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The Shift to Hydrogen (S2H2): Elemental Change

WHAT NEEDS TO BE DECARBONISED? AND WHAT ROLE CAN HYDROGEN PLAY?

Welcome

Welcome to the second article in **The Shift to Hydrogen (S2H2): Elemental Change** series – **What needs to be decarbonised? And what role can hydrogen play?**

In December 2020, the Ashurst Global Towards Zero Emissions team published the first article in **The Shift to Hydrogen (S2H2): Elemental Change** series – **Why H2? Why now?**

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Given the subject matter of this article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series, to give the subject matter appropriate depth, it is to be published in two parts:

- This **Part 1** frames, and answers, the question "How may H2 be used to decarbonise activities?" and outlines the net-benefit of the use of hydrogen to reduce GHG emissions and as such the impact on the global carbon budget. In framing How H2 may be used? we use the Ashurst Hydrogen Rainbow graphic to describe sources, and means of hydrogen (**H2**), production;
- **Part 2** of this article considers Roadmaps, Plans and Strategies and the policy settings developed by, or emerging, in countries for the purposes of decarbonising sectors and industries, including the use of H2. This is done in the broader context of progress towards zero emissions: effectively, **Part 2** is a roadmap to Hydrogen Road Maps, Plans and Strategies.

As will be apparent, while the Agriculture, Forestry and Land Use and the Waste sectors may provide feedstock for H2 production, the means of decarbonising them is different, and more nuanced, than other sectors[1]. The Ashurst Global Towards Zero Emissions team will publish standalone articles and features that explain how to reduce GHG emissions in these sectors (and achieving net-zero GHG emissions targets), including in Q3 2021 an article on the emerging realisation of the need for ***"Adaption to Climate Change and Negative GHG Emission Initiatives"***[2].

Part 2 of this article will dovetail with the third article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series entitled ***The key legal issues arising on each aspect of the H2 industry (including projects and transactions)***. The fourth article in the series titled – ***CCS and CCUS***[3]***, and DAC***[4] ***Why? How? And what are the uses for GHGs captured for use?*** – will consider the need for, and the role of, CCS / CCUS. Having published these articles by the end of Q3 2021, further articles will be published (likely quarterly), each responding to emerging themes and areas of interest.

The Ashurst Global Towards Zero Emissions team publishes the Low Carbon Pulse on a two week cycle (Low Carbon Pulse: Edition 1, Edition 2, Edition 3, Edition 4, Edition 5, Edition 6, Edition 7, Edition 8, Edition 9, Edition 10, Edition 11, Edition 12). In addition to longer articles and the Low Carbon Pulse, Ashurst are publishing ***Hydrogen For Industry*** (H24I) features, providing a deeper sector and industry perspective. During April 2021 the first H24I will be published, entitled **Hydrogen from Waste**. Every other month thereafter a H24I feature will be published, including Hydrogen and the Automotive Industry, Difficult to Decarbonise Industries (Cement, Chemical and Steel), Energy Mix During Energy Transition, Energy Transition and the Building and Construction sector, Hydrogen and Freight Haulage (Road, Rail and Shipping) and Hydrogen in the Public Transport sector.

OVERVIEW OF THIS PART 1:

This **Part 1** provides:

- a description of the key themes that are emerging generally in the context of policy settings, in particular in the context of the use of renewable electrical energy and the use of hydrogen as the means to achieving net-zero GHG emissions by 2050, and the areas in which policy settings need to develop; (**Section 1 – On The Road to Net-Zero**);
- a description of the mass of GHG emissions arising globally, and specifically from the Building sector, Industrial sector (in particular the Difficult to Decarbonise industries), and Transport sector. In doing so, the "size of the decarbonisation prize" is described[5] (**Section 2 – The "Size of the Decarbonisation Prize"**); and
- an overview of how H2 can be used to decarbonise the Building sector, the Difficult to Decarbonise industries and the Transport sector (**Section 3 – Realising the Decarbonisation Prize - Decarbonisation of Energy Use**).

1. There are "low-hanging fruit" policy pickings to be had in each of the Agriculture, Forestry and Land Use and the Waste sectors, but they are beyond the scope of this article. They will be covered in a later Ashurst publications, including on "Adaption to Climate Change and Negative GHG Emission Initiatives", distinct from (carbon credit and emissions trading mechanisms). Suffice it to say that policy settings are required to change land use and waste landfilling and processing to remove GHG permanently from the atmosphere.
2. This article will focus on the sectors that are able plausibly and cost efficiently to provide the means to achieve Negative GHG Emissions, being Agriculture, Forestry and Land Use and Waste sectors.
3. The term **CCS** connotes carbon-dioxide capture and storage. The term **CCUS** connotes carbon-dioxide capture storage or use, or both, and is a term coined by the International Energy Agency (IEA). CCUS is becoming the more often used of the two terms.
4. The term **DAC** connotes direct air capture of CO_2 from the atmosphere for CCS or CCUS, rather than being captured as part of an industrial or manufacturing process or on electrical energy / power generation. In each case, being the point at which GHG emissions arise on oxidation. DAC is electrical energy intensive, and involves the use of solid sorbent material filters that capture CO_2 by chemical bonding to the CO_2 captured.
5. In this context, the importance of renewable energy sources will be apparent, both to generate electrical energy for use as electricity at the point of ultimate use and, for use as electrical energy, to derive / produce Blue Hydrogen (while renewable electrical energy is not a requirement to be blue hydrogen, it will make the hydrogen light blue) and Green Hydrogen as an energy carrier, that is then oxidised at the ultimate point of use to derive energy without giving rise to GHG emissions.

What you need to know

- **Renewable Electrical Energy is core to decarbonisation of global energy use, and the need for increased renewable energy is huge;**
- **The "size of the decarbonisation prize" for decarbonising the Building sector, Difficult to Decarbonise Industries and Transport sector is up to a 45% reduction in current global GHG emissions; and**
- **The global carbon budget is not static, but there is next to no room for the global carbon budget to expand materialy.**

Section 1 – On The Road to Net-Zero

1.1 RENEWABLE ELECTRICAL ENERGY IS, AND WILL REMAIN, AN EVER PRESENT:

In respect of Difficult to Decarbonise industries, a common theme arises: the need to displace fossil fuels and other carbon intensive fuel sources (that give rise to CO2 and other GHGs on use (oxidation)) with electrical energy and energy carriers produced from renewable sources. This displacement is achievable using current technology, the issue is the cost of doing so, and the time taken to do so[6], including the time taken for innovation to reduce the unit costs of the production of Blue and Green Hydrogen.

In considering the Roadmaps, Plans and Strategies for the purposes of **Part 2** of this article, renewable energy does not feature overly because the Roadmaps, Plan and Strategies focus on hydrogen. In some Roadmaps, Plans and Strategies the need for renewable electrical energy in each Roadmap, Plan and Strategy is simply assumed[7]. In this regard, it is noted that the cost of electrical renewable energy continues to fall, setting record low-levels around the world as the benefits of lower costs of equipment and scale (and structured low financing costs, often in the context of government credit risk support) result in the lowest electrical energy costs in history (see Editions 6 and 8 the Low Carbon Pulse). This is particularly the case in respect of renewable electrical energy from solar sources.

It is important to recognise that the continued, and ever increasing, development of renewable electrical energy is at the core of progress towards net-zero GHG emissions, and the development of the clean hydrogen industry.

The low cost (and the anticipated lower costs) of renewable electrical energy is, and will continue to be, the most important enabler of progress towards net-zero emissions, whether to generate electrical energy or to produce hydrogen (as an energy carrier). It is important that while renewable electrical energy is not required to produce Blue Hydrogen, if renewable energy is not used for production, and non-renewable energy is, GHG emissions will increase.

For net-zero GHG emissions to be achieved, it is key that the use of renewable electrical energy is maximised in new electrification development, and that more carbon intensive electrical energy is displaced over time.

6. For the purposes of this **Part 1**, electrical energy, in particular renewable energy is not a focus, because the means to the abatement of GHGs in the electrical energy sector is well-established and known, there is only one issue, the speed of transition, which is a function of the grandparenting of electrical energy generation using fossil fuel, and a moratorium on new fossil fuel generation capacity (other than to effect transition), and for new demand for electrical energy to be sourced from renewable sources. This will not happen consistently because countries still developing need to achieve electrification by the lowest cost route.

7. The assumption is not new, it is well-established: see Hydrogen: A Renewable Energy Perspective, IRENA (International Renewable Energy Agency) Report, dated September 2019 prepared for the second Hydrogen Energy Ministerial Meetings in Tokyo, Japan.

8. This is the case in all countries, not only countries that are continuing to develop. Currently, the US has around 1,100 GW of installed electrical energy generation capacity, the majority of which uses fossil fuel. By 2050, the US is projected to have at least 3,200 GW of installed electrical energy generation capacity (assuming the needed switch to higher levels of electrification). To achieve net-zero GHG emissions by 2050, in the US coal-fired electrical energy generation needs to be phased out by the middle of this decade or the end of the decade at the latest, and the proportion of natural gas fired generation needs to be reduced by two-thirds (at least) by 2050 in the US. This need not result in higher costs of electrical energy. As has been demonstrated in Australia in recent times, the use of renewable electrical energy can result in low or lower electrical energy prices, not higher prices.

9. "Hydrogen Insights 2021: A Perspective on Hydrogen Investment, Deployment and Cost Competitiveness".

1.2 TIMING OF THE SHIFT TO HYDROGEN (THE S2H2):

Section 1.3 of the first article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series – ***Why H2? Why now?*** quoted Jochen Eickholt, executive board member of Siemens Energy AG as stating that:

"It won't take decades for the hydrogen industry to develop, like it took LNG, but it won't happen overnight".

In early February 2021, in a report entitled "2050: The Hydrogen Possibility", Wood Mackenzie temporalizes the momentum around Green Hydrogen: since Q4 of 2019 the pipeline of Green Hydrogen projects has grown to 26 GW of installed electrolysers. This is consistent with the Roadmaps, Plans and Strategies considered in **Part 2** of this article. In mid-February 2021 the Hydrogen Council and McKinsey & Company released a report that provides a summary of current momentum and deployment.

The momentum in the development of electrolyser capacity seems to be matched by the speed at which some electrolyser technology providers are anticipating that the unit cost of producing 1 kg of hydrogen using electrolyser technology will fall. For example, NEL SA (NEL) considers that USD 1.50 is achievable by 2025, and NEL's confidence in achieving this price point appears to be firming. Others are suggesting USD 1.20, and lower, by 2022/2023.

If even the highest of these price points is achieved (or, depending on policy settings, an even higher pricing point) by the middle of the current decade, it is reasonable to assume that the demand side for Green Hydrogen as an energy carrier will increase, because there will be acceptance of the benefit of the shift to use of Green Hydrogen as an energy carrier, and as a means of progressing to net-zero GHG emissions. The issue then will be how much Green Hydrogen can be produced at this price point: a function of procurement and installation of renewable electrical energy and electrolysers. This will then inform the mass of Green Hydrogen that needs to be produced for supply to match demand. In addtion to Green Hydrogen, Blue Hydrogen is likely to be key, and the cost of CCS / CCUS needs to fall, to reduce the unit cost of production of Blue Hydrogen.

While not certain, it is looking more likely that during the current decade the hydrogen industry will develop in-line with current policy settings (and that Roadmaps, Plans and Strategies). If NEL is right, it is reasonable to assume that the pace of development will outstrip policy settings (and the Roadmaps, etc). The supply side price is half-the-story with users of energy on demand side needing to be convinced as to the mass of supply as well as to price, and the stability of both.

1.3 THE ROLE OF H2 AND NH3 IN ELECTRICAL ENERGY GENERATION:

While hydrogen (H2) and ammonia (NH3) may be used as an energy carrier to provide fuel for electrical energy generation, there is an issue as to whether, longer term, they will be used for this purpose. In the context of use, it seems more likely in the longer term that H2 (as an energy carrier) will be used as an energy storage medium and to blend with natural gas for heating, and in the near to medium term that NH3 will be used as an additive / blending media for coal-fired electrical energy generation and as a means of "carrying" H2. Because of current thinking around efficiency issues, it may be that green ammonia will have a greater role to play as a primary fuel for electricity generation[10], than H2.

If H2 is to have a role in primary electrical energy generation it may be transitional or niche, with the focus expected to be use for energy storage as part of grid integrity and stabilisation strategies (noting however that it seems increasingly likely that battery energy storage systems (**BESS**) will fulfil this function).

In recent demand studies for H2 in Japan, at least until 2030, the two principal uses of H2 were identified as hydrogen-to-power and chemical and petrochemical, with the hydrogen to be delivered using pipelines to the point of use in both instances.

Front-and-centre in the thinking of policy makers (and development banks) are the efficiency issues that arise in using H2 as a primary fuel for electricity generation as a direct replacement for fossil fuels (or other carbon intensive fuels), rather than the use of renewable electrical energy.

