Hydrogen for Industry (*H24I*)

FEATURE 1:
HYDROGEN FROM WASTE

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Introduction

Welcome to the first feature in a series entitled *Hydrogen for Industry (H24I)* from the Ashurst Global Towards Net-Zero Emissions team. This *H24I* feature is entitled *Hydrogen from Waste*.

ASHURST SUITE:

The ***H24I*** features are intended to complement other Ashurst initiatives, including publications ***Low Carbon Pulse*** and ***The Shift to Hydrogen (S2H2): Elemental Change*** series. ***Low Carbon Pulse*** is published every other week (Edition 1, Edition 2, Edition 3, Edition 4, Edition 5, Edition 6, Edition 7, Edition 8, Edition 9, Edition 10, Edition 11, Edition 12, Edition 13, Edition 14, Edition 15, Edition 16, Edition 17) to provide an update on significant current news on progress towards net-zero GHG emissions. ***S2H2*** articles are published once a quarter or so to provide a more detailed review of matters of general application to all industries (**Article 1**: ***Why H2? Why now?***, **Article 2**: ***What needs to be decarbonized? And what role can hydrogen play?***). The intention is to publish a *H24I* feature every other month. Each *H24I* feature will take a more detailed look at an industry or sector, or part of it, and the role of hydrogen in that industry or sector.

During the next twelve to fifteen months or so the intention is publish *H24I* features covering the following subject matter: ***Hydrogen and Freight Haulage (Road, Rail and Shipping)***, ***Hydrogen and the Public Transport sector***, ***Hydrogen and the Automotive Industry***, ***Hydrogen in the Difficult to Decarbonise Industries***, ***Hydrogen in the Energy Mix During Energy Transition*** and ***Energy Transition and the Building and Construction sector***.

The intention is to keep each *H24I* feature to between 6,000 and 7,500 words in its published form: each feature is derived from fuller form materials prepared for Ashurst clients to allow a broader and deeper understanding of the subject matter, critically, the commercial, legal and technical issues that arise in development and transactional settings, and transition to net-zero.

CONTEXT AND TIME DEFINE:

Much of the text in this *H24I* feature (***Hydrogen from Waste***) was drafted over 12 months ago for inclusion in an article titled Part 1: Fuel and Feedstock Resource Recovery – Energy Carriers from Waste (published April 21, 2020), the seventh article in the ***Ashurst Waste-to-Wealth*** series. At that time, hydrogen from waste was recognised as likely to develop in the context of waste processing and treatment projects generally. The authors chose not to include reference to hydrogen as one of the energy carriers from waste in that article because the thinking was that it was too early to do so.

Since that time, the momentum towards the use of hydrogen as an energy carrier has increased dramatically, and appears increasingly likely to be critical as part of progress towards net-zero with the use of CH_4-rich wastewater and the organic fraction of waste streams as a feedstock to derive and to produce hydrogen.

On May 18, 2021, the International Energy Agency (***IEA***) released a publication entitled "Net Zero by 2050, A Roadmap for the Global Energy Sector" (***IEA Special Report***) (link). The *IEA Special Report* focuses on the Energy Sector. The Energy Sector includes bioenergy, which includes deriving or producing energy from waste, what the *IEA* refers to as ***advanced bioenergy***. The use of wastewater and waste to derive and to produce hydrogen greatly increases the potential of bioenergy.

OVERVIEW OF THIS FEATURE:

This *H24I* feature is divided into two sections:

- **Section 1 – On the Road to Net-Zero:** providing background on the GHG emissions that arise from wastewater and waste, the type of wastewater and waste used as a feedstock to derive or to produce hydrogen, the characterisation and colour of hydrogen used to describe hydrogen derived and produced from wastewater and waste, and an introduction to the technologies used to derive or to produce hydrogen; and
- **Section 2 – From Wastewater and Waste to Energy Carrier to Oxidation:** providing background on hydrogen, the production and use of hydrogen as an energy carrier, and, in this context, the energy content of hydrogen compared to other energy carriers, such as diesel and motor spirit (gasoline and petrol), and more detail on thermo-chemistry.

