Aluminium production pathway to zero carbon 2050

Much has been made of aluminium's environmental credentials as a metal, with its infinite low energy recyclability and ability to contribute to decarbonisation through light-weighting effects of transportation, however a pathway to full decarbonisation has proven elusive and remained in the too-hard basket.

At the Green Technologies session of the Aluminium Showcase earlier this month, **Geoff Matthews*** presented an Aluminium Production Pathway to Zero Carbon 2050, with co-authors **Dr. Mark Dorreen**** and **Dr. Nick Depree*****. Here, the trio are joined by **Dr. David Wong****** and take a more in-depth look at the pathway and discuss further the challenges of full decarbonisation of aluminium production.

The development of this pathway was stimulated by the International Energy Agency's (IEA) Tracking Report June 2020. The blunt assessment of "more effort needed", propelled us to look at what actions would be required to place aluminium production on a pathway in alignment with the CO_2 goals in the IEA's Sustainable Development Scenario (SDS). The IEA point out that efforts on multiple fronts will be required including:

- Greater secondary production (recycling)
- Reduced direct emissions from primary production and combustion processes
- Decarbonising power supply.

Before we dive into an analysis of each, it is important to recognise that in laying out a pathway to decarbonisation for any industry is initially confronting. One of the fundamentals of business is that there is no change without threats. The current trajectory models below show that aluminium production faces a clear and imminent threat, which we can no longer ignore. Aluminium smelting has by and large flown under the radar. This is not a guarantee of commercial success going forward.

It is also important to recognise that pathways are designed to set us in motion in the right direction. We don't necessarily have to have a clear route to the end before setting off. We need to accept that technological innovation over the next three decades will be required to 'get us there in the end'. Delaying getting started however, only increases the risk of aluminium being replaced as a relevant material and exponentially increases the burden in future years.

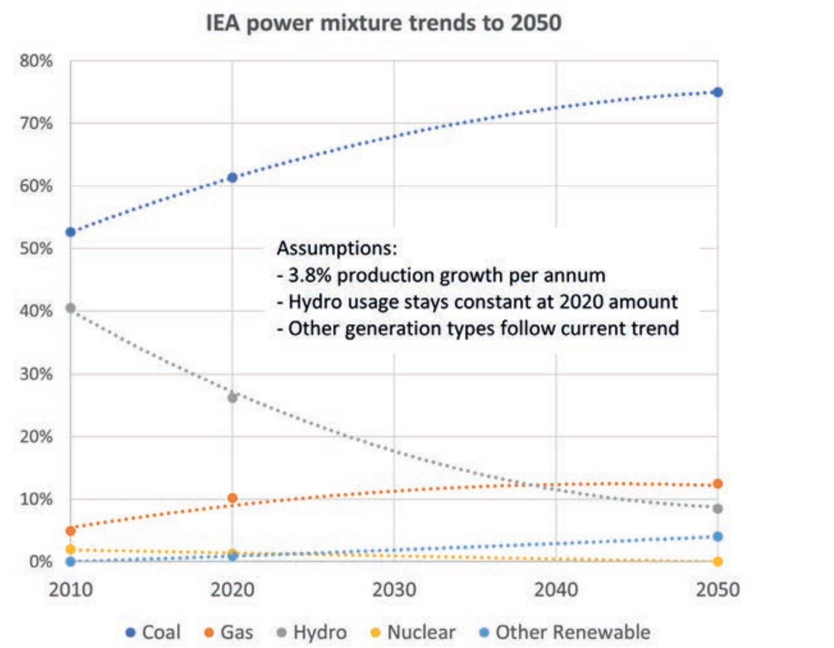

Fig 1. The current energy mix trajectory for primary aluminium shows a continued increase in coal and diminishing percentage of 'green' aluminium. Note: We assume in this projection that today's existing hydro will remain. Source: https://www.iea.org/reports/aluminium

This article concentrates on primary and secondary production (excludes alumina refining), and we have used both the CM Group post Covid-19 growth model as a high growth scenario, and the IEA/IAI projections as a low growth scenario in projecting our current trajectory models.