At the moment policy makers (and development banks) and some participants in energy markets with higher levels of installed renewable electrical energy consider that the use of renewable electrical energy (in particular from solar and wind sources) as a more appropriate source of renewable electrical energy than the use of H2 (or NH3). **Narrative Box 1** outlines the efficiency issues that arise from the use of Green Hydrogen as a primary fuel for the generation of electrical energy.

There is, however, no hard and fast rule. Because H2 may be regarded as part of a transition with, and in due course from, natural gas (in particular in North and South Asia), rather than as an alternative to renewable electrical energy, the use of pipelines to haul H2 as a gas gives rise to a lesser efficiency issue than if electrical energy is derived from the oxidation of Green Hydrogen, and the electrons generated dispatched over a grid.

Narrative Box 1: The Efficiency Issues arising in respect of the use of Green Hydrogen as an energy carrier for power generation

Given the current efficiency of electrolysers, the production of 1 kg of Green Hydrogen (containing 33.3 kWh) requires around 50 to 55 kWh of renewable electrical energy (sometimes more). Unless Green Hydrogen is stored in its gaseous state for use close to the point of production (in some parts of the world unlikely, but in others possible), further renewable electrical energy is required to cool and to compress or to liquefy, and to store, that Green Hydrogen (conservatively another 5 kWh of renewable electrical energy per kg of Green Hydrogen). The transportation of that Green Hydrogen will give rise to further energy use to the point of delivery and possible further use on storage and transportation to the point of use (oxidation). If the point of use is a power station, energy will be lost as parasitic load at the power station, and across the grid as line loss to the point of delivery of electricity. It should be noted that current perception on the efficiency issue may change as the efficiency of electrolysers increases.

Given the current efficiency and energy loss issues, those framing policy settings and those implementing them (and providing development funding), certainly in countries with higher levels of installed renewable electrical energy, are likely to question the use of Green Hydrogen as an energy carrier for use as a fuel to generate electrical energy.

As a result, it remains unclear whether liquified H2 gas (**LHG**) will displace liquified natural gas (**LNG**) on the basis of being a straight substitute, in particular in the context of a fuel for electrical energy generation. There are competing views. The perspective of many commentators is that LHG will not be a straight substitute for LNG for power generation over the long term, rather renewable electrical energy (using solar and wind, and possibly hydro-electric and nuclear) will substitute electrical energy currently using natural gas derived from LNG. NH3 may be used as an energy carrier to blend with other energy carriers (for example, with coal, in the near to medium term) and may have a longer term role as a means of storing energy from the point of production to the point the H2 is extracted from it (see ***The Shift to Hydrogen (S2H2): Elemental Change*** series – ***Why H2? Why now?***).

For the Ashurst Global Towards Net-Zero Emissions team, decarbonisation of energy use towards net-zero is more nuanced than this: this as a jurisdiction by jurisdiction, region by region issue, with natural gas/LNG, renewable energy and e-fuels / future fuels (including hydrogen) each having a role to play.

1.4 A CLEAR SENSE OF WHAT NEEDS TO BE DONE:

It is apparent that while there is a good sense of what needs to be done to achieve GHG reduction targets, and to fulfil some of the more aspirational GHG reduction aims, the timeframes for real progress are likely to be medium to longer term. While a start has been made on reduction of GHG emissions, it may be anticipated that the pace of change will likely, and indeed needs to, increase.

As it becomes clear, with increasing clarity, that the rate of progress towards decarbonisation and as such net-zero GHG emissions (and broader aims for carbon neutrality and economic, environmental and social sustainability) needs to increase, policy settings will change-including so as to achieve alignment and cooperation across countries[11]. The recent UN Initial NDC Synthesis Report indicated this in relation to Nationally Determined Contributions (**NDCs**).

As indicated in other publications, whether or not a country will progress towards net-zero is a function of both its NDC, and what it is actually doing, with the rate of progress of some countries exceeding the nominal achievement of an NDC, and vice versa. This can be expected to be a focus of in the lead up to, and at, COP 26 in Glasgow, Scotland, in November 2021.

Part 2 of this article outlines timeframes to which countries are working on H2 initiatives, as expressed in Roadmaps, Plans and Strategies (in each case in the context of in their net-zero GHG emission commitments). A theme emerges: countries (in particular developed countries) need to increase the rate of reduction in GHG emissions by 2030. This is already being acted upon in some countries, but all developed countries need to do more.

1.5 A CLEAR SENSE THAT WE ARE WORKING TO A GLOBAL CARBON BUDGET:

In framing thinking, it is helpful to understand that increasing population and urbanisation, and economic development, increases resource use, and energy use. For example in the recent Shell / Deloitte report – Decarbonising Road Freight: Getting Into Gear (see Edition 8 of Low Carbon Pulse), it was noted that globally, road freight transportation is expected to double by 2050, with a projected concomitant increase in GHG emissions as a result. GHG will continue to increase until peak GHG emissions are reduced.

As with other sectors and industries, the global carbon budget makes no allowance for this increase in GHG emissions. Policy settings are best introduced now to ensure that the required abatement of GHGs takes into account expected sectoral and industry growth, in that the growth does not increase GHG emissions. In context, the world has yet to reach peak oil production, let alone peak GHG emissions.

If the Stabilisation Goal and the Stretch Goals[12] in the Paris Agreement are to be achieved, the majority of commentators suggest that activities that can be decarbonised now, need to be: this includes newly installed electrical energy sourced from renewable sources (and nuclear sources) and the acceleration of the decarbonisation of the road freight haulage industry and Difficult to Decarbonise industries. These industries are going to continue to grow well-beyond 2050, as will GHG emissions if these industries are not decarbonised.

It is apparent that this is a theme that policy makers have yet to grapple with effectively on a consistent basis, as part of coherent and complete set of policy settings. This is an area that needs to be grasped more firmly by policy makers than has been the case to date, and, in due course, those implementing policy settings.

This theme will be expanded upon in **Part 2** of this article and the third article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series entitled ***The key legal issues arising on each aspect of the H2 industry (including projects and transactions)*** to be published during Q3 of 2021[13].

10. It is important to note that NH3 is not GHG free at the point of use, on oxidation NOx arise.

11. For example The European Union countries are, Australia and Germany, Canada and Germany, Portugal and The Netherlands are working cooperatively. More broadly, coordination is required to allow the development of world renewable resources sufficient to allow the supply of hydrogen to countries that will consume it. This includes aligned policies and positions across: 1. industries and sectors, 2. supply and demand, 3. international standards (including to certify the colour of H2, feedstock and electrical energy source); and 4. integration of energy systems across borders. Many aspects of which will be covered in the third article – in ***The Shift to Hydrogen (S2H2): Elemental Change*** series ***The key legal issues arising on each aspect of the H2 industry (including projects and transactions)***.

12. Article 2.1(a): "Holding the increase in the global average temperature to well below 2OC [Stabilization Goal] above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5OC [Stretch Goal] above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change …".

13. **Part 2** of this article and the third article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series will explore existing, and describe the required, policy settings and regulation, including the need to provide certainty, and yet allow for change, and to safeguard competition by avoiding barriers to entry for new entrants, and safe-havens for incumbents, while at the same time providing a regulatory environment in which the supply side and the demand side is able to develop in an efficient way. In addition to policy settings, there are roles for governments, including in CCS / CCUS development, as an intermediate buyer (and wholesale seller) of H2 and NH3 and possibly as the owner, but not the operator, of HRS/HRI in respect of which concessions are granted.

1.6 ORIGIN OF NET-ZERO GHG EMISSIONS:

The Paris Agreement[14] is known best for Article 2.1, being the Article that sets out the Stabilisation Goal and the Stretch Goal. Among other things, Article 2.1 also contemplates adaption to climate change.

Article 4[15] is known less well, but it is from Article 4 that the concept of net-zero GHG emissions by 2050 emerges. Article 4 contemplates achieving peak GHG emissions as soon as possible, and, having achieved peak GHG emissions, achieving the reduction of GHG emissions rapidly to a point of balance (i.e., net-zero), and the removal of GHGs during the second half of the 21st century. The concept of negative GHG emissions (**Negative GHG Emmissions** or **NGHGE**) is a concept that arises from the aim to remove GHG during the second half of the century.

Narrative Box 2 provides a guide to the various terms used in the context of net-zero and carbon neutrality.

In order to achieve net-zero emissions by 2050, and to balance the global carbon budget along the way, it is likely that it will be necessary to develop and to deploy Negative GHG Emission Initiatives (**NGEI**) before 2050 (in fact, well before 2050).

While achieving net-zero GHG emissions will continue to be the key focus, it is likely that policy makers will turn increasingly to NGEI, including as part of adaption to climate change and the context of GHG arising from Agriculture, Forestry and Land Use. In the context of increasing focus on NGEI, it is likely that policy makers will consider the use of carbon-offset mechanisms by countries and corporations to achieve their net-zero GHG emission commitments. In this context, the contrast of actual reductions in GHG emissions (and as such certain and sustainable) versus virtual reductions in GHG emissions (as such, some may say, not certain, and possibly not sustainable) to achieve net-zero outcomes is likely to receive particular attention[16]. Institutional investors are already looking closely.

It is becoming increasingly apparent that actual reductions in GHG emissions are needed to achieve net-zero GHG emission commitments and that NGEI are, or will be, needed, to ensure that in addition to actual reductions in GHG emissions GHGs will have to be removed from the atmosphere.

This is not to say that carbon-credits do not have a role, including to accustom users of certain fossil fuels, and other carbon intensive fuels, to pay premiums for not progressing to actual net-zero outcomes: for example, on a cargo-by-cargo basis carbon-credits may be used to provide the seller and the buyer of the LNG with a net-zero GHG emission outcome. Also there is an argument, in certain sectors and industries, for off-sets to be used and paid for across that sector or industry as part of energy transition.

But, over time, it may be expected that the projects from which carbon-offsets arise may be used to achieve NGEI outcomes, being outcomes that actually remove GHG emissions from the atmosphere, rather than allowing activities that give rise to GHG emissions to continue resulting in the release GHG emissions to the atmosphere. There is a distinct difference between the (motivations underpinning the) two, notwithstanding that the means of decarbonisation is identical.

Further, and this is likely to be challenging in due course, in order to reduce GHGs emissions arising from the Agriculture, Forestry and Land use sector it may be necessary to repurpose or to reshape policy settings giving rise to carbon credits.

14. On November 4, 2016 the Paris Agreement entered into force. The Paris Agreement is an agreement between the Parties to the United Nations Framework Convention on Climate Change (**UNFCCC**).

15. Article 4 provides that: "To achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties and to undertake rapid reductions thereafter in accordance with the best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."

16. One approach reflects a change in which activities are undertaken so that GHG emissions cease, the other reflects the continuation of activities that result in GHG emissions that are off-set by initiatives that result in the removal of an equivalent mass of GHG emissions from the atmosphere to those GHGs arising from the continuation of these activities.

Narrative Box 2: Framing, Testing and Understanding any commitment to zero, net or otherwise

In considering any commitment to net-zero or carbon neutrality from any country (or corporation) it is helpful to frame and to test that commitment, so as to understand it, as follows:

Net-zero GHG emissions: achieving a balance between GHG emissions produced and GHG removed from the atmosphere: consistent with the Paris Agreement.

Gross-zero GHG emissions: the cessation of the production of GHG emissions (zero means zero): not consistent with basis of current human activities, on the basis that it is not practicable, some may say possible, to cease release of all GHG emissions.

Net-zero CO_2 emissions: achieving a balance of CO_2 emissions produced and CO_2 removed from the atmosphere: not consistent with the Paris Agreement, because not all GHGs are included.

Net-zero CO_2-e emissions: achieving a balance of CO_2 equivalent emissions (hence CO_2-e) produced and CO_2 equivalent emissions removed from the atmosphere: consistent with the Paris Agreement.

Carbon neutral commitment: achieving a balance between CO and CO_2 emissions produced, and removed from the atmosphere: not consistent with the Paris Agreement, because not all GHGs are included.

In addition, phrases such as **zero carbon emissions, carbon neutral** and **net zero** are commonly used. More often than not it is not clear whether they are intended to refer to all GHGs, rather than being limited to carbon (CO and CO_2).

Net Negative and **Negative GHG Emissions** are used to refer to the production of a lesser mass of GHG emissions than the mass of GHG emissions removed from the atmosphere (whether by a country or a corporation).

Carbon Negative is used to refer to the removal of a greater mass of GHG emissions from that atmosphere than the mass of GHG emissions that are being, in real time, or have been, historically, emitted.

1.7 ADAPTION AND NGHI:

While achieving net-zero GHG emissions (as the means of achieving the Stabilisation Goal as a minimum and to pursue efforts to achieve the Stretch Goal) and setting and achieving appropriately calibrated NDCs has been the key focus of climate change policy settings, it is helpful to remember that the Paris Agreement had two other objectives:

- increasing the ability to adapt to the adverse impacts of climate change and to foster climate resilience and low greenhouse gas emission development, in a manner that does not does not threaten food production; and
- making finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient development.

While neither of these objectives has been ignored, it is likely that there will be increased focus on them of them, including in the context of NGHI.