ASHURST GLOBAL TOWARDS NET-ZERO EMISSIONS TEAM:

A good number of the members of the Ashurst Global Towards Net-Zero Emissions team work across a number of industries and sectors, including the water and waste industries. Attached is a link to the ***Ashurst Waste Compendium***. The subject matter in some of the chapters in the ***Ashurst Waste Compendium*** is referenced in the body of this *H24I* feature to provide further detail and reading.

Narrative Box 1: What a difference a year makes!

While production of hydrogen from waste is still to commence at a scale necessary for demand side to rely on it, on April 27, 2021, Hyzon Motors Inc (***Hyzon***) and Raven SR LLC (***Raven SR***) agreed to develop jointly up to 100 waste-to-hydrogen production hubs (***3 H Projects***) across the US, and globally. *Hyzon* and *Raven SR* say that the waste-to-hydrogen production hubs will produce renewable hydrogen at a cost comparable to that of grey hydrogen (and as such at a cost that is lower than the current production cost of Blue and Green Hydrogen).

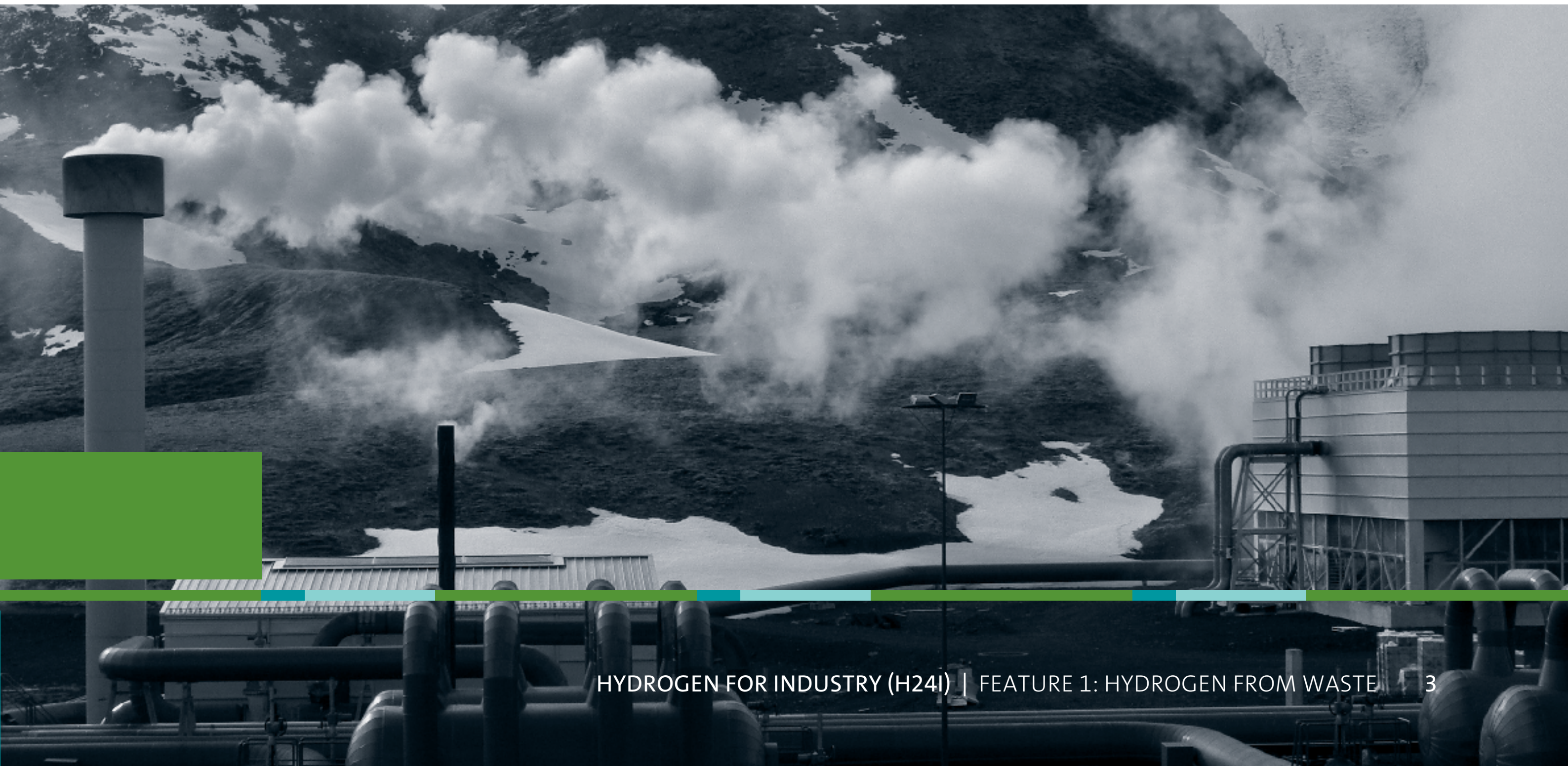
It is estimated that the *3 H Projects* could convert over 5,000 tonnes of waste a day into hydrogen: each waste-to-hydrogen hub is stated to be able to process 50 tonnes of waste a day to yield 4.5 tonnes of renewable hydrogen a day using *Raven SR*'s propriety technology that derives CH_4-rich syngas from organic matter, from which it is possible to derive hydrogen. The *Raven SR* technology is stated not to involve oxidation. It is understood that the *Raven SR* technology uses rotary kiln technology, in the absence of oxygen, thereby avoiding oxidation (i.e. combustion). As with other rotary kiln technologies, temperature control is key to avoiding ash or slag arising, and instead producing biocarbon (and in so doing capturing carbon dioxide and carbon monoxide as residual material) and synthetic biogas, which syngas is then reformed to produce hydrogen. The *Raven SR* technology may be considered as combining well-proven technologies.