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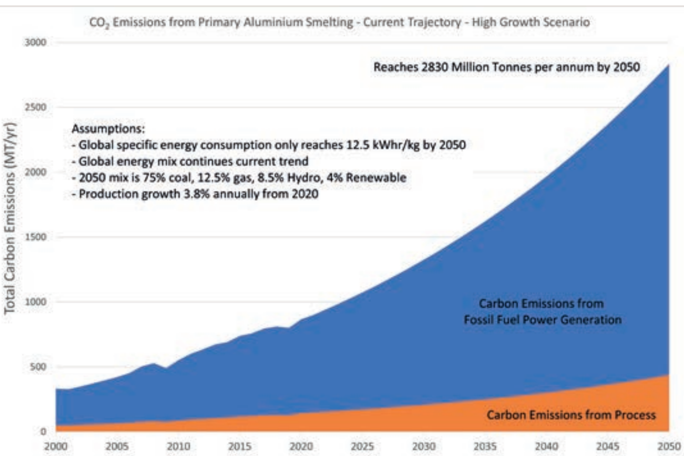

Fig 2. Modelling high growth scenario, with 52.7 billion tonnes of CO_2 emitted by primary aluminium smelting over 2020 – 2050.

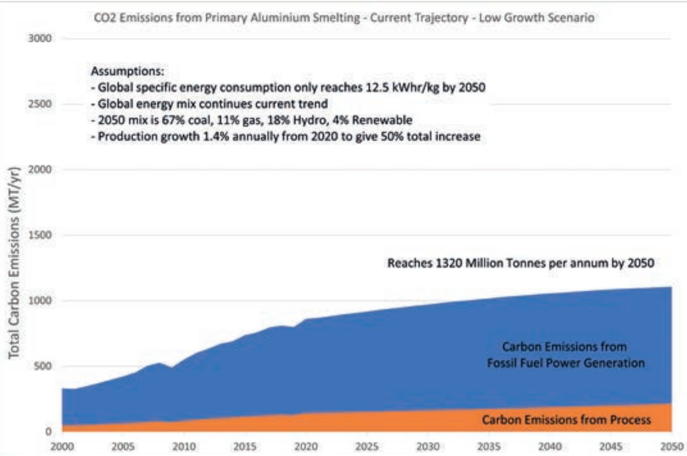

Fig 3. Modelled low growth scenario still amounting to 34.3 billion tonnes of CO_2 cumulatively from 2020-2050

Fig 2: Sources:
http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/
https://www.eia.gov/tools/faqs/faq.php?id=74&t=11
https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co$_2$- emissions-from-cars-facts-and-figures-infographics
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Primary Aluminium Production – Energy Mix Trends

Changes to the power mix used by primary aluminium smelting over the past 10 years, if extrapolated out to 2050, show a continued increase in coal and diminishing percentage of 'green' aluminium. Over the past 10 years very little 'other' renewable energy (non-hydro) has come into the mix, meaning that on current trend lines 'other' renewable energy only makes up 4% of the power mix by 2050.

Our Current Trajectory - High Growth Scenario (3.8% p.a)

Our current high-growth trajectory sees primary aluminium smelting contribute a total 52.7 billion tonnes of CO_2 into the atmosphere from 2020 – 2050.

Furthermore, on this trajectory by 2050 Al smelting will be the consumer responsible for 100% of the CO_2 from fossil fuel power generation globally, assuming the rest of the world's power systems become decarbonised as predicted by the IEA.

By 2050, CO_2 emissions reach 2830 million tonnes per annum, which is equivalent to over 90% of the CO_2 emissions from all of the passenger vehicles in the world today. This in itself would completely overshadow the decarbonisation-effect from light-weighting of transport with the use of aluminium.

We see this scenario as not only unsustainable, but also as socially unacceptable. At these levels of carbon emissions, no one in primary aluminium production will be left unaffected, as the most likely scenario is that aluminium will be replaced as a relevant material.

Our Current Trajectory - Low Growth Scenario (1.4% p.a)

The low growth scenario presents less of a mountain to climb but is still confronting. CO_2 emissions still contribute 34.3 billion tonnes cumulatively from 2020-2050, reaching 1320 million tonnes per annum by 2050. This is the equivalent of approximately 45% of all the passenger vehicles in the world today and will still be unacceptable to humanity on a global scale.