In Q3 of 2021, the Ashurst Global Progress Towards Zero Emissions team will outline how these objectives are being achieved in an article on the emerging realisation of the need for ***Adaptation to Climate Change and Negative GHG Emissions Initiatives***.

Among other things, the article will consider carbon-offset regimes (and, as a point of policy setting contrast, off-set regimes with carbon tax and carbon-trading schemes / emissions trading schemes and their role within them).

1.8 WORLD ROADMAP AND PATHWAY TO NET ZERO ARE ON THE WAY:

No doubt with some or all of these dynamics in mind, the International Energy Agency (**IEA**) is developing The World's Roadmap to Net Zero by 2050. This World Roadmap is intended to provide all participants (private sector and government / public sector) with a description of what is required to achieve the Stretch Goal under the Paris Agreement i.e., to limit the increase in global temperature to 1.5°C above pre-industrial levels (see ***The Shift to Hydrogen (S2H2): Elemental Change*** series – ***Why H2? Why now?***).

It will be interesting to read the IEA's perspective on the global carbon budget.

On Tuesday March 16, 2021 the International Renewable Energy Agency (**IRENA**) published a preview to its 1.5°C Pathway paper on how to achieve the Stretch Goal.

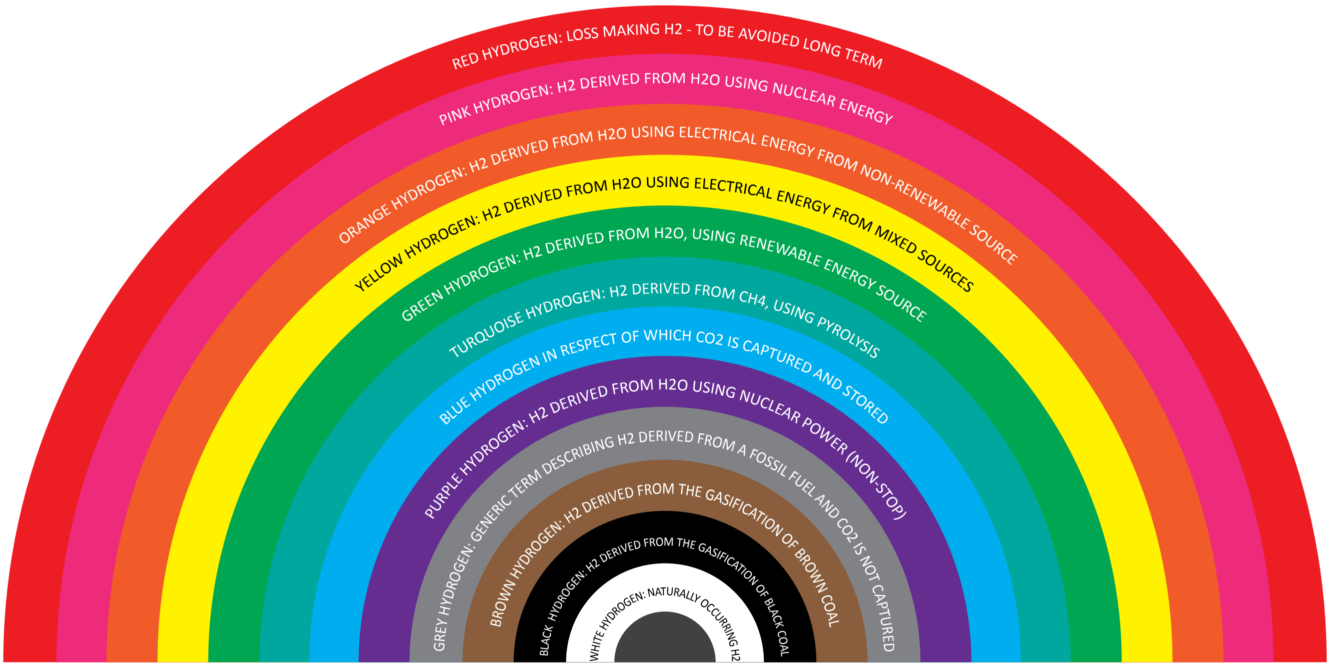
The Ashurst Global Towards Zero Emissions team will publish standalone publications soon after the release of the IEA World's Roadmap to Net Zero by 2050 and the IRENA Pathway paper.

1.9 THE ASHURST HYDROGEN RAINBOW:

The Ashurst Global Towards Zero Emissions team has developed a graphic to represent the colours of hydrogen: all the colours of the rainbow, with the addition (and taking something of a liberty with the spectrum) of Grey, Black, Brown and White at the "earth-bound" end of the Rainbow.

To many commentators the current narrative is that the development of projects to produce any colour of hydrogen results in red ink on profit and loss ledgers of those developing the projects to produced hydrogen as an energy carrier (other than Grey Hydrogen (or Black or Brown Hydrogen) for use as an industrial gas). This will change, but for the purposes of the Ashurst Hydrogen Rainbow, Red Hydrogen is described **To Be Avoided Long Term**: while current and possibly to medium term losses are a likely means to an end, this state of affairs is not sustainable long term. For some projects, however, government support will be required, including over the medium to long term.

Figure 1: - Ashurst Hydrogen Rainbow



1.10 H2 AS AN ENERGY CARRIER / ENERGY VECTOR

Background: To those active in the energy and power sector, and the resources sector for that matter (in particular electrical energy, natural gas and LNG), **energy carrier** and **energy vector** are well-understood terms, but rarely used day-to-day. These terms are used frequently in the context of H2, in particular the term "energy carrier".

The reason for this is that H2 has to be produced: H2 is stated not to occur naturally on earth in a form that can be used as a fuel. While H2 occurs naturally, free H2 is scarce. While H2 is relatively rare on earth in its gaseous form (other than in simple, lighter hydrocarbon compound), it is one of the most common elements in the crust of the earth by elemental mass.

As on earth as it is in heaven[17]: H2 is the most common element in the universe (it is estimated that 75% of the elemental mass of the universe is H2) H2 needs to be captured by gravity to provide the mass to allow to nuclear fusion in stars or to form compounds with other elements.

To be used to source energy as an energy carrier, H2 needs to be produced from a feedstock. H2 is not a primary source of energy (i.e., a fuel), it is a secondary source of energy (i.e., a fuel produced from a feedstock). H2 is derived and produced from compounds containing it (including the thousands of compounds to be found in hydrocarbons from which fossil fuels are derived and produced, and in H2O).

As an energy carrier, H2 has latent energy, allowing H2 to be used at a different time and place than its point of production. H2 carries a lot of energy. By mass 1 kg / H2 contains 33 KWh, or nearly three times as much (by mass) as motor spirit (gasoline or petrol). The principal technologies used to produce H2 require energy, whether to separate H2 from carbon compounds or to split water (to allow H2 and O to be derived), and once separated / split to compress or to liquify the H2O, or to hydrogenate it. Using current proven and scalable technology the production of H2 is energy intensive. In fact it takes more energy to produce 1 kg / H2 than that 1 kg carries, but in liquid form H2 is rocket fuel.

Unlike energy carriers derived or produced from hydrocarbons as fossil fuels, or other organic compounds, on use (including on combustion H2) H2 does not produce CO2 or CO, because H2 does not contain carbon. Instead of producing CO2 or CO, on use (or on its oxidation) H2 produces water vapour which while a GHG it is a GHG that remains in the atmosphere for a limited time. On use H2, the water vapour produced is pure: as well as being rocket fuel necessary to get into space, H2 powers the life-support systems on board space vessels using fuel cell technology, with the water vapour produced providing drinking water. On one basis, this cycle allows the production of the most renewable of all renewable sources.

If H2 had a manifesto in an energy carrier election, it would be that it is the most prospective energy carrier for a world in which the reduction of GHG emissions has become an imperative.

As an energy carrier, H2 can displace the use of almost all (if not all) other energy carriers, providing efficient and clean fuel for transportation, heating, energy and power and the high temperatures required in Difficult to Decarbonise industries. As the level of H2 production increases, and unit costs fall, we might wonder what took us so long.

17. The author has no direct experience of celestial matter or heaven, but is familiar with the Lord's Prayer.

Section 2 – The "Size of the Decarbonisation Prize"

2.1 STATE OF PLAY AT THE START OF 2021:

Global GHG Emissions: To provide context and a sense of scale, it is helpful to ground thinking by reference to the mass of GHG emissions arising each year (from anthropogenic activities[18]), and what percentage of global GHG emissions arise from the oxidation of fossil fuels (and other carbon intensive fuels and feedstocks), and the sectors and industries from which those GHG emissions arise.

It is estimated that 50 billion tonnes of GHG emissions[19] arise each year[20] from anthropogenic (human) activities, and approximately 30 billion tonnes of GHG emissions arise "naturally"[21] each year. Anthropogenic GHG emissions arising globally have not peaked yet[22]. It might be expected that peak GHGs will not arise until the late 2030s at the earliest[23] (more likely in the 2040s, or later).

Energy Use: Around 75% (estimated as around 36 billion tonnes) of GHG emissions arising from human activity arise from the oxidation of fossil fuels and feedstocks (and other carbon intensive fuels and feedstocks). In other words, energy use and Unallocated Fuel Combustion emissions and Fugitive GHG emissions arising from production and use of energy (including energy carriers) are responsible for 3/4 of GHG emissions. **Table 1** and **Narrative Box 3** provides some background on the Unallocated Fuel Use and Fugitive GHG emissions (together 13.6% total global GHG emissions). The most important point to make in respect of Unallocated Fuel and Fugitive Emissions is that as decarbonisation occurs across the Building, Cement, Chemical and Petrochemical and Iron and Steel, and Transport industries and sectors, Unallocated Fuel Use and Fugitive Emissions will reduce.

The vast majority of those emissions are CO_2 (but CH_4 and NO_x contribute too). CO_2 and CH_4 also arise from the Agricultural, Forestry and Land Use and Waste sectors. Of the sectors, the Agricultural, Forestry and Land Use and Waste sectors offer plausible (some would say the most plausible) and cost effective means of achieving Negative GHG Emission (**NGHGE**) outcomes using Negative GHG Emission Initiatives (**NGEIs**).

Table 1 below indicates the sectors and industries from which those GHGs arise. In summary, **Table 1** represents the following:

- **Energy Use** being GHGs arising arise from use of energy, including electrical energy, heat, and energy carriers used by each of the Building sector, Industrial sector, and Transport sector (including Unallocated Fuel Use and Fugitive Emissions predominantly from the Oil and Gas and Coal industries), together giving rise to between 73% and 75% of global GHGs;
- **Direct Industrial Processes** being GHGs arising from the use of energy carriers (non-electrical energy) in the cement and chemical and petrochemical production industries, which energy carrier use, and GHGs arising from the chemical reactions arising from the processes themselves, give rise to a little over 5% of global GHGs;
- **Agriculture, Forestry and Land Use** being GHG emissions arising from the production of food (crops and livestock) and forestry activities, and land use, giving rise to around 18.5 to 20% of global GHG emissions (with the most referenced being 19% of global GHG emissions); and
- **Waste** being GHG emissions arising from the decomposition of organic matter as waste water or in landfill (and to a much lesser extent arising from the processing and treatment of waste, including thermal treatment), giving rise to between 3.2 and 3.5% of global GHGs.

Agriculture, Forestry and Land Use: The Agriculture, Forestry and Land Use sector is the most challenging sector to decarbonise for many reasons, critically, because the sector is tied inextricably to food production, and attendant land clearance for the purposes of food production[24]. Also traditional means of food production (crops and livestock), contribute to CH_4 emissions with traditional means of

18. GHG emissions arise naturally. Over the last 15 years it has become apparent that GHG emissions are arising from natural sources as a result human activities: for example, the "defrosting" of the permafrost. It is estimated that 1.4 trillion tonnes of GHGs are contained by the permafrost or, stated another way, close to 30 years of anthropogenic GHG emissions.
19. While GHG emissions are measured by mass in $GtCO_2$-e, for the purposes of giving a more readily understood metric, billions of tonnes is used.
20. GHGs are measured in comparison to CO_2-e, which connotes the equivalent of a GHG to CO_2. There are a number of estimates, but this estimate appears the most likely, and realistic, although some may consider that the estimate is on the high side.
21. Naturally arising GHG emissions are CO_2, CH_4 and NO_x, and water vapour, occurring from forest fires, oceans, wetlands, mud and peat, volcanoes and earthquakes, and weather systems.
22. The Paris Agreement contemplates that each country that is a Party should seek to achieve GHG peak emissions as soon as possible.
23. World population, urbanisation and development have not peaked yet, and GHG emissions are unlikely to peak until this has occurred. Some activities are unlikely to be decarbonised completely, including Agriculture, Forestry and Land Use sector, and Aviation and Chemical and Petrochemical industries. As part of decarbonisation, achieving effective negative GHG emissions is likely to be necessary if net-zero GHG emissions are to be achieved so as to stabilise climate change. Negative GHG Emissions (NGHGE) are achievable by restoring natural absorbers of CO_2 (**natural climate solutions** or **NCS**), and, possibly, DAC. In principle, NCS could have a material impact on CO_2 emission levels in the atmosphere. This is an area in which those developing policy settings may wish to place more emphasis.
24. Land clearance often results in CO_2 emissions (as are result of burning to clear), and always resulting in an overall reduction in the capacity of fauna to absorb CO_2.

production giving rise to greater GHG emissions (in absolute terms) as population growth continues, and development of economies affords greater prosperity, it should be expected that the proportion of GHG arising from this sector will increase.