The *Hyzon* / *Raven SR* model is that renewable hydrogen will be available at the point of production i.e. at each waste-to-hydrogen hub, with fuel cells being used by garbage collection vehicles (***GCVs***) and heavy goods vehicles (***HGVs***). For *Hyzon* this avoids (or lessens) reliance on third party development of hydrogen refuelling infrastructure (***HRI***) and third party supply of hydrogen.

- ***Hyzon*** co-founder and CEO, Mr Craig Knight, said: "*Hyzon* aims to be one of the first companies to supply our customers with a hydrogen fuel cell truck, including our own garbage trucks, at a total cost of ownership [***TCO***] parity with diesel-powered vehicles".
- ***Raven SR*** co-founder and CEO, Mr Matt Murdock, said: "Our planet produces over 5.5 million tonnes of municipal solid waste and 16.5 million tonnes of agricultural waste every day. Theoretically, if we convert all this waste, we could produce over two million tonnes of renewable hydrogen per day – enough to satisfy over 25% of total global oil demand".

The *Hyzon* / *Raven SR* transaction shows what a difference a year makes: from too early to call, to solid result.

Narrative Boxes 3 and **4** and **Section 2.6** provide details of other technologies and models. Each technology is well-proven, and is able to operate efficiently with, and is responsive to feedstock that has a broad range of net-calorific values, and feedstock that ranges from dry to wet organic matter.