Five Options to Achieve Zero Carbon

There are only five possible options to significantly reduce carbon emissions by 2050 (four while maintaining growth). They are:

A. Continued process efficiency improvements

B. The adoption of inert (non-consumable) anodes

C. The transition to 100% renewable power

D. The use of carbon capture, utilisation and storage (CCUS) for direct process emissions

E. Decrease production to hydro powered only. (**Fig 4**)

For the purposes of this paper, we present some hypothetical models of the impact of options A to C (whilst maintaining growth) in reaching net zero carbon by 2050, and given each a star rating from 1-5, with 5 being the best. We have also provided some commentary around options D and E.

Three things should be noted here:

1. The carbon abatement potential from continued improvements to process efficiencies could be rendered redundant by the adoption of 100% renewable energy, which in the end may be a cheaper and technologically easier route to carbon abatement. Process efficiencies may still be worthwhile in terms of production cost savings and for speeding up the transition to zero carbon. For the sake of context and comparison however, we have factored in the decarbonisation effect of continued incremental process efficiency improvements.

2. The use of CCUS has also been included as it may be needed as a back-up carbon abatement method if inert anodes can't be deployed across the entire smelting fleet (see inert anode section below). Another factor for consideration is that CCUS is predicted to be in widespread use across the industrial landscape by 2050, and therefore may be a cheaper option in the long-run than the Al-specific solution of inert anodes.

3. Decreasing production (to hydro powered only i.e 27% of current production) would likely see aluminium replaced as a relevant material, as the world would 'move-on' to other more readily available and cheaper options. *

*Source: https://www.iea.org/reports/ccus-in-clean-energy-transitions

A - PROCESS EFFICIENCY IMPROVEMENTS

Reducing energy intensity of primary aluminium to a present-day vision target of 10 DC kWh/kg presents major technological challenges, and while it saves 487 million tonnes p.a. from power generation emissions by 2050. It doesn't meaningfully change the trajectory either (see **fig 5**).

To achieve a specific energy consumption of 10kWh/kg we are assuming that 50% of today's existing smelting capacity is replaced with new, and the remaining 50% is upgraded (at 50% of the cost of replacement). Taking the average price paid for new smelter builds in 2019, this would equal US$128 billion.

Reducing specific energy consumption does present a return on investment of approximately 15 years (at a 25% reduction of electricity usage at US$35 / MWh). When abatement costs are taken into consideration, (dividing the overall spend on a decarbonisation scheme by the carbon emissions savings), the conclusion could be drawn that the effort and capital required may in-fact be better deployed elsewhere.

MORE ON ENERGY INTENSITY

The Hall-Héroult smelting process (with carbon anodes) theoretically requires ~6.4 DC kWh to electrochemically produce 1 kg of aluminium metal; however actual energy used is much greater due to electrical resistances in the cell (anodes, cathodes, electrolyte, busbars), the need to heat/dissolve raw materials (alumina, carbon anodes) and heat losses to the environment that is necessary to maintain the protective, frozen ledge of electrolyte around the walls of the aluminium reduction cell.

Since 1980, energy intensity for aluminium smelters worldwide has improved considerably, falling from an average of 16 to 13.4 DC kWh/kg Al in 2019 (source: IAI). Whilst the best performing smelters today can operate at ~11.5 DC kWh/kg, there is significant variation across smelters worldwide. The 2.5 kWh/kg reduction over the past 35 years was achieved through technological advances (point feeders and automated cell control, magnetic compensation, prebaked slotted anodes, reduced external voltage drops, etc). However further reductions, e.g. from 13.4 to 10 DC kWh/kg will be a major technological challenge (e.g. via digitalisation and automation to minimise process variation, further cuts in external cell resistance, heat recovery, etc), with diminishing returns on effort / investment.

Sources: http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/
https://www.lightmetalage.com/news/industry-news/smelting/karmoy-technology-pilot-world-leader-primary-aluminum-energy-efficiency

B - INERT ANODES

Replacement of carbon anodes with a non-consumable material that does not emit carbon is hugely important towards a zero emissions pathway, however the technical challenges are undoubtedly significant.

It should also be noted that reduction in emissions from the smelting process must be seen in context of indirect emissions from power generation – if an inert anode process requires more power, the overall emissions may still be worse, based on current trends in power generation from fossil fuels (as well as reversing any process efficiency gains).

By 2050, inert anodes could save 436 million tonnes p.a. in direct process emissions if deployed across the entire smelting fleet. These emissions will be the hardest to abate from aluminium smelting and are unlikely to have any return on investment, furthermore it doesn't really change the trajectory much either (see **fig 5**).