In addition to land clearance for food production, land clearance is continuing to occur to allow the production of non-food crops, including for the production of fuels and feedstock from crops (**Fuel Crops**), and to a lesser extent to allow the increasing world population (that does not have access to electricity) to source fuel for cooking and heating.

In an article entitled ***Energy Carriers from Waste and Fuel Crops – Markets, Waste as Feedstock and Technologies*** (to be published in the Ashurst Publication, InfraRead 16, in May / June 2021), the Ashurst Global Towards Zero Emissions team considers the economic, environmental, and social dynamics of Fuel Crops, alongside the legal and commercial issues relevent to them. In the article, current policy settings and thinking are considered, including around the use of perennial crops to achieve carbon natural outcomes.

Table 1: - Anthropogenic GHG Emissions By Sector and Industry

<table>
<tr><th>GHG emissions arising by sector (expressed as % of total Global GHG emissions)</th><th colspan="5">Estimated Percentage of GHG arising by industry (expressed as % of total Global GHG emissions)</th><th>Commentary</th></tr>
<tr><td rowspan="4">Energy Use (73 – 75)</td><td>Buildings (17.5):</td><td colspan="2">Commercial and Industrial: 6.6</td><td colspan="2">Residential: 10.9</td><td rowspan="3">These are the sectors that offer the greatest opportunities for GHG emission reductions using renewable electrical energy and hydrogen</td></tr>
<tr><td>Industry (24.2):</td><td>Fe / Steel: 7.5</td><td>Chem & Pet: 3.5</td><td>FT / N-Fe / P&P / M[25]: 2.8</td><td>Others[26]: 10.6</td></tr>
<tr><td>Transport (16.2):</td><td>Road: 12</td><td>Aviation: 2</td><td>Shipping: 1.5</td><td>Rail: 0.4</td></tr>
<tr><td colspan="2">Unallocated Fuel Use: 7.8</td><td>Fugitive Emissions: 5.8[27]</td><td>Oil & Gas: 3.9 of 5.8</td><td>Coal: 1.9 of 5.8</td><td>The fossil fuel industry recognises, and is responding to, the Fugitive Emissions issue</td></tr>
<tr><td>Direct Industrial Processes (5.2 – 5.5)</td><td colspan="2">Cement: 3: CO_2 arising as result of the process of producing clinker</td><td colspan="3">Chemicals and Petrochemicals: 2.2: arising as a result of processes used to produce chemicals and petrochemicals</td><td>The cement industry offers opportunities for GHG emission reductions using hydrogen</td></tr>
<tr><td>Waste (3.2 – 3.5)</td><td colspan="2">Wastewater: 1.3 / 1.5: arising as result of decomposition of organic matter</td><td colspan="3">Landfill: 1.9 / 2: arising as a result of the CH_4 and CO_2 emitted on decomposition of organic matter</td><td>Directly related to population and urbanisation</td></tr>
<tr><td>Agriculture, Forestry and Land Use (18.5 – 20)</td><td colspan="5">These activities account directly for between 18.5 and 20% of GHG emissions. It is unlikely that net-zero outcomes will be achieved across these activities, and as a result Negative GHG Emissions Initiatives[28] will be required, and in due course land use repurposed.</td><td>It is estimated that the food system as a whole (direct and indirect emissions) is responsible for up to 36% of GHG</td></tr>
</table>

The industries highlighted in yellow in **Table 1** are considered in detail in **Sections 3.1**, **3.2** and **3.3**.

25. **FT** connotes Food and Tabaco Production (1% of GHG emissions), **N-Fe** connotes non-ferrous metal production (0.7%), **P&P** connotes Paper and Pulp production (0.6% of GHG emissions), and **M** connotes machinery production, but excluding transport vehicles and shipping (0.5% of GHG emissions).
26. Others "Industries" relates to energy related emissions from other industries, including mining and quarrying, construction, textile and wood product derivation and production, and manufacture of transport vehicles and shipping.
27. **Fugitive Emissions** are beyond the scope of this **Part 1**. Low Carbon Pulse covers initiatives to address fugitive emissions by the Oil and Gas industry, and IEA (for example, see Edition 7 of Low Carbon Pulse). And it is anticipated that a soon to be finalised article on **Refining and Petrochemicals** will cover them.
28. As noted elsewhere, negative GHG Emissions Initiatives (NGEIs) will be the subject of an Ashurst Global Towards Zero Emissions publication - Adaption to Climate change and Negative GHG Emission Initiatives.

Narrative Box 3: Unallocated Fuel Use and Fugitive Emissions, Waste and Agriculture, Forestry and Land Use covered in other articles

For the purposes of this **Part 1**, Unallocated Fuel Use and Fugitive Emissions, Waste and Agriculture, Forestry and Land Use, are not considered in detail. The reason for this is that it is not anticipated that H_2 will have a direct material role to play in the decarbonisation of them[29], although H_2 may be derived from Waste (and from the residue of Agricultural, Forestry and Land Use activities).

Note however that as fossil fuels and feedstocks (and other carbon intensive fuels and feedstocks) are displaced by non-carbon, or lower-carbon intensive, fuels and feedstocks, there should be an indirect, and correlative, reduction in the Unallocated Fuel Use and Fugitive Emissions.

Note also that the CH_4 and CO_2 arising from putrescible organic matter in waste water and landfill can may be captured as biogas for direct combustion, or captured and further processed to derive bio-methane for use in gas networks, or to derive H_2.

For waste water, this is possible using anaerobic digestion technologies. For waste, if the putrescible organic material is landfilled, while it is possible to capture landfill gas (CH_4 and CO_2) as the putrescible organic matter decomposes, this is not as efficient as capturing putrescible organic matter before it is landfilled and using anaerobic technologies to process and to derive CH_4 and to capture CO_2 or to derive H_2 and to capture CO_2 (see Chapters 5 and 6 in Ashurst Compendium: Waste to Wealth Initiatives).

The first feature in the H24I series, **Hydrogen from Waste**, provides an overview of H_2 how hydrogen can be derived from waste using different technologies.

29. This does not mean that Fugitive Emissions, Agriculture, Forestry and Land Use and Waste are not on the radar of the Ashurst Global Towards Zero Emissions team, they are:
(a). developments in respect of Fugitive Emissions are being covered in the Low Carbon Pulse publication, as the Oil and Gas industry in particular is turning to monitoring effectively, and regulation of fugitive emissions is being developed and the release by the IEA of A Regulatory Roadmap and Toolkit (see Edition 7 of the Low Carbon Pulse);
(b). Waste is covered in a number of publications from the Ashurst Global Towards Zero Emissions team – Ashurst Compendium: Waste to Wealth Initiatives, the first feature H24I publication (to be published in April 2021) covers Hydrogen from Waste, and at least two further articles on waste will be published during 2021; and
(c). the Ashurst Global Towards Zero Emissions team will publish an overview of GHG emissions arising from the Agriculture and Food sector later in 2021, which will consider all aspects of the sector, and the policy settings intended to monitor and to manage the GHG emissions in the context of the global carbon budget.

2.2 THE PRINCIPAL MEANS OF GHG EMISSIONS REDUCTION:

As apparent from, and outlined in this **Part 1**, there are two principal means of reducing GHG emissions (including reducing the extent to which GHGs arise in the future):

- first, from progress towards the maximisation of renewable energy use, including to produce clean hydrogen using electrical energy from renewable energy sources to allow decarbonisation; and
- secondly, from initiatives in the Agricultural, Forestry and Land Use and Waste sectors to reduce GHG emissions, and to develop and to deploy NGEIs to allow each jurisdiction to live sustainably within its carbon budget (and the global carbon budget).

It is most unlikely that it will be possible to rely on maximisation of renewable energy use to achieve the level of GHG emission reduction necessary to achieve the either Goal of the Paris Agreement.

In any event, the electrification of the world will continue[30], including in response increasing urbanisation and economic and social development.

It is estimated that the total final consumption of electrical energy, as a minimum, is likely to double by 2050 (and this is before taking account of the renewable energy required to produce H2[31]).

> "To stay within the [global] carbon budget, the world will need to ... decrease energy-related [GHG] emissions by 60% until 2050 (**60% Reduction**) – even as the population grows by more than 2 billion people and hundreds of millions of [people in countries that are developing] join the global middle class."[32]

Even if it is assumed that renewable energy provides the majority of new electrical energy supply capacity required to match growth in demand for electrical energy, in calculating the global carbon budget to allow for urbanisation and economic and social development, it will be necessary to develop and to deploy NEGIs. (Edition 9 of Low Carbon Pulse – Negative GHG Emissions, relating to California's carbon budget calculations to achieve net-zero emissions by 2045 provides examples of NGEI.)

In addition to an article entitled Adaption to Climate Change and Negative GHG Emission Initiatives in Q3 of 2021, the Ashurst Global Towards Zero Emissions team will publish a longer form article (as part of ***The Shift to Hydrogen (S2H2): Elemental Change*** series) on the need for, and the sectors able, to deliver on NEGIs.

It will be apparent from these articles that the Agricultural, Forestry and Land Use and Waste sectors have a key role to play, and for the Waste sector this is likely to include the production of H2 (a specific colour for which has yet to be ascribed for the Ashurst Hydrogen Rainbow, probably a lighter shade of turquoise given the technology more likely to be used to derive or to produce it).

30. Up to 950 million people globally do not have access to electrical energy, and around 3 billion people do not have access to clean and reliable sources of material to use in food preparation. What this means is that use of fauna sourced biomass continues at a level that gives rise to GHG emissions, some of which will be included in the Unallocated fuel use, and which is not sustainable.
31. See **The Shift to Hydrogen (S2H2): Elemental Change** series – **Why H2? Why Now?** for further background.
32. See page 16 of Hydrogen Council Publication – Hydrogen Scaling Up.

Narrative Box 4 provides a brief background on Blue Hydrogen and Green Hydrogen. **Figures 2** and **3** provide Ashurst diagrams explaining, at a high level, feedstock and process technologies used in the production of hydrogen.

Narrative Box 4: Blue Hydrogen and Green Hydrogen – A Clean Pathway

Blue Hydrogen and Green Hydrogen provide a clean pathway to decarbonisation.

Blue Hydrogen and Green Hydrogen offer a means to decarbonise the use of fossil fuels and feedstocks (and other carbon intensive fuels and feedstocks). This is because:

- Blue Hydrogen is a clean energy carrier: assuming effective CCS / CCUS, use of renewable electrical energy for the purposes of production or the capture of GHGs arising from the use of non-renewable energy, and control of fugitive emissions; and
- Green Hydrogen is a clean and green energy carrier.[33]

In each case, no GHGs arise on oxidation i.e, on use.

The use of Grey Hydrogen (or Black or Brown Hydrogen) does not provide the same pathway to decarbonisation: while on oxidation of any colour of hydrogen no GHG emissions arise, around 850 million tonnes of GHG emissions arise from the production of Grey Hydrogen (or Black or Brown Hydrogen) globally each year.

Stated another way, to produce around 80 million tonnes of Grey Hydrogen (or Black or Brown Hydrogen) about 1.7% of global GHG emissions arise as a direct result. (See ***The Shift to Hydrogen (S2H2): Elemental Change*** series – ***Why H2? Why Now?*** for further background, and statistical underpinning.)

For the purposes of framing thinking, lets assume that by 2050 there is production of 250 mtpa of clean hydrogen[34] (in addition to current hydrogen produced and used) as an energy carrier. This is possible using the shift is possible by use of Blue and Green Hydrogen. The use of Grey Hydrogen (or Black or Brown Hydrogen), rather than Blue or Green to achieve this shift would result in approximately 2.5 billion tonnes of GHG emissions a year. The 250 mpta has been picked for illustrative purposes only. In fact the mass of H_2 for use as an energy carrier is more likely to be between 50% and 60% of this.

Clearly, using Grey Hydrogen is not a zero sum game. The GHG emissions arising from the displacement of other energy carriers would reduce the GHG emissions arising from production of Grey Hydrogen. In contrast, the effective deployment of CCS / CCUS to derive Blue Hydrogen (as contemplated above) and the production of Green Hydrogen is a zero sum game, in that zero GHG emissions will arise in production, storage, transportation and on oxidation at the point of use.

In this context, assuming electrolyser efficiency of 66.67%, it is noted that to produce 1 mtpa of Green Hydrogen requires 50 TWh of renewable electrical energy.

33. The Hydrogen Council defines Blue and Green Hydrogen as follows: "Blue Hydrogen is clean but not green: it is produced from renewable energy and natural gas, but the carbon is not released into the atmosphere; it is captured and stored" and "Green Hydrogen is carbon free: it is produced from renewable energy and non-fossil fuel sources".