What you need to know

- **All wastewater and waste projects, including those to derive and to produce hydrogen, are regarded primarily as public health and environmental projects, rather than as energy projects. The fact hydrogen can be derived makes them energy projects too;**
- **The use of wastewater and waste as a feedstock to derive and to produce hydrogen will give rise to GHGs to the point of production of hydrogen, as such it is not Blue Hydrogen (unless GHG emissions arising are captured) or Green Hydrogen, but it is renewable hydrogen, and, depending on the technology used, is a lighter shade of Turquoise – see Sections 1.9 and 1.10;**
- **The wide-spread use of hydrogen hubs co-located with existing wastewater and landfill facilities offers a feedstock for hydrogen production close to demand for hydrogen in urban environments;**
- **While waste-to-hydrogen hubs remain to be developed, the development of them offers the prospect of achieving three distinct positive health and environmental outcomes:**
    - the diversion of organic waste from landfill achieving the reduction or the avoidance of the need to landfill waste, and the surface and sub-surface issues that arise from landfill use;
    - the diversion of waste from landfill achieves the reduction or the avoidance of GHG emissions arising from organic waste in landfill as it decomposes over time; and
    - the reduction in GHG emissions arising from extraction, production and use of energy carriers derived and produced from fossil fuels which the use of hydrogen (as an energy carrier from waste) displaces.
- **As a practical matter, if the roll-out of waste-to-hydrogen hubs proceeds, renewable hydrogen can be produced to accelerate the use of Fuel Cell Electric Vehicles or FCEVs (including *GCVs* and *HGVs*) well-ahead of the previously projected transition to scale use of FCEV technology: waste-to-hydrogen hubs provide the means to allow supply to match demand for hydrogen in tandem, providing those purchasing *GCVs* and *HGVs* with assurance of both supply of hydrogen and its price.**

Section 1 – On The Road to Net-Zero

1.1 ALL ROADS LEAD FROM PARIS:

On November 4, 2016 the Paris Agreement entered into force. Article 2 of the Paris Agreement recognises that to respond to the effects of increased concentrations of GHG in the atmosphere and the resulting increase in average temperature globally, it is necessary to hold: "the increase in the global average temperature to well below 2°C above pre-industrial levels [***Stabilisation Goal***] and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels [***Stretch Goal***]".

To achieve this, the Paris Agreement provides a framework under which each country that is a party to the Paris Agreement commits to reduce its GHG emissions by a stated percentage of the GHG emissions arising at an earlier date, so called nationally determined contributions (***NDCs***).

For more detail on the Paris Agreement, see the first article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series entitled, ***Why H2? Why now?***

1.2 REDUCTION RATES NEED TO INCREASE:

The Paris Agreement provides for a stocktake of *NDCs*, i.e., whether *NDCs* are being achieved and whether they are sufficient to achieve the Goals. The first stocktake took place in 2018. The second stocktake is scheduled for 2023.

Well-ahead of the second stocktake, and at an ever increasing pace, parties to the Paris Agreement have assessed their commitments to GHG emission reductions, in particular in the context of achieving current *NDCs* by 2025 and 2030 and, longer term, achieving net-zero GHG emissions by 2050. In the context of the second stocktake and more broadly, governments and the private sector alike have realised the existential imperative of reducing GHG emissions at a faster rate, and to greater levels, than current commitments. Also there has been an ever increasing focus on achieving the *Stretch Goal*, and setting a roadmap to achieve the *Stretch Goal*: the imperative appears to be to achieve the *Stretch Goal*, not "to make do" with the *Stabilisation Goal*. The *IEA Special Report* provides the most current assessment.

Narrative Box 2: Possible Scale of hydrogen production from waste and wastewater

Mass of solid waste available as feedstock to produce renewable hydrogen:

Raven SR co-founder and CEO, Mr Matt Murdock, estimates that "… over 5.5 million tonnes of municipal solid waste and 16.5 million tonnes agricultural waste [arises] every day. Theoretically, if we convert all this waste, we could produce over two million tonnes of renewable hydrogen per day – enough to satisfy over 25% of total global oil demand".

The estimates provided by Mr Murdock suggest a theoretical ability to produce 730 mtpa of renewable hydrogen annually from solid waste. This is staggering. To produce an equivalent mass of Green Hydrogen would require, as a minimum (given current technology), 35,000 TWh of renewable electrical energy (current global electrical energy production is around 26,500 TWh). By way of a point of reference, the EU is contemplating use of 100 mtpa of hydrogen within the EU by 2050, and the International Energy Agency up to 520 mtpa globally by 2050, of which 320 mtpa will be Green Hydrogen.

Leaving to one side the theory, the production of say half of this mass of renewable hydrogen (i.e., 365 mtpa of hydrogen) would require considerable further development in the recovery and collection of waste. This is particularly the case in countries that are continuing to develop their waste management systems. Further, the net effect of the production of renewable hydrogen needs further work – it is not a zero sum game, because production is not GHG free. What is certain is that the mass of solid waste arising is going to increase as the population increases (see **Chapter 1** of the ***Ashurst Waste Compendium***), as will the mass of GHG emissions arising.