While still an unknown, we have taken the assumption that any replacement and upgrading of smelters will be conducted at the same time, and in combination with, the cost of reduced energy consumption, which is US$128 billion, (i.e. you wouldn't rebuild the same smelting capacity twice).

Current development of inert anodes is being undertaken by smelting companies with captive hydro-electric power generation. It is important that to be useful across the industry inert anode development should be undertaken with flexible energy use in mind as a 'hydro only' technology will have little effect on the overall carbon abatement of the industry (40 million tonnes pa by 2050). If inert anodes cannot be deployed across the entire smelting fleet, then CCUS will become necessary.

MORE ON INERT ANODES

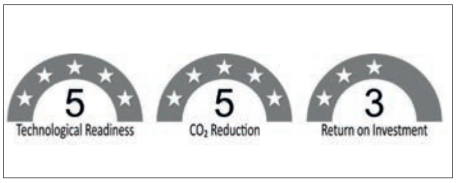
The Hall-Heroult aluminium smelting process, since 1886, has always relied on consumption of carbon at the anode to reduce the raw material alumina (Al_2O_3) to aluminium metal, with a by-product of CO_2 gas emitted at a rate of roughly 1.5kg per kg of metal.

Inert anodes have been a 'holy grail' of aluminium smelting since the process was first invented, and long assumed impossible, however recent technical developments have appeared to be very promising. Alcoa and Rio Tinto are now promoting inert anodes to be imminently ready for deployment, as early as 2024, via their 'Elysis' technology. The technical details and smelter operational effects of these anodes are still a closely kept secret, and the impact on other factors such as the energy efficiency especially are yet unknown to the wider smelting community.

It can be expected from some theoretical knowledge however that the energy intensity is likely to be higher rather than lower using inert anodes, if existing potlines are only retrofitted without complete redesign (e.g. with vertical anodes and cathodes). While this is opposite to the required trends in emission levels, removal of the direct carbon from the actual smelting process is a significant advantage, and assuming the power supply transitions to fully renewable energy by 2050, the lost energy efficiency is not a factor regarding emissions. One question still to be answered is how smelters with inert anodes will react when the power supply is modulated – whether if they will perform as traditional smelters do, or whether the modulation window is increased or reduced. The overall technological level of difficulty is therefore high, reliant on proprietary technology, and the details still unknown to most.

C - 100% RENEWABLE ELECTRICITY GENERATION

The adoption of 100% renewable electricity generation is the only way aluminium will remain a relevant material throughout this century. Variable Renewable Energy (VRE, primarily solar and wind) is the lowest cost option of new electricity generation globally, with the cost of building new VRE now cheaper than operating existing coal-fired generators.



The cost of replacing all of today's coal-fired electricity used by Al smelters using the lowest cost 2019 figures would be US$142 billion. This is assuming replacing 70GW of coal with 230GW installed VRE capacity at a 30% load factor, at an installed cost of US$618 per kW. The operational savings over coal-fired generation would amount to between US$5-9 billion p.a. giving an ROI period of 16-28 years.

By 2050 this would amount to CO_2 savings of 1900 million tonnes p.a., over twice the combined CO_2 savings from both inert anodes and a 25% reduction in specific energy consumption from energy efficiencies.

Sources: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf
https://www.sciencedirect.com/science/article/pii/S0140988316303528
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C1 - SELF-FIRMING VRE WITH MODULATION

The elephant in the room when discussing VRE and aluminium smelting is the cost of firming VRE. The cost of electricity in a decarbonised power system will be dictated by the cost of firming. Already markets with increasing percentages of electricity generated from variable renewable sources have shown increased price volatility with an increasing number of high-priced events per annum. Furthermore, as the percentage of variable renewables in the power system increases it is expected that there will also be increased times of low-priced events. Flexibility of energy use will be the key going forward.

All aluminium smelters have the latent potential to become large-scale Virtual Power Plants (VPPs) for the power system. They are, with the installation of modulation technology, inherently capable of self-firming up to 40% of their electricity usage. That is, they can swing or flex their load (electricity usage) by 40%.

MORE ON FIRMING

Firming is how you can purchase (or trade) electricity to ensure constant supply, and includes:

- Short duration storage (batteries et al)
- Long-term storage (pump hydro et al)
- Demand side response (energy modulation et al)
- Over-generation (installed capacity greater than peak use)
- Peaking plants
- All of the above.