34. Clean Hydrogen includes Blue Hydrogen and Green Hydrogen more broadly, but in an EU context Clean Hydrogen or Renewable Hydrogen is hydrogen produced through the electrolysis of water in an electrolyser, powered by electricity, and with electricity coming from renewable sources. The life-cycle of GHG emissions of producing clean or renewable hydrogen are close to zero.

Figure 2: - Green and Clean Hydrogen

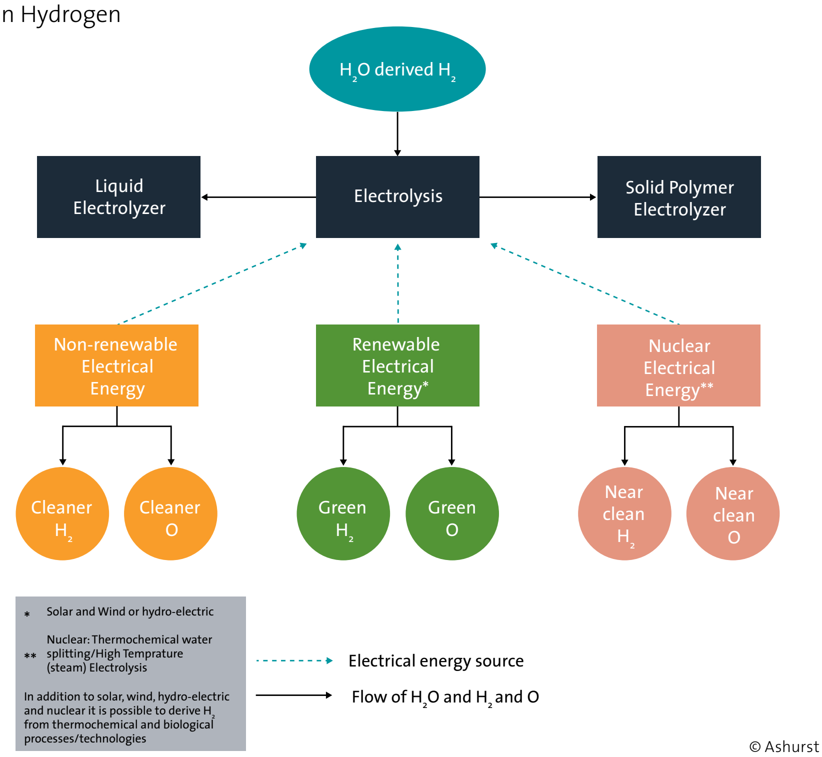
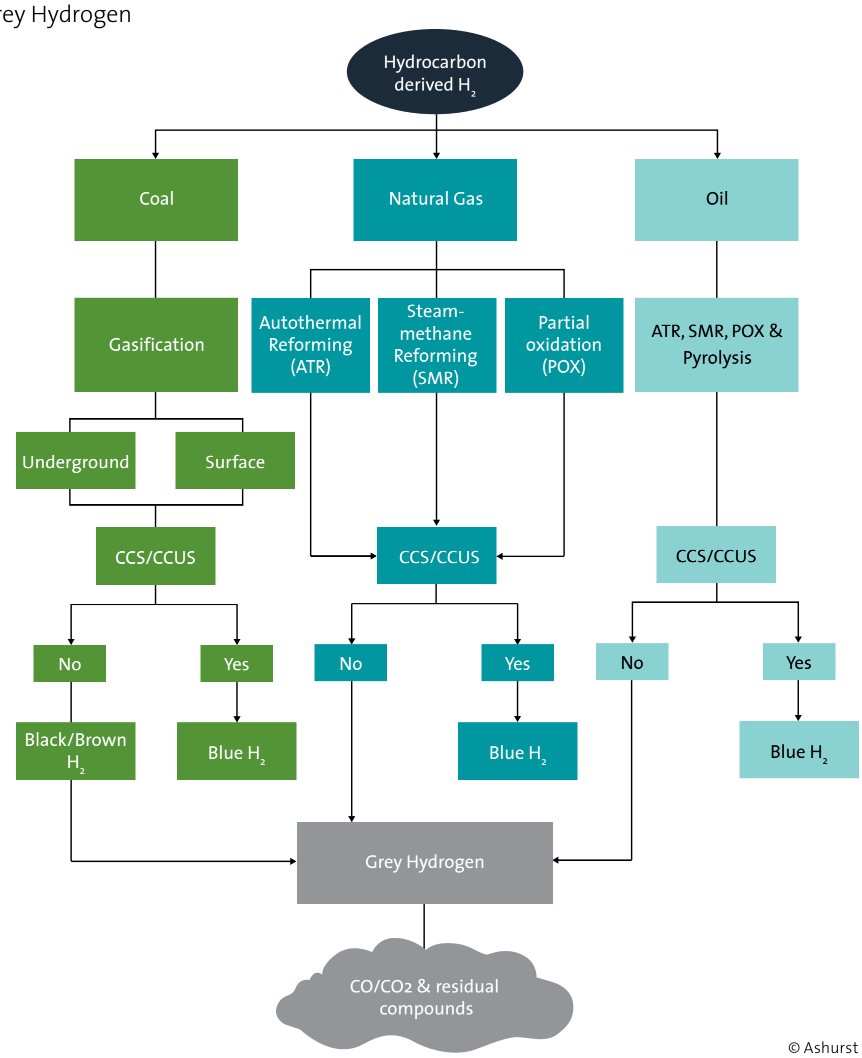


Figure 3: - Blue and Grey Hydrogen



2.3 STATE OF PLAY BY THE START OF 2050:

2.3.1 Is there going to be a Shift to Hydrogen?

It has been stated that H2 could meet around 25% of the world's energy use needs by 2050. On the basis of current GHG emissions, this would result in a reduction in GHG emissions of around 8 billion tonnes of CO2-e per year: around 16% of total current global GHG emissions and 22% of total global GHG emissions arising from energy use. This 25% projection may be regarded as bold. The Hydrogen Council[35] contemplates that by 2050 18% of energy demand will be met by clean hydrogen[36] (both Blue and Green Hydrogen) with a reduction in GHG emissions of 6 billion tonnes of CO2-e per year. IRENA has a different perspective again.

As will be apparent from **Narrative Box 4**, the H2 produced for these purposes must be Blue Hydrogen and Green Hydrogen, with the expectation being that over-time Green Hydrogen will satisfy an ever increasing proportion of increasing demand for clean hydrogen. Sourcing between 15% to 25% of the world's energy use needs from hydrogen by 2050 may be regarded as achievable with effective policy settings. For what it is worth, the view of the Ashurst Global Towards Net-Zero Emissions team is a more conservative – 10% to 15%.

2.3.2 REE is key

While the "size of the decarbonisation prize" is greater than this, decarbonisation is not all about use of hydrogen as an energy carrier. While hydrogen has a meaningful contribution to make, of the 60% Reduction (in energy-related GHG emissions) identified by the Hydrogen Council, overwhelmingly renewable electrical energy has the most important contribution to make. It is the decarbonisation of electrical energy generation that will provide most of the 60% Reduction. It is difficult to overstate the importance of the role of renewable electrical energy generation in decabonisation of energy use. Further, it is difficult to overstate the scale of the increase in renewable electrical energy required to produce the mass of Green Hydrogen being contemplated.

2.3.3 What are the key issues to achieving the hoped for Shift to Hydrogen?

In addition to the development of renewable electrical energy capacity, the key issues with achieving any shift to clean hydrogen are the entirely related issues of cost and time, and supply and demand, as follows:

- **the cost and time taken:** given the current cost of Blue Hydrogen and Green Hydrogen, and the time it will take for either or both of them to become cost competitive with fossil fuel (or other carbon intensive) energy carriers it is anticipated they will displace, the cost of CCS / CCUS and the cost electrolysers must fall (thereby reducing capital costs), while at the same time their efficiency (in particular that of electrolysers) must rise, thereby reducing the principal operating cost, electrical energy; and
- **the development of both the supply and demand side:** the efficient development of the hydrogen industry requires supply and demand side to develop in tandem, supply just ahead of demand (see ***The Shift to Hydrogen (S2H2): Elemental Change*** series – ***Why H2? Why Now?*** for more detail on the need to develop supply and demand on an aligned basis): supply will not develop without demand side, and demand side will not develop without clean hydrogen being cost competitive or use of clean hydrogen being encouraged or mandated.

2.3.4 Which sectors and industries need to become dedicated users of hydrogen?

Consistent with the framing of this article (including **Table 2**), the Hydrogen Council recognises the primary uses as H2 being:

1. **Buildings-Heat and Power:** H2 can be used to decarbonise activities that otherwise are not capable of transitioning to electrical energy use from renewable sources;

35. The Hydrogen Council was established / launched in January 2017 at the World Economic Forum.
36. The Hydrogen Council definition is: "'Clean' generally means there is very low or zero carbon emissions in the production of hydrogen. This term covers hydrogen both with and without carbon capture and storage". In summary, Blue Hydrogen is Clean, but not Green. Green Hydrogen is Clean.

2. **Industrial Energy:** H_2 as an energy carrier can provide high-temperature heat energy for industrial processes;
3. **Industrial Feedstock:** H_2 as an energy carrier feedstock can be used to decarbonise industrial processes by replacing fossil fuels and feedstocks;
4. **Energy Carriers:** H_2 as an energy carrier can be integrated into the renewable electrical energy systems to provide energy storage (and possibly to provide fuel for electrical energy generation); and
5. **Transportation:** H_2 and fuel cells can be used to decarbonise the transportation sector (using FCEV). Battery electrical vehicles (BEVs) can also decarbonise the transportation sector, and will be used for this purpose.

In addition to these primary uses of H_2, the Hydrogen Council recognises that current sources of H_2 for feedstock can be phased out, and the CO_2 captured by CCS / CCUS can be used to produce methanol (anticipated by some commentators as recycling as much as 350 mtpa of CO_2 into energy carrier products).

Achieving this level and range of H_2 usage, would not complete the shift to hydrogen, but it would provide the world with a clear basis for achieving the Stabilisation Goal[37] of the Paris Agreement and, possibly, for achieving the Stretch Goal[38] (see ***The Shift to Hydrogen (S2H2): Elemental Change*** series – ***Why H2? Why now?***).

Table 2: - Anthropogenic GHG Emissions By Sector and Industry for the purposes of **Sections 3.1**, **3.2** and **3.3**

<table>
<tr><th>GHG emissions arising by sector (expressed as %)</th><th colspan="5">Estimated Percentage of GHG arising by industry (expressed as % of total GHG emissions)</th></tr>
<tr><td rowspan="3">Energy Use (73 – 75):</td><td>Buildings (17.5):</td><td colspan="2">Commercial and Industrial: 6.6</td><td colspan="2">Residential: 10.9</td></tr>
<tr><td>Industry (24.2):</td><td>Fe / Steel: 7.5</td><td>Chem & Petro: 3.5/5</td><td>FT / N-Fe / P&P / M[39]: 1.6</td><td>Others[40]: 10.6</td></tr>
<tr><td>Transport (16.2):</td><td>Road: 12</td><td>Aviation: 2</td><td>Shipping: 1.5</td><td>Rail: 0.4</td></tr>
<tr><td>Direct Industrial Processes (5.2)</td><td colspan="2">Cement: 3: CO_2 arising as result of process of producing clinker, with GHG emissions arising from the generation of electrical energy used to crush and grind the clinker included in Industry, and GHG used to Transport cement included in Transport.</td><td colspan="3">Chem's and Petrochemicals: 2.2 CO_2 arising as a result of processes used to produce chemicals and petrochemicals: GHG emissions arising from generation of electrical energy used in the processes are included separately in Industry, and GHG arising on Transportation of products are included in Transport.</td></tr>
<tr><td colspan="6">Notes on Table 2: This Table 2 uses Table 1 as its base.
From Table 1 the following have been removed: from the energy sector Unallocated Fuel Use (accounting for 7.8% of GHG emissions) and Fugitive Emissions (from which it is estimated that 5.8% of GHG emissions arise) (Oil and Gas (3.9%) and Coal 1.9%); the Waste sector from which it is estimated that between 3.2 and 3.5% of GHG emissions arise (Wastewater (1.3 to 1.5%) and Landfill (1.9 to 2%)), and the Agriculture, Forestry and Land Use sector from which it is estimated that between 18.5 and 20% of GHG emissions arise.
This means that in this <u>Table 2 emissions arising by sector do not equal 100%</u>.</td></tr>
</table>

37. To limit the increase in global temperature to 2°C above pre-industrial levels.
38. To limit the increase in global temperature to 1.5°C above pre-industrial levels.
39. **FT** connotes Food and Tabaco Production (1% of GHG emissions), **N-Fe** connotes non-ferrous metal production (0.7%), **P&P** connotes Paper and Pulp production (0.6% of GHG emissions), and machinery production, but excluding transport vehicles and shipping (0.5% of GHG emissions), and **M** connotes manufacture of transport vehicles (including shipping).
40. **Others Industries** relates to energy related emissions from other industries, including mining and quarrying, construction, textile and wood product derivation and production.