Mass of wastewater available as feedstock to produce renewable hydrogen:

In a study released on February 21, 2021 by Utrecht University and the United Nations University (link), it was estimated that half of wastewater arising globally is captured and treated: "Globally, about 359 billion cubic metres of wastewater is produced each year, equivalent to 144 million Olympic-sized swimming pools."

This estimate does not give a sense as to how much of the wastewater arising has an appropriate concentration of organic matter to make it suitable for use as feedstock to derive or to produce renewable hydrogen. Further, wastewater is likely to be used as feedstock for processing and treatment to derive grey water or potable water, or both, with the resulting residual biosolids / sewage sludge fraction being the likely feedstock for hydrogen production.

As is the case with solid waste, what is certain is that the mass of wastewater arising globally is going to increase as the population increases, with the absolute mass of GHGs arising increasing commensurately.

1.3 WASTEWATER AND WASTE – PART OF THE GHG EMISSION REDUCTION SOLUTION:

Most of the focus on achieving net-zero GHG emissions has been on the decarbonisation of energy production and use. This is because close to 75% of anthropogenic GHG emissions arise from the extraction, production and use of fossil fuels or other carbon intensive feedstocks and fuels – see *IEA Special Report*. The balance of GHG emissions arise from Agriculture, Forestry and Other Land Use (***AFOLU***), Industrial Process industries (principally cement and iron and steel) and the Waste sector (wastewater and landfill). The GHG emissions arising from the *AFOLU* and Waste sectors comprise a relatively high proportion of methane (***CH_4***). CH_4 has a higher global warming potential than CO_2.

GHG emissions arising from these sectors are related directly to population growth and economic development – GHG emissions arising increasing with population growth and economic development[1].

Narrative Box 3: This is not an issue of technology

Hydrogen from wastewater (*H2* from *WH2*):

On March 30, 2021 the completion of a hydrogen from wastewater facility was announced. The facility is co-located at the Sunamachi Water Reclamation Centre, Tokyo, Japan (***H2 from WH2 Project***). The facility used technology developed by Ways2H, Inc. and, one of its shareholders and its technical partner, Japan Blue Energy Co (***JBEC***). Ways2H is a joint venture between *JBEC* and Clean Energy Enterprises. As is the case with the *3 H Projects*, the renewable hydrogen produced from the *H2 from WH2 Project* is produced for use to power and to propel FCEVs. Also it is contemplated that the renewable hydrogen may be used for power generation.

The *H2 from WH2 Project* was developed in partnership with the Tokyo Metropolitan Government, TODA Corporation, TOKYU Construction (leading construction) and CHIYODA Kenko and the Tokyo University of Science. Again illustrating the ability of the public and private sectors in Japan to come together to achieve world leading outcomes.

The *H2 from WH2 Project* uses "wastewater sludge" (biosolids / sewage sludge) as feedstock. The *Project* processes one tonne of feedstock a day which generates 40 to 50 kgs of hydrogen a day. In addition to wastewater sludge, the *Project* is able to use municipal solid waste and cardboard and paper, and plastics, as feedstock. It is understood that these additional feedstocks are likely to be used. The feedstock is heated to a high-temperature to derive synthetic gas (rich in CH_4) from which renewable hydrogen is derived. The technology is thermo-chemical, and uses heat energy from the process to power the process.

Hydrogen from waste (*H2 from W*):

On March 31, 2021 Pure Hydrogen and Wildfire Energy announced the development of a project south of Brisbane, Queensland, Australia. The partnering arrangement involves production and distribution of renewable hydrogen.

The renewable hydrogen will be derived using the Wildfire Energy technology: Moving Injection Horizontal Gasification (***MIHG***). Waste feedstock is loaded into the *MIHG* reactor to derive synthetic gas (rich in CH_4), the syngas is then reformed and scrubbed to produce renewable hydrogen. Pure Hydrogen is to distribute the renewable hydrogen from the point of production to the point of use.