The first 20% of smelter self-firming is relatively straight forward with cost-effective retrofitting of modulation technology for instantaneous downwards modulation of 20% below nominal set-point operations. For full modulation of 40%, a further 20% is gained through upwards modulation above nominal set-point operations, which most likely requires additional upgrades to smelter infrastructure to deliver more amperage to potlines.

The bonus is that much of this upwards modulation will be from low priced over-generation in the power system.

The installed cost of EnPot Modulation Technology is estimated to be US$13 billion, plus allowing for smelter infrastructure upgrades to allow upwards modulation at US$17 billion, for a total of US$30 billion for 764 million tonnes CO_2 annual savings by 2050. Return on investment with a 20% reduction of electricity cost at US$35/MWh is 4.5 years. A further bonus is that modulation technology is eminently suitable to older smelters giving them a useful end-of-life kicker.

For ease of comparison here we have assumed all smelting capacity would become flexible including captive hydro, which may have modulation needs due to climate change and power supply unpredictability in the future.

C2 – FIRMING THE LAST 60% OF VRE

Abating the last 1,000 million tonnes is more difficult, as aluminium smelting requires at least 60% constant power supply. It is likely that to move this 60% constant power to VRE sources will require collaboration with other users in the electricity grid, new purchasing arrangements, and technological innovation in the power system to bridge the gap in supply and demand. This is likely to include:

- More consistent renewable generation being developed (geothermal, tidal, wave, biomass et al)
- New not-yet-seen energy storage options developed
- Increased participation in demand side response services by all users in the power system.

It should also be noted that the current doubling effect of the capacity of VRE (especially from solar) should mean the world will be able to generate many times over its energy requirements by 2050.

Electrification of transport and other industry will also see a power system many times greater than the one we have today. Aluminium smelters may not be the largest users in the grid by 2050.

THE USE OF GAS AND CCUS TO FIRM RENEWABLES

While CCUS could be used to capture carbon emissions from coal-fired power generation, we have formed the view that this would be adding and extra layer of expense to an already expensive power generation option.

Gas with CCUS could however be an option for peaking plants, if it's still socially acceptable to burn fossil fuels by 2050.

Summary for Primary Aluminium

The current trajectory of primary aluminium production will be socially unacceptable going forward. We must as an industry start on the pathway to zero carbon. The most effective method of carbon abatement is to start with increased use of renewable energy enabled by energy modulation. Energy modulation technology is technologically ready for deployment, has a high carbon abatement and a high ROI.

Inert anode uptake across the entire smelting fleet is also required, and if this proves to be too technologically challenging, then CCUS will be required to achieve full decarbonisation of direct process emissions.

Continued energy efficiency may be able to play an important transitional role as we move towards 100% renewable power generation, however long-term the cost of abatement may fall in favour of increased renewable generation capacity, rather than continued energy efficiency gains.

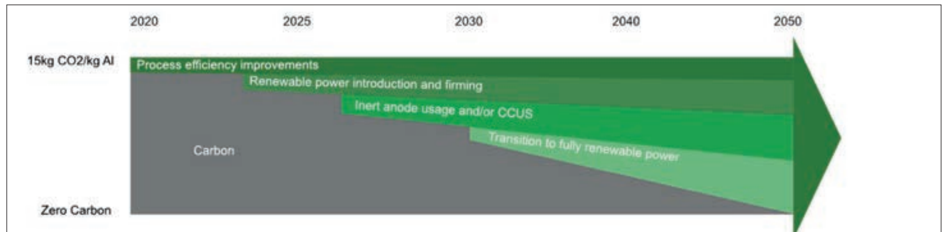

Fig 4. Of the five options presented, only four can maintaining production growth while significantly reducing carbon