2.3.5 Renewable Electrical Energy the "fuel" of the future:

As noted in **Section 1.1**, renewable electrical energy is, and will remain, an ever present. The IEA regards electrical energy as the "fuel" of the future (**IEA Thesis**). The IEA Thesis is based on some or all of the following factors:

- an increasing proportion of total energy use as the electrification of the world continues;
- increased use of utility scale battery electrical energy storage (**BESS**) to store electrical energy generated by renewable electrical energy sources (**REE** or **RES**) but not capable of dispatch or stored so as to dispatch to achieve better pricing points in pooling systems, and to provide assurance of grid integrity and stability (as is the case and the plan in Australia, the UK and increasingly in a number of other countries);
- increased use of battery electric vehicles (**BEVs**), net-zero commitments of corporations creating a market for corporate PPAs / Clean Energy Contracts (see Edition 9 of the Low Carbon Pulse); and
- last, but not least, the need for a huge increase in REE to generate electrical energy to allow the production of Green Hydrogen (and it is likely Blue Hydrogen).

If electrical energy is the "fuel" of the future, that "fuel" needs to be produced from REE.

IRENA has a like thesis to that of the IEA. IRENA estimates that to achieve the Stretch Goal, 90% of global final consumption of electricity will have to be derived from REE. To achieve this, IRENA estimates that REE capacity needs to increase from 2,500 GW to 27,000 GW by 2050.

2.4 2021 TO 2050 – A LONG AND WINDING ROAD?

The starting point for the shift to hydrogen from fossil fuels (and other intensive carbon fuels) is understanding which sectors give rise to GHG emissions, these are:

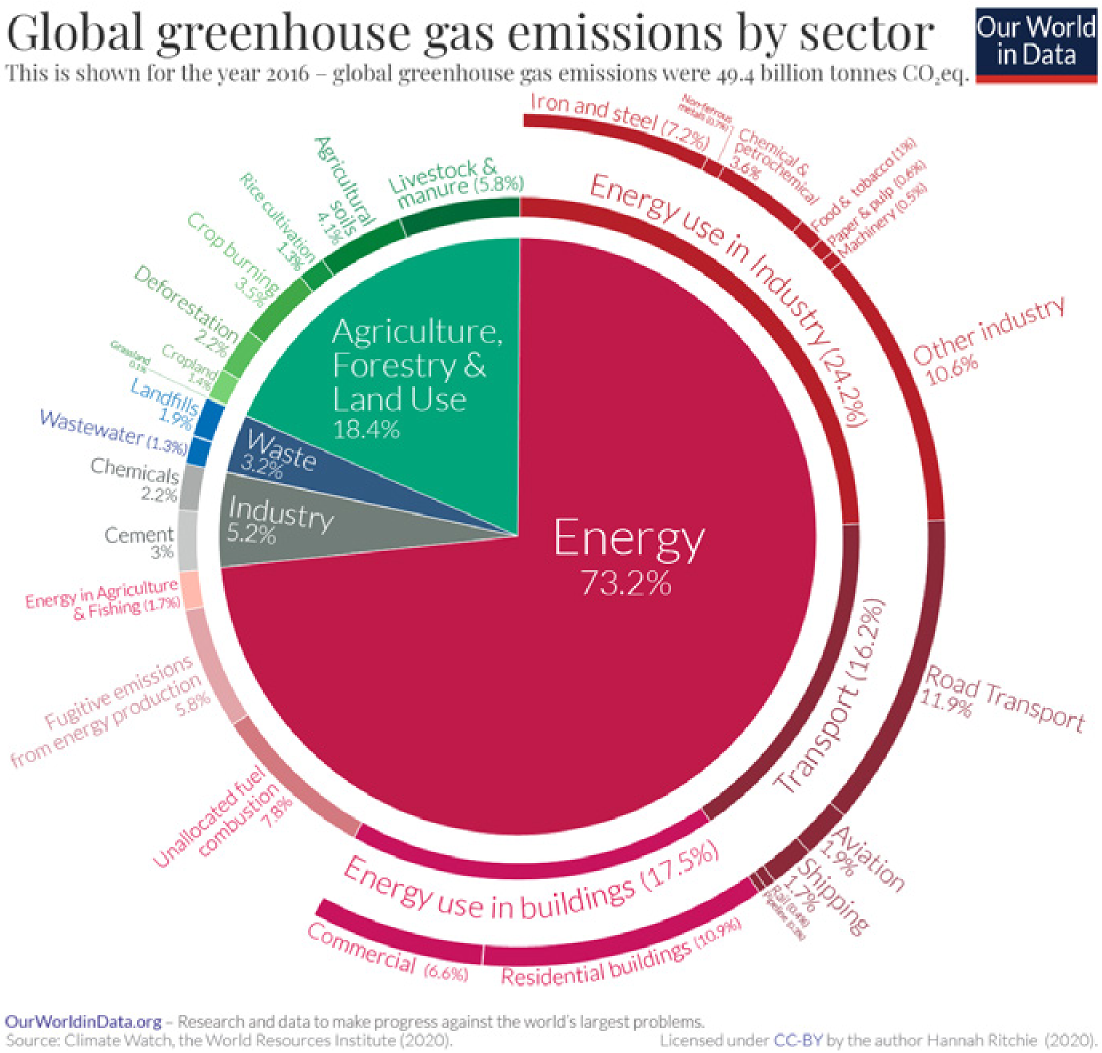
(a) Buildings (**Section 3.1**);

(b) Difficult to Decarbonise industries – Cement, Chemicals and Petrochemical and Iron and Steel (**Section 3.2**); and

(c) Transportation (**Section 3.3**).

As is noted above, Unallocated Fuel Use and Fugitive Emissions (equating to 13.6% of GHG emissions) may be regarded as arising (at least in part, and more likely predominantly) from energy carriers produced for and used by these sectors. As these sectors decarbonise, it is reasonable to assume that there will be a reduction in the GHG emissions currently accounted for as Unallocated Fuel Use or Fugitive Emissions.

Figure 4:



Section 3 – Realising the Decarbonisation Prize – Decarbonisation of Energy Use

3.1 ENERGY USED IN BUILDINGS:

3.1.1 Direct Energy Use:

In the built environment, the most common energy sources for buildings (commercial, industrial and residential) are electrical energy (for air-conditioning / space cooling, lighting, electrical appliances and equipment, electrical fixtures (including doors), powering motors, including for lifts), and natural gas for heating and cooking.

It is estimated that between 18.5 to 20% (noting that **Figure 4** show figures from 2016 which from other sources may be a little on the low side) of direct GHG emissions arise from the supply of electrical energy and natural gas, to, and the use of electrical energy and natural gas, in buildings. The split of energy use, between electrical energy and natural gas, is estimated as 78% to 22% respectively. Energy use can be decarbonised in Buildings by the use of renewable electrical energy for the most part.

- **Electrical energy source:**

  The continued progress towards maximising renewable electrical energy (through the displacement of electrical energy sourced from non-renewable sources), both from grid and off-grid, and off-grid to grid (rooftop solar), will result in a proportionate abatement in GHG emissions. This may be expected to be the case particularly in the case of Commercial and Industrial buildings.

  In a way, the ongoing "renewal of the electrical energy" industry may be regarded as likely to achieve decarbonisation of electrical energy usage across the Building sector, with a limited role for H2.

- **Energy carrier role:**

  The use of natural gas for heating (ambient and water) and for cooking may be regarded as more difficult to decarbonise. In a number of countries around the world, policy settings are mandating that natural gas boilers and cooker facilities are not installed in new buildings, and are to be phased-out in all buildings, in some cases by 2035.

  The blending of natural gas and H2 will contribute to a proportionate reduction in GHG, but does not decarbonise completely. The UK may be regarded as one of the countries taking the lead on this, including the development of blending guidelines (to allow GHG reduction by use of natural gas blended with H2) and regulation to allow transition from natural gas[41] (including transition from natural gas heating systems (ambient and water)).

3.1.2 New cities for the hydrogen economy:

While retrofitting the built environment, and regulating new buildings in existing urban environments is likely to be the norm, some countries are planning to develop new urban environments consistent with net-zero GHG emissions.

In the Republic of Korea (**South Korea**) policy settings[42] are resulting in the use of hydrogen

41. Subject to regulation, H2 (20%) is to be blended with CH4 (80%) to provide gas to the village of Winlanton, in the North East of England. In the UK context, approximately 85% of homes and 63% of commercial and public buildings are heated using natural gas (comprising CH4). The use of hydrogen as a heating fuel is not new in the UK, but this will be the first time that the public gas distribution network (operated by Northern Gas Networks) will have been used for the purpose of transporting and delivery of CH4 and H2 blended gas.

42. The power industry is required to source electrical energy from fuel cell technology sources (see Edition 2 of the Low Carbon Pulse).

fuel cell technology in new built environments. In addition, South Korea is planning "hydrogen powered cities"[43]. The plan is that hydrogen-powered cities will use H2 as a source of energy for cooling and heating, and as a source of electrical energy for buildings (and as an energy carrier for transportation). This is consistent with the broader plans to shift to H2 use in the built urban environment, with H2 to power 10% of towns and cities by 2030 and 30% by 2040. This is integral to the shift to a hydrogen economy.

The Kingdom of Saudi Arabia plans to develop a USD 500 billion city, Neom (meaning "New Future"[44]), as a smart city powered by renewable sources of energy, including hydrogen. Neom will cover a land area equivalent to that of Belgium, or stated another way, 30 times that of New York City, divided into 16 boroughs, compared to New York's five.

Neom is located on the coastline of the Red Sea. In mid-2020, it was announced that Air Products (leading US industrial gases company) is to develop a USD 5 billion Green Hydrogen plant using electrical energy from 4 GW of solar and wind capacity. It is stated that the Green Hydrogen plant is to be designed to produce 650 tonnes of Green Hydrogen per day (around 237,500 tonnes a year)[45].

3.1.3 Indirect energy use:

It is noted that the life-cycle assessment (**LCA**) of any building (and infrastructure associated with, and to support it) covers construction and maintenance of buildings to abate the GHG emissions arising from foundation to demolition[46]. While LCAs are beyond the scope of this article, it is recognised that effective LCAs are becoming increasingly important to ensure that the abatement in GHGs (**Abatement Gains**) through decarbonisation of one industry or sector are not lost in another industry or activity.

From the findings of both IEA and United Nations Environment Program (**UNEP**) (very much leading the way in this area), there is considered to be a clear need for action by policy makers to address the building sector's direct and indirect energy use: by the estimates of some commentators (taking a broader direct and indirect view) the building sector (including all aspects of construction and operation and maintenance) accounts for upto 38% of total energy related GHGs emissions.

In this regard, it is important to note that the decarbonisation of the cement and iron and steel industries will have a material indirect impact on the decarbonisation of the building sector (and construction industry). More broadly the building sector may be regarded as able to respond to policy settings that decarbonise energy use and reduce emissions, more readily and effectively.

This is an area in which alignment across jurisdictional boundaries could yield material reductions in GHG emissions.

3.1.4 Recycling construction and demolition waste:

See **Section 3.2.4(c)** below for recycling of construction and demolition (C&D) waste.

43. South Korea plans to develop three new H2 powered cities, as part of a broader strategy for H2 to provide 10% of energy needs by 2030, and 30% by 2040.
44. Neom is reported to be a combination of **New** in Greek and **Future** in Arabic.
45. It would seem that both Green Hydrogen for domestic use, and Green Ammonia (combining the Green Hydrogen with nitrogen) for export.
46. The United Nations Environment Program (UNEP) publishes an informative publication each year: Global Status Report For Buildings and Construction – Towards a zero emissions, efficient and resilient buildings and construction sector. The Report provides a sense of the global GHG emissions arising from the lifecycle of buildings and infrastructure.

3.2 ENERGY USED IN DIFFICULT TO DECARBONISE INDUSTRIES:

3.2.1 Context, and the size of the decarbonisation prize:

To provide context, and the "size of the decarbonisation prize", this **Section 3.2** provides an overview of each of the Difficult to Decarbonise industries in the Industrial sector. Each of these industries is fully integrated into the world economy, and the products produced by them have no current substitute, or no likely scalable substitute, and as such in the context of achieving net-zero GHG emissions it is critical to decarbonise energy use in these industries.

The need to decarbonise each of the Difficult to Decarbonise industries is emphasised because each of them is going to grow and may double (or more) in size before 2050. Certainly cement and iron and steel production may be expected to double in size: as world population continues to increase, and the urbanisation of the global population continues, and accelerates, so will building and infrastructure development with the associated use of cement and iron and steel[47].

Necessarily the overview of each Difficult to Decarbonise industry is expressed in "short-hand" (and as such without nuance), but the overarching point to be made is that the "size of the decarbonisation prize" in realising decarbonisation of energy use is huge.

