Calcination: existing process knowledge is based on combustion
Business case barriers	• Policy uncertainty • Risk premiums and higher financing costs for new technologies • Higher capital cost of low emissions technologies • Value of sustainability difficult to incorporate into NPV • Current business model ignores broader value to society e.g. waste disposal • Skews in existing regulations e.g. RDF counted as having high CO_2 emissions, despite renewable content • Cost of capital is higher locally than overseas • Long life of plants • Slow development and implementation due to protection of IP
Integration challenges	• For electric technologies e.g EAF – characteristics of electricity grids with high renewables share e.g. fault levels, reactive power • Insufficient land for CST and/or modest DNI in some existing plants • Long life cycle, high capex assets • Remote location • Lack of ecosystem e.g. hydrogen production and distribution, biomass supply chain • Intermittency of operation
People and culture barriers	• 'Clay layer' (middle management not incentivised to make change) • Risk of new technology, production focus • KPIs poorly aligned with implementing new technology • Short term focus • High profile of new technology failures • Poor record of collaboration of industry and research

Table 4.4: Categories of enablers identified to support successful implementation.

Category	Enablers
Technology risk and development	• Strategic (international) long-term R&D, pilot and demonstration programs between researchers, government and industry (including customers and OEMs) • Learning from international experience, and sharing internationally • Thoroughness in each stage of tech development – test properly • Get experience with more mature renewables e.g. PV + batteries • Hybridisation with existing plant, plus fall-back option to existing operation • Underwrite risk to investors, e.g. in developing bio-coke supply chain • Test facility (prototype evaluation) for high temperature CST (10-20MWth)
Market pull	• Demand for green products/supply chains (starting with premium segments) • Certification of low carbon products
Cost	• Reduction in fuel price risk • Standardisation of components • Lower O&M cost for CST system • Energy efficiency (reduced energy demand) • Hydrogen infrastructure and other sources of demand e.g. FCEVs, export • Emphasise smaller, modular systems to reduce risk and increase rate of iterations • Increased knowledge of learning curves to justify first-of-a-kind demonstrations • International coordination to decarbonise energy intensive trade exposed commodities
Policy and regulation	• National long-term decarbonisation targets and strategy • Carbon policy/regulation (including risk of eventual C price) • Standards/regulations for embodied emissions • Safety standards for hydrogen • Sector roadmaps • Consistent policy between states regarding landfill levies • Recognition of biomass content in RDF in NGERS • Government support for new projects • Leadership (E.g. Specialised CRCs) • REC for Solar fuels/process heat • Energy certificate for building material
People and culture	• Social attitudes – which can be fostered by increased engagement with sector • Culture change in companies • Drop quarterly reporting • Harnessing co-benefits – e.g. jobs • Stakeholder expectations – financiers, shareholders, customers, community • Skills development

8. Conclusions

Strong incentives exist to drive the transition toward net-zero CO_2 high-temperature minerals processing, but further investment is needed to enable the economic opportunity to be grasped. New markets are already emerging in certified low-carbon products and the costs of renewable energy continue to fall, generating incentive to invest in low-carbon technologies. However, while industry is already investing to lower CO_2 intensity through increased efficiency, no technologies are yet commercially available for high temperature processing with net-zero CO_2 emissions at a competitive price. While there are several technologies with potential to meet this need, further co-investment by government is needed to continue their development and demonstrate their cost-effective and reliable operation at sufficient scale for them to be implemented commercially without subsidy.

The key technologies identified at the forum as having the greatest potential to achieve sufficiently low cost in the iron/steel, alumina and cement/lime industries are as follows:

- **Direct use of concentrated solar thermal (CST) heat:** Technologies are under development with a realistic expectation to supply heat at ~800 – 1000°C for AUD$10/GJ, which is thought to be competitive with present prices of natural gas, although this is yet to be demonstrated. The direct use of heat from CST is some three times more efficient than using the same heat to generate electricity, giving this technology a competitive advantage over electricity in the production of heat. In addition, further development is also needed to achieve the temperatures needed in iron/steel, cement/lime and alumina production, since CST is presently only demonstrated commercially at about 600 °C for power generation. While a series of technologies have been demonstrated at pilot-scale to achieve the temperature range and others are under development globally, further investment is needed for development and demonstration to reach the cost targets and reliability necessary for commercial implementation.
- **Solar fuels, such as hydrogen and syngas:** New technologies are needed to achieve the production of solar hydrogen and/or syngas with costs competitive with fossil fuels. Even the best-case projected cost of hydrogen production by 2025 in Australia with electrolysis and PV is double the cost of natural gas in Australia which, in turn, is more than double that of natural gas in the USA. A series of new technologies are under development seeking to meet this need. However, further investment is needed to continue both their development and demonstration to reach the cost targets and reliability necessary for commercial implementation.
- **Refuse Derived Fuels:** The use of refuse derived fuels is well established in industries such as cement and lime, whose long residence time and potential to adsorb gas phase species enables potentially harmful products to be managed safely. A key barrier to their wider implementation is the investment needed to establish better supply chains. Furthermore, these materials are also a potential feedstock for more valuable products, such as plastics and liquid fuels, via solar gasification and other processes.

A key barrier to the acceptance of emerging technologies with ample confidence to implement commercially is the availability of facility suitable for demonstrating new technologies at industrially realistic scales (of order 10 MW). Long term operation at sufficient scale is needed to enable new technologies to be de-risked sufficiently to justify commercial implementation.

A key further enabler is the potential for global cost-share, to harness the complementary value proposition for different countries and regions. Countries with a coincidence of mineral and renewable energy can cost-share to develop a technology of mutual benefit, countries with high-value downstream manufacturing can benefit from supporting development to lower the cost in the supply-chain of net-zero CO_2 energy-intensive metals and ceramics, while countries with technology providers can benefit from participating in the investment to transform the sector. Nevertheless, new mechanisms are needed to better harness these complementary drivers and enable the barriers to be overcome.

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