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[1] As noted in the second article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series entitled ***What needs to be decarbonised? And what role can hydrogen play?*** the Agriculture, Forestry and Other Land Use (AFOLU) sector is the most challenging sector to decarbonise for many reasons, critically, because the sector is tied inextricably to food production (and existing policy settings including around food security and domestic food production), and attendant land clearance for the purposes of food production (which results in CO_2 emissions, if undertaken using burning, and always results in an overall reduction in the capacity of fauna to absorb CO_2). Also traditional means of food production (crops and livestock, including crops produced to feed livestock), contribute to CH_4 emissions with traditional means of production giving rise to greater GHG emissions (in absolute terms). As population growth continues, and the development of economies affords greater prosperity, it should be expected that the proportion of GHG emissions arising from the AFOLU sector will increase.

1.4 WASTEWATER AND WASTE PROVIDE FEEDSTOCK FOR HYDROGEN PRODUCTION:

While decarbonisation of energy extraction, production and use has been the focus in GHG emission reduction:

- the *AFOLU* and Waste sectors together account for between 21.5% and 24% of anthropogenic global GHG emissions arising annually; and
- the Waste sector alone is responsible for between 3.2% and 3.5% of anthropogenic GHG emissions arising annually, (1.9% to 2.2% landfill and 1.3% to 1.5% wastewater).

The maximisation of the recovery and collection of waste from *AFOLU* activities and the Waste sector, including the organic fraction from municipal solid waste, will allow the maximisation of the production of hydrogen from waste, and diversion of the organic waste fraction from landfill and avoid the decomposition of waste in landfill.

If wastewater or any organic fraction of the waste stream is used as feedstock to derive or to produce hydrogen the GHGs that otherwise arise from the processing and treatment of that wastewater and waste will be avoided or reduced, and the GHGs arising from the decomposition of that wastewater residue or that waste in landfill (or in situ uncollected or burned in situ) will be avoided or reduced.

As such, while it is not possible to decarbonise *AFOLU* activities and the Waste sector through transition in the source and use of energy carrier (other than at the margin in the technologies used by vehicles), it is possible to reduce GHG emissions arising by the use of waste arising from these activities and the Waste sector to derive hydrogen as an energy carrier so as to displace the use of fossil fuels.

1.5 HYDROGEN DERIVED AND PRODUCED FROM WASTE:

It is important to note that the technology exists to avoid GHG emissions arising from wastewater and waste, the challenge is the development of wastewater and waste management systems that maximise collection of wastewater and waste and treat them before the organic fraction decomposes or, more realistically, so as to get "ahead of" the decomposition of the organic fraction. Note that the GHG emission figures detailed in **Section 1.4** do not include GHG emissions arising from other processing and treatment of waste, including thermal treatment of waste[2].

The production of renewable hydrogen is a function of the use of established technologies to derive CH_4-rich synthetic gas from wastewater and waste. This contrasts with the production of Blue Hydrogen and Green Hydrogen. The former is a function of the cost of carbon capture and storage (***CCS***) or carbon capture, use and storage[3] (***CCUS***), the latter is a function of renewable energy costs and the scale, efficiency and utilisation of electrolysers.

1.6 ORIGIN OF NET-ZERO GHG EMISSIONS:

(a) Possible sources of feedstock for hydrogen production from waste:

It will be apparent that if the organic material that would otherwise be landfilled (both dry and wet organics) or, in the case of wastewater, liquid waste being treated to derive grey or potable water or disposed of by some other means, is to be used as feedstock to derive or to produce hydrogen, that feedstock is sourced from material that on processing

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[2] These issues are considered in chapters of the ***Ashurst Waste Compendium***. In Q3 of 2021, a further article will be published (in Ashurst's InfraRead publication), amongst other things, detailing how to maximise capture and collection of waste for processing and treatment.

[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.

and treatment will yield hydrogen and GHG emissions. The use of any feedstock derived from any carbon source, will give rise to carbon dioxide (**CO_2**) and carbon monoxide (**CO**) emissions on the derivation or production of biogas and synthetic gas from which hydrogen is derived.