Table 3 is intended to provide an indication of the benefit of realising decarbonisation of energy use (including for Cement and Chemical and Petrochemical production from both GHG emissions from Direct Industrial Processes and electrical energy use).

Table 3: - GHG emissions by Industry, before and after Decarbonisation

Industry	**Estimated Current GHG emission profile** (expressed as a percentage of global GHG emissions)	**Possible GHG emission profile after Decarbonisation of Energy Use** (expressed as a percentage of global GHG emissions)	**Current Energy Cost as % of Total Production Cost**
Cement	7 to 8%[48]	Zero to less than 2%	25 to 35%
Chemical and Petrochemical	4 to 5%[49]	Less than 2%	29 to 33%
Iron (Fe) and Steel (metallic iron)	8 to 10%[50]	Zero to less than 2%	20 to 40% (efficiency dependent)
Other Industries and Sectors[51]	12 to 12.5%	Less than 5%	Industry dependent

47. One of the many interesting factoids from Mr Bill Gates' book, "How to avoid climate disaster – The solutions we have and the breakthroughs we need" is that "The world will be building the equivalent of another New York City every month for the next 40 years".
48. This percentage includes GHGs arising as a by-product of the production of clinker: sintering to produce clinker involves the conversion of limestone ($CaCO_3$) to lime (CaO), which chemistry dictates results in the emission of CO_2.
49. Including arising as a by-product of the production of a chemical or a petrochemical, for example, CO_2 arises on the production of NH_3 if natural gas is used as the feedstock.
50. This amounts to approximately for one third of industrial emissions, and a little less than one third of coal mined.
51. These industries include mining and quarrying activities, textile production, wood product production, and transport equipment production, including the production of motor vehicles (including aircraft, buses, light and heavy good vehicles, private passenger vehicles, trains and ships).

3.2.2 Quantifying the "size of the decarbonisation prize":

If these Difficult to Decarbonise industries are decarbonised effectively (but not necessarily completely, as explained below), this will have a material and significant (some would say huge) impact on global net-GHG emissions.

Taking the bottom-end of the range of each Current GHG emissions profile (see **Tables 1** and **2**), on a net-basis (assuming that around 10% of GHGs will continue to arise from the Difficult to Decarbonise industries) 20% of the total global GHG emissions is the "size of the decarbonisation prize" if decarbonisation of energy use in the Industrial Sector is realised. (As noted above, including a proportion of GHG emissions arising from Direct Industrial Processes.)[52]

As noted above, taking a proportion of the reduction in GHG emissions arising from Unallocated Fuel Use and Fugitive Emissions that will arise from decarbonisation, conservatively 5% of global GHG emissions, the size of the decarbonisation prize is increased to 25% of global GHG emissions.

3.2.3 Composite headline:

If this level of reduction in GHG emissions is added to the a halving (again a conservative estimate) of the GHG emissions arising from the Direct Use of Energy by the Building Sector, the running totalizer on the "size of the decarbonisation prize" is a little under 34% of current global GHG emissions.

Stated another way, a 34% reduction in the current global carbon budget is equivalent to 17 billion tonnes of the current estimate of 50 billion tonnes of anthropogenic GHG emissions arising each year.

If the Transport sector is able to decarbonise on a similar basis the size of the decarbonisation price is up to 45% of GHG emissions.

In **Section 3.2.4**, each of the Difficult to Decarbonise industries is considered to give a sense of the energy used in each of them, and as such the means of decarbonisation.

It is important to emphasise that this level decarbonisation will allow progress to net-zero GHG emissions, but will not achieve with zero GHG emissions across the Difficult to Decarbonise industries – to achieve this, more will be required.

52. As noted in **Sections 3.2.4** and **3.2.5**, it is going to be easier to decarbonise the Direct Industrial Processes in the Cement Industry than in the Chemical and Petrochemical Industry given the current feedstocks used in the Chemical and Petrochemical Industry.

3.2.4 Cement industry:

(a) GHG budget:

The production of cement may be regarded as giving rise to up to 7 to 8% of global GHG emissions or between 3,500 and 4,000 mmt (or 3.5 to 4 billion tonnes) of GHG a year: roughly and readily, the production of 1 tonne of cement production gives rise to approximately 1 tonne of GHGs (rounded-up).

(b) Primary production:

Mass of product: Cement is derived and produced, predominantly, from limestone and clay, using established cement kiln technologies (to heat the raw material to its sintering temperature[53], requiring a high-temperature heat) to derive clinker. Clinker is then ground and mixed mechanically with gypsum to create cement (with electrical energy required for this purpose).

Cement is the most consumed manufactured material globally, and is the second most consumed resource globally, water being the most-consumed (by mass). It is estimated that over 4,000 mmt (or 4 billion tonnes) of cement is produced each year (and over 10,000 mmt (or 10 billion tonnes of concrete) is produced and used each year using cement). If the cement industry were a country it would be the world's third largest emitter of GHG: while the cement industry is responsible for between 7 and 8 per cent of GHG emissions (both from electrical energy and from the processes undertaken to produce cement) the cement industry is a critical part of modern economies.

The cement industry uses carbon fuel / feedstock (fossil and renewable carbon sources) to achieve the required high-temperature heat conditions to undertake sintering, and electrical energy in the mechanical grinding and mixing of clinker and gypsum.

If electrical energy from a renewable energy source is used:

- to derive / produce the H2 from H2O, the H2 produced will be Green Hydrogen;
- to power the production of cement by kiln,

cement production will be green.

Raw material and indirect GHG emissions: Those with a keen eye, will argue that to be truly green, Blue Hydrogen or Green Hydrogen through FCEVs, or electrical energy through BEVs, needs to be used as an energy carrier to power and to propel the means of freight transport (road, train and ship) used to deliver the raw materials to the point of production of cement and then to deliver cement to the point of production of concrete.

Taking this forward, the scale of renewable energy carriers will reflect that it takes between 1.5 and 1.75 tonnes of raw material to produce one tonne of cement, and 4,000 mmt (or 4 billion of tonnes) of cement is produced each

53. Sintering involves compaction / fusing of minerals / materials using heat (or pressure) without liquefaction / melting of the mineral / materials, which in the case of limestone and clay occurs at around 1,450°C. (By way of further background, sintering is sometimes referred to at frittage.)

year, at least 6,000 mmt (or 6 billion tonnes) of raw material needs to be delivered to the point of cement production. As such, a total of 10,000 mmt (or 10 billion tonnes) of freight needs to be hauled each year to deliver cement to the point of concrete production. The concrete then needs to be delivered.

Use of hydrogen: H_2 is able to displace fossil (and other carbon intensive) fuel / feedstock in the production of cement, because it burns at high-temperature, with no emissions of CO_2, just H_2O, on oxidation. Blue Hydrogen and Green Hydrogen may be regarded as medium to longer term sources of energy carriers necessary to provide high-temperature heat for the clinker production process, with electrical energy from renewable sources being used to power the mechanical crushing and grinding of the clinker. FCEV (or BEV, or both) could displace fossil fuel derived energy carriers[54] required to haul raw material to the point of cement production, and cement from the point of production. In addition, if renewable electrical energy is used to displace non-renewable electrical energy, the production of cement could be close to GHG emission free.

Energy used: The amount of energy required to produce cement is dependent on whether wet or dry-process kilns are used, and the place of production. The vast majority of energy used to produce cement is sourced from fossil fuel, with limited energy being sourced from non-renewable waste, and biomass and renewable waste. While difficult to estimate becasue of the variables, the total energy used is estimated to be 640 TWh[55] (this is necessarily an extrapolation from various sources and metrics). "To green" the production of cement, new renewable electrical energy is required to generate this quantity of electrical energy.

GHG capture and avoidance: CCS / CCUS are considered to be viable options to capture CO_2 arising from the clinker production process.

(c) Secondary production:

Concrete (as with other construction and demolition (**C&D**) waste) can be recycled to derive materials for use in construction of new buildings and infrastructure: concrete (as is the case with brick and masonry) can be used to provide fill and subbase material.

The benefits of recovery and recycling for these purposes arise primarily because primary production of materials that would otherwise be necessary to provide these materials is not required, resulting in avoided GHG at source, to process, and to transport that primary production to the point of use.

It is not the case however that concrete can be recycled to produce cement. As such, while recycling concrete may reduce the global carbon budget, it does not do so by reducing the global carbon budget for the production of cement.

54. The GHG emissions arising from freight transport of raw material for cement production, and delivery of cement to the point of concrete production, are not counted for the purposes of the statistics in **Table 2**, rather these GHG emissions are counted for the purpose of freight transportation. Likewise, the energy used to mine / quarry limestone and clay are not included.

55. From a range of sources, estimates range widely from 120 KWh to 200 KWh of energy to produce 1 tonne of cement.

3.2.5 Chemical industry (including petrochemical industry[56]):

(a) GHG budget: The production of chemicals (including petrochemicals) may be regarded as giving rise to up to 4 to 5% of global GHG emissions or 2,000 to 2,500 mmt (or 2 to 2.5 billion tonnes) of GHG a year. (For the purposes of this **Part 1**, petrochemicals are treated as a subset of chemicals.)

Unlike cement and iron and steel, a rough and ready estimate of GHG per tonne is not helpful in the context of the chemical and petrochemical industry because of the range of products produced (and the feedstocks and sources from which they are produced).

Like cement, and iron and steel, the world economy is dependent on chemical production. The principal issue in the chemical and petrochemical industry is whether it is possible to decarbonise feedstock use, and, if so, how. If it is not possible to decarbonise feedstock use, is it possible to capture and to store the GHG emissions arising on the production and use of the feedstock? As is explained in Section **3.2.5(b)**, with the exception of the production of ammonia (NH_3) (which can be decarbonised by the use of Green Hydrogen as a feedstock, rather than natural gas, predominantly CH_4), currently it is likely that CCS / CCUS offers the most likely solution to the reduction of GHG emissions otherwise arising on chemical production.

It is important to distinguish between the supply of hydrocarbon products by the oil and gas industry for use as energy carriers derived from fossil fuels (and other carbon intensive fuels), considered in **Section 3.3** below, and hydrocarbon products provided by the oil and gas industry for use as feedstock by the chemical to produce chemical and petrochemical products. Some hydrocarbons are used as both feedstock to derive and to produce energy carriers and as feedstock for the production of chemical petrochemical products, for example, the BTX aromatics (Benzene (C_6H_6), Toluene (C_7H_8), Xylene (C_8H_{10})). The mass of BTX aromatics used from the production of energy carriers, dwarfs that of the mass of BTX aromatics used as feedstock for the chemical industry.

(b) Primary production:

Mass of raw material and product: Over 70,000 products are derived and produced across the global chemical industry. Chemical and petrochemical products are derived and produced from many different feedstocks and using different sources of energy[57], and technologies. This said, seven primary feedstocks are used to derive or to produce the majority of chemicals[58]. The mass of the seven primary feedstocks produced is detailed in Footnote 58.

By mass, around 90% of feedstock and fuel (including used for electrical energy) for the production of petrochemicals are sourced from oil and gas, and petroleum products that have been derived from them. The balance of the feedstock and fuel for petrochemical production is from coal and biomass.

The chemical and petrochemical sector is the largest industrial consumer for oil and natural gas, and third behind the iron and steel and cement industries in in terms of direct GHG emissions arising from processes used[59]. If it were a country it would be the world's fourth largest emitter of GHG (just behind India, and some distance ahead of Russia).

56. It is helpful to regard the chemical and petrochemical industry as comprising at least four different types of production: 1. Inorganic and organic chemical production, 2. Fertiliser production; 3. Pesticide production; and 4. Refining and Petrochemical production.

57. For these purposes, we include high value chemicals (HVC), NH_3 and methanol production (see Table below in Footnote 58 detailing Seven Primary Chemical Feedstocks).

58. Primary feedstocks to the chemical / petrochemical industry are:

Seven Primary Chemical Feedstocks		
Chemical Feedstocks	**Mass Produced (expressed in mmt per year)**	**Use as Chemical Feedstock**
Ammonia (NH_3), about 50% used to derive Urea and Ammonium Nitrate	200 to 230	NH_3 is the primary feedstock for fertilisers for agricultural use.
BTX aromatics: Benzene (C_6H_6), Toluene (C_7H_8), Xylene (C_8H_{10})	110 to 130	BTX used as feedstock across a range of applications, not for energy carriers
Methanol (CH_2OH), an alcohol – about 40% used to derive formaldehyde	110 to 120	CH_2OH is the primary feedstock for the production of other chemicals.
Olefins (Light): Ethylene (C_2H_4) and Propylene (C_3H_6)	255 to 275	Olefins are used as feedstocks to produce plastics
Estimated Total Global Production (taking median point):	**715**	**HVCs:** Aromatics and Olefins are High Value Chemicals

59. To many this will be counter-intuitive, and it should be: about half of the chemical industries oil and gas usage is in the form of feedstock with emissions arising downstream of production of the chemical on the consumption of the product produce from the feedstock.