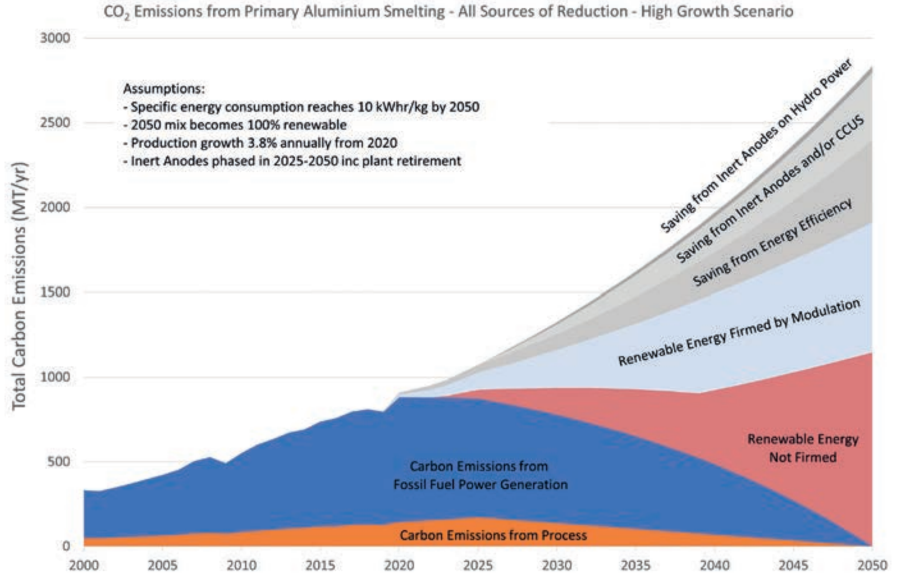

Fig 5. Failure to meaningfully undertake emissions reductions today exponentially increases the burden (and steepness of change required) in future years if we are to still meet the same 2050 goals and increases the risk of aluminium being replaced as a relevant material

A FINAL COMMENT ON SECONDARY PRODUCTION (ALUMINIUM RECYCLING)

Recycled aluminium has the potential to be one of the most environmentally friendly materials on the planet. Pathway to zero carbon emissions for aluminium recycling relies on three things:

1. Increased collection

2. Sourcing electricity from renewable sources to eliminate Scope 2 emissions

3. Conversion to green hydrogen to reduce combustion carbon emissions effectively to zero.

Compared to primary aluminium production, recycling faces no step-changes to the process to reach zero emissions, rather just a conversion of process-fuel sources to renewables, and the contracting of renewable power supply. Increased collection also reduces the need for primary aluminium, although with long-life span products new production will always be necessary.

Renewable energy generation is becoming increasingly available to purchase in most regions, via Power Purchase Agreements (PPAs), although increased 'freedom-of-renewables' is still required in some markets as tightly controlled state ownership of the power generation and/or transmission systems still restricts and controls the introduction of new renewable generation.

Investment in hydrogen R&D is starting to ramp up to the level required to deliver material advancements to hydrogen's industrial process heat potential. A bonus for aluminium recycling is that its use of hydrogen will not be 'bespoke' rather it should be able to ultilise hydrogen technology currently being developed across other sectors. Both the process of recycling of aluminium, and the onsite production of hydrogen, are ideally suited to flexible electricity arrangements.

Cost

Cost of implementation will be low to moderate as upgrades can be scheduled at end-of-life of component parts and included in any new builds.

ROI

The most likely scenario for ROI is that the conversion to zero carbon yields no useful efficiency gains or return on investment. This will be problematic for the industry as without financial incentives (or steep carbon pricing) there will be little reason to change. For governments looking to set incentives or regulate to force change, aluminium recycling would be low on any priority list as it is not a large emitter in the first place.

Therefore, even though aluminium recycling would be the easiest part of aluminium production to become zero carbon, we see it only moving slowly over time towards that goal unless driven by carbon pricing.

MORE ABOUT HYDROGEN

Green hydrogen is produced by using variable renewable energy (VRE) to power an electrolyser that splits H_2O into its component elements. The hydrogen is captured, while the oxygen is released into the atmosphere. The captured hydrogen can be stored at both low and high pressures and can be combusted directly for process heat, thus replacing the direct combustion of fossil fuels.

In certain situations, hydrogen might even be able to be used as a direct replacement for natural gas with re-engineering rather than complete replacement costs. Alternatively, existing plant can be replaced with hydrogen compatible equipment at scheduled end-of-life replacement.

While hydrogen's widespread industrial use is still ahead of us and there are obstacles to overcome, the learning-rate of development should see industrial hydrogen use start to become common place by the latter half of this decade. Obstacles include; the improvement of round-trip efficiency and cost in comparison to fossil fuels, workplace health and safety, and re-engineering. Hydrogen electrolysers have the advantage of being both modular and having a reasonably small footprint. In many cases hydrogen will be able to be manufactured onsite.

Contact:

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