From a policy perspective, while CO_2 and CO will not preclude hydrogen derived from wastewater or the organic fraction of waste from being regarded as renewable hydrogen, the source of energy to provide electrical energy and heat for use in the applicable technology and the capture of CO_2 and CO will however colour how the renewable hydrogen can be characterised, including the colour used to describe that hydrogen.

(b) Further background on waste arising:

By way of further background, the organic fraction in municipal solid waste has different characteristics, including organics having a higher water content by mass decomposing at a higher rate than dry or drier organics. The characteristic of the waste will tend to determine the most appropriate technology to be used, which may not necessarily include use of technology to derive or to produce hydrogen.

Municipal solid waste is not the only source of organic matter, other sources include: biomass, typically, arising as residue from agricultural (***Agriculture and Farming Waste***) and forestry (***Forestry Waste***) activities and commercial / industrial wastewater, typically arising from animal slaughter, food preparation and food waste (***Food Cycle Waste*** and ***Food Organics***). Also Events Waste and Green Waste (including Garden and Parks Waste) may arise.

Chapters 5, **6** and **7** in the ***Ashurst Waste Compendium*** detail each waste stream containing an organic fraction, and other processing and treatment technologies that may use the organic fraction in that waste stream as feedstock.

(c) Other sources of feedstock:

In many jurisdictions, certain streams, most typically, commercial and industrial (***C&I***) waste and construction and demolition (***C&D***), waste are recovered and collected separately from municipal solid waste and other waste streams. To the extent that *C&I* and *C&D* waste contain an organic fraction, that fraction tends to be dry, or drier than the organic fraction in the municipal solid waste and other waste streams.

Some of *C&I* and *C&D* waste may be processed and sorted to derive fuels that overtime may be displaced by hydrogen derived or produced from waste – for, example, *C&I* waste can be used to derive high calorific value solid fuel energy carriers[4] that burn at high-heat temperatures and that can be used in cement kilns to produce clinker[5].

(d) Hydrogen production is not the only use for waste:

It is possible to process and to treat waste streams in a number of ways, including to produce electrical energy or heat energy, or both, using a waste to energy technology: effectively, the waste itself is an energy carrier. (**Chapter 2** of the ***Ashurst Waste Compendium*** details the principal waste-to-energy technologies used to derive electrical energy or heat, or both, from the thermal treatment of waste.)

Table 1 provides a summary of technologies (other than waste to energy) that may be used to process and to treat other waste streams that may contain an organic fraction (although obviously **E-Waste** or **electronic waste** does not have an organic fraction).

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[4] These high calorific value solid fuels include the following:

High Calorific Value Solid Fuels derived from waste (FfW)	**PEF**	Processed Engineered Fuel
	RDF	Refuse Derived Fuel
	SRF	Solid Recovered Fuel or Specified Recovered Fuel
	Bagasse	biomass derived or produced from the dry organic residue from agricultural, farming or forestry or land use

[5] As noted in the second article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series entitled ***What needs to be decarbonised? And what role can hydrogen play?*** hydrogen can be used to decarbonise the production of clinker by the displacement of any fossil fuel or other carbon intensive fuel used to achieve high-heat temperature for the production of clinker.

Table 1:

Waste Stream	**Aerobic Digestion: Derives/ Produces:** Compost/ RDF	**Anaerobic Digestion: Derives/ Produces:** Biogas/ Bio-fertilizer	**FOGO** – Compost/ RDF	**MBT** – Compost, Mixed Organics/ RDF	**MT** – Compost, Mixed Organics/ RDF	**Dry MRF: Devires/ Produces: Recyclables**	**Dirty/Wet MRF: Derives/ Produces:**	**C&I Facility PEF/ SRF**	**C&D Facility PEF/ SRF**
MSW	✕	✕	✕	✓	✓	✓✕	✓	✕	✕
C&I Waste	✕	✕	✕	✓	✓	✕	✓	✓	✕
C&D Waste	✕	✕	✕	✕	✕	✕	✕	✕	✓
Events Waste	✕	✕	✕	✓	✓	✓	✓	✓	✕
E-Waste	✕	✕	✕	✕	✕	✕	✕	✕	✕
Food Cycle Waste	✓	✓	✓	✓	✓	✕	✕	✕	✕
Food Organics	✓	✓	✓	✓	✓	✕	✕	✕	✕
Green Waste	✓	✓✕	✓	✓	✓	✓✕	✕	✕	✕
Agri and Farming	✓✕	✓✕	✓✕	✓	✓	✕	✕	✕	✕
Forestry	✓	✓✕	✓	✓	✓	✕	✕	✕	✕