Raw material and indirect GHG emissions: In the chemical industry, there are two major energy sources of primary hydrocarbon feedstocks, first, natural gas (CH_4) and secondly, other lighter hydrocarbons (categorised as liquid petroleum gases (LPG) and natural gas liquids (NGLs)).

Each primary hydrocarbon feedstock gives rise to GHG emissions on production (including Fugitive Emissions) and on the use of them to produce feedstock, including the seven primary feedstocks. This is not to say that other hydrocarbons are not used: as noted above (and included as one of the seven primary feedstocks), the chemical and petrochemical products are produced using BTX aromatics, being heavier hydrocarbons.

Use of hydrogen: For present purposes, the question is whether or not it is possible to use hydrogen to displace the use of these hydrocarbons in the production of the seven primary feedstocks. At the moment the answer is yes in respect of NH_3 only[60] and otherwise only to the extent that H_2 can displace CH_4 as a feedstock.

As such, it is likely that the chemical and petrochemical industry will continue to give rise to GHG emissions. Given current technologies and products produced using them, the decarbonisation of the chemical and petrochemical industry is likely to take place primarily from the production of Green Ammonia (and possibly Blue Ammonia), the use of CCS and CCUS to capture and to store GHG arising on the production of feedstocks, and the use of renewable electrical energy in respect of the electrical load of the industry.

The chemical industry is both the largest producer and the largest user of hydrogen. The production and use of Green Hydrogen to displace current hydrogen production would reduce global GHG emissions by 850 mmt a year. "To green" the current mass of global hydrogen production, around 3,750 TWh of renewable electrical energy is required (assuming electrolyser efficiency of 66.67%).

Energy used: Consistent and verifiable assessments of final energy use by the chemical industry is not something that is readily available other than through extrapolation.

(c) Secondary production:

Given the nature of the products produced by the chemical industry the only products that offer a means to secondary production are plastics.

The Ashurst Global Towards Zero Emissions team is authoring an article on plastics that is close to finalisation. The article considers the mass of plastic waste arising globally, and the policy settings necessary to maximise the collection of plastics, and the means of recycling plastics to allow secondary production of plastic from them. The article places plastic waste arising in the context of global and local policy settings, critically, the Norwegian Amendment to the Basel Convention.

In short, while it is possible to collect plastics to recycle them, current heat and mechanical technologies do not allow the recycling of the majority of plastics (by mass), and the market for recycled plastics has proven to be volatile, including as are result of the low / lower cost of the production of virgin plastics in a low or lower price environment for oil and natural gas, and as such hydrocarbon products from which plastics are derived and produced.

60. By way of background, currently:
(a) ammonia (NH_3) production is energy intensive, using natural gas, critically CH_4 (the pre-dominant compound in natural gas) to source hydrogen. It is technically possible to continue to use CH_4 as the feedstock to source hydrogen, and to capture and to store the CO and CO_2 arising on oxidation of that CH_4. Using long established and proven technologies, it is possible to produce Green Ammonia using Green Hydrogen as the feedstock and then combining with nitrogen. The production of NH_3 in this way will be GHG emission free; and
(b) methanol (CH_2OH) production is energy intensive, as with ammonia, using natural gas as the feedstock to produce CH_4, effectively liquifying the CH_4 as an alcohol. Leaving to one side the application of this process to produce an energy carrier, and regarding methanol as a feedstock, the most appropriate means of decarbonising energy use in the production of methanol is to capture and to store the CO and CO_2 arising on production.
Given that both BTX aromatics and Olefins are sourced from hydrocarbon feedstocks (BTX heavier, Olefins lighter), the only means of decarbonising the production of feedstocks from them is to use CCS / CCUS.

3.2.6 Iron and Steel:

(a) GHG budget:

The production of steel may be regarded as giving rise to between 7 and 10% of global GHG emissions or between 3,500 and 5,000 mmt (or 4 to 5 billion tonnes) of GHG a year. This spread is too wide to make sense and as such our best estimate is based on a mix of virgin crude steel and scrap steel production (**Section 3.2.6(c)**). Global crude steel production is around 1,900 mmt (1.9 billion tonnes[61]) a year. The best estimate is that between 1.90 to 2.1 tonnes of CO_2 arises in respect of each tonne of steel produced. But not every tonne gives rise to the same GHG emissions because some is virgin steel, other derived from scrap steel (with scrap steel using electric arc, rather than blast furnace).

On the metrics discernable consistently, it is estimated that a little over 3,500 mmt (or 3.5 billion tonnes) of CO_2 arise each year from steel production. The EU has this higher at closer to 4,000 mmt (or 4 billion tonnes).

(b) Primary production:

Background: Steel is derived and produced from iron ore, using either blast furnace or electric arc technology. The production of steel requires energy, electrical and thermal. The steel industry has a number of means of reducing its carbon and GHG footprint[62]. If the steel industry were a country it would the world's 3 largest emitter: each of the cement and iron and steel industries give rise to more GHG emissions than India (the country with the world's third largest GHG's emissions, by country).

In the EU, steel makers are looking to displace coal (or natural gas) as a reduction agent for iron ore (LCP Edition 5). H_2 is able to displace coal (and natural gas) because it burns at high-temperature, with no CO_2, just H_2O on oxidation. Also in the EU, CCUS is being used to capture CO_2, and, in one instance, to produce methanol.

Raw material and indirect GHG emissions: To produce crude steel, iron ore and metallurgical coal is used. Currently around 3,000 mmt (3 billion tonnes) of iron ore, and around 1,050 mmt (1.05 billion tonnes) of coking coal, is produced annually for the purposes of producing steel. Extrapolating from this, to produce 1.9 billion tonnes of crude steel (using the current steel technology mix) requires over 4,000 mmt (or 4 billion tonnes) of raw material. (In fact the figure is a little higher because other raw materials are used in the production of crude steel, including other metals.)

As such, in addition to the GHG emissions arising from the production of crude steel, indirect GHG emissions arise from the transportation of iron ore and coking coal (and other metals) from source to the point of steel production. The majority of iron ore and coking coal (and other metals) is transported by freight train if to be used to produce steel "in country" or by freight train and ship on iron ore and coal carriers if exported for production of steel overseas.

61. As in this case with Cement and Chemicals the use of iron and steel is integrated into the global economy, and with increased population and urbanisation, and economic development, production will increase.

62. Initiatives include progressively grandparenting blast furnace technology and moving to electric arc technology, using natural gas (predominantly CH_4) rather than coal as a reduction agent, and using CCS / CCUS to capture carbon rich gas (GHG) arising from production to derive / produce bio-fuels.

In total (rounded down), the crude steel industry has to transport 6,000 mmt (6 billion tonnes) of freight, two thirds raw material, one third finished crude steel.

Use of hydrogen: H_2 is able to displace fossil (and other carbon intensive) fuel / feedstock in the production of steel, because it burns at high-temperature, with no emission of CO_2, just H_2O, on oxidation. FCEV (or BEV possibly on road haulage) could displace fossil fuel derived energy carriers[63] required to transport material to the point of steel production and steel from the point of production. If renewable electrical energy is used to displace non-renewable electrical energy use, the use of energy in the production of steel could be decarbonised.

Energy used: The amount of energy required to produce steel is dependent on whether blast furnace or electric arc technology is used, and the place of production. The vast majority of energy used to produce steel is sourced from fossil fuel. On the basis of 1,300 mmt of virgin crude steel, and 600 mmt of scrap steel.

On the basis of the EU estimate of 50 kg of Green Hydrogen to produce 1 tonne of green steel, a little under 5,000 TWh of renewable electrical energy would be required to produce the 95 Mt of Green Hydrogen needed to produce 1,900 Mt of green steel.

GHG capture and avoidance: CCS / CCUS are considered to be viable options to capture CO_2 arising from steel production. As with the cement industry, Blue Hydrogen and Green Hydrogen may be regarded as medium to longer term sources of energy carriers necessary to provide high-temperature heat for the steel production process. The fact that it may be possible to transition to replacing fossil fuel (and other carbon intensive fuel) used in the production of steel is the starting point. To move forward from the starting point, the steel industry will have to transition incrementally. It will do this only if the net price of H_2 is competitive with the cost of the use of fossil fuels (and other carbon intensive fuels), both the delivered market price, and any costs that arise as a result of policy settings (for example the carbon price under any emissions trading scheme).

Supply and demand: In Europe steel makers are decarbonising steel making using Green Hydrogen from electrolyses that the steel makers are developing themselves. It seems likely that this trend will continue, and become global.

(c) Secondary production (AKA recycling):

For the purposes of this **Part 1**, recycling of steel[65] is not covered in detail. This is not to ignore the recycling of scrap steel, and without question recycling of scrap steel has, and continues to have a role to play: it is estimated that between 550 to 620 mmt of scrap metal is recycled each year, around 30% of total steel production. Recycling in the steel industry has by far the greatest recycling role to play of any Difficult to Decarbonise industry.

Depending on the use of steel (including the design-life of any asset or infrastructure into which it is incorporated) and the country in which it is used, recycling rates vary (and will continue to do so), as is the case with other recyclable materials.

Also, as with other recyclables, while the mass of scrap steel may be increasing, so is the demand for steel.

Finally, scrap steel itself needs to be liquified to produce steel to be sold to users of the steel, and as such even if there were sufficient scrap metal to match demand it does not decarbonise steel production, because while production of secondary steel (from scrap) is less energy intensive than primary steel, it is still energy intensive.

Members of the Ashurst Global Towards Zero Emissions team advise participants in the waste and recycling industries, (including those trading in and recycling scrap steel (and other scrap metals). During 2021, the Ashurst Global Towards Zero Emissions team is publishing a number of articles on recycling, starting with Plastics to be followed by an article on scrap steel (and other metals, and including recycling of mega-structures).

63. The GHG emissions arising from freight transport of raw material for cement production, and delivery of cement to the point of steel production, are not counted for the purposes of the statistics in **Tables 1** and **2**, rather these GHG emissions are counted in for the purpose of freight transportation. Likewise, the energy used to mine iron ore and coking coal are not included.

64. From a range of sources, estimates range widely from taking the mid-point of energy to produce 1 tonne of steel, and weighting virgin crude steel to scrap.

65. In theory all scrap steel is capable of recycling. In practice, some scrap steel is more recyclable than other steel, and some not at all.

3.3 THE TRANSPORT SECTOR:

The Transport sector is energy intensive, at the moment predominantly sourced from non-renewable sources, in the form of fossil fuel (and other carbon intensive fuel).

As noted in **Figure 2**, the dominant source of the GHG emissions arising from the Transport sector is Road Transport, which is both passenger and freight road traffic: estimated currently to be between 12 and 12.5% of global GHG emissions. Aviation and Shipping each account for up to 2% of global GHG emissions.

The primary source of final energy use in the Transport sector is fossil fuel (and other carbon intensive fuels, and additives), primarily motor spirit (gasoline and petrol) and diesel for road transport, kerosene for the Aviation industry and heavy fuel oil for the Shipping industry[66].

In the context of the Transport sector, BEV and FCEV will be the primary means of the decarbonisation of final energy use. In many jurisdictions policy settings are in place to transition to BEVs and FCEVs. BEV to use REE only. FCEV use Blue Hydrogen and Green Hydrogen. In respect of all, REE is central.

While hydrogen is likely to have a key role in decarbonising the Transport sector, it is likely to be in the freight sector, road freight in particular in the medium term, and Shipping in the longer term.

As noted above, every other month a H24I feature will be published, including during 2021, a trilogy of features: Hydrogen and the Automotive Industry, the Hydrogen and Freight Haulage (Road, Rail and Shipping), and the Hydrogen in the Public Transport sector.

These features will cover in detail the facts and stats of the Transport sector in a more granular way than space permits here.

66. In an upcoming article on Refining and Petrochemicals the spread of use of hydrocarbons will be considered in detail. The article will consider the forms of hydrocarbons and the use to which they are put.

Section 4 – Conclusion

The decarbonation of energy use by the Building sector, the Difficult to Decarbonise industries in the Industrial Sector and the Transport sector by the use of both renewable electrical energy and hydrogen provides a clear pathway to reducing GHG emissions by up to (and possibly beyond) 45% of total current global GHG emissions.

While there is a clear pathway, as will be apparent from this **Part 1**, it is not an easy pathway. **Part 2** of this article considers, and assesses, the extent to which governments around the world have Roadmaps, Plans and Strategies that acknowledge this pathway, and have set a course to follow it. **Part 2** will be published in Q2 of 2021.

In the third article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series, entitled ***The key legal issues arising on each aspect of the H2 industry (including projects and transactions)***, amongst other things, the laws and regulations necessary to allow the development of the hydrogen industry (to allow decarbonisation to occur) will be outlined, both as contemplated in this **Part 1** and in **Part 2**, and more broadly.

If you have any questions or comments on this **Part 1**, feel free to send them to the author, Michael Harrison, at michael.harrison@ashurst.com.

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Ashurst's Global Towards Zero Emissions team offer a powerful combination of global expertise and experience, together with regional and local market knowledge. An overview of our Partner team is provided below, who are further supported by a skilled team of Counsel, Senior Associates and Lawyers.

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