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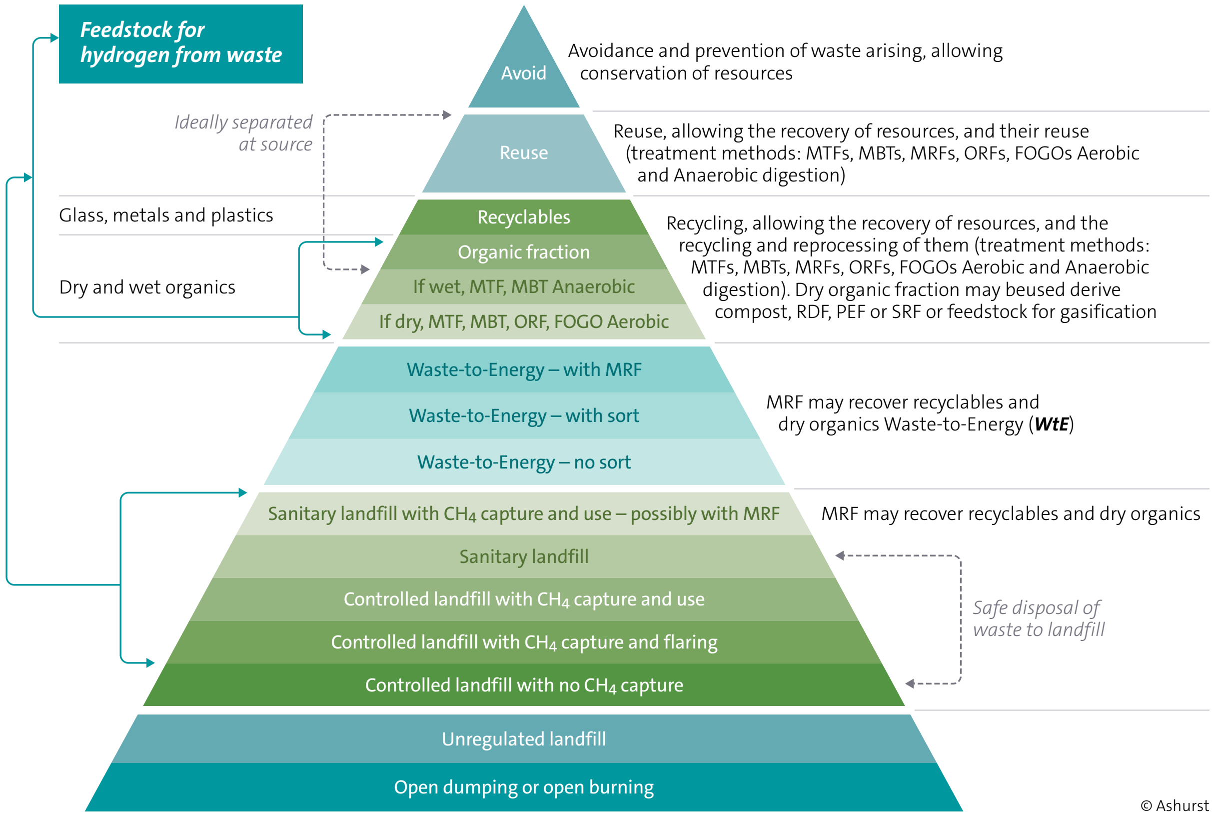
(e) The Waste Management Hierarchy:

Figure 1 outlines the source of organic fraction for hydrogen production from waste in the context of the Waste Management Hierachy.

Figure 1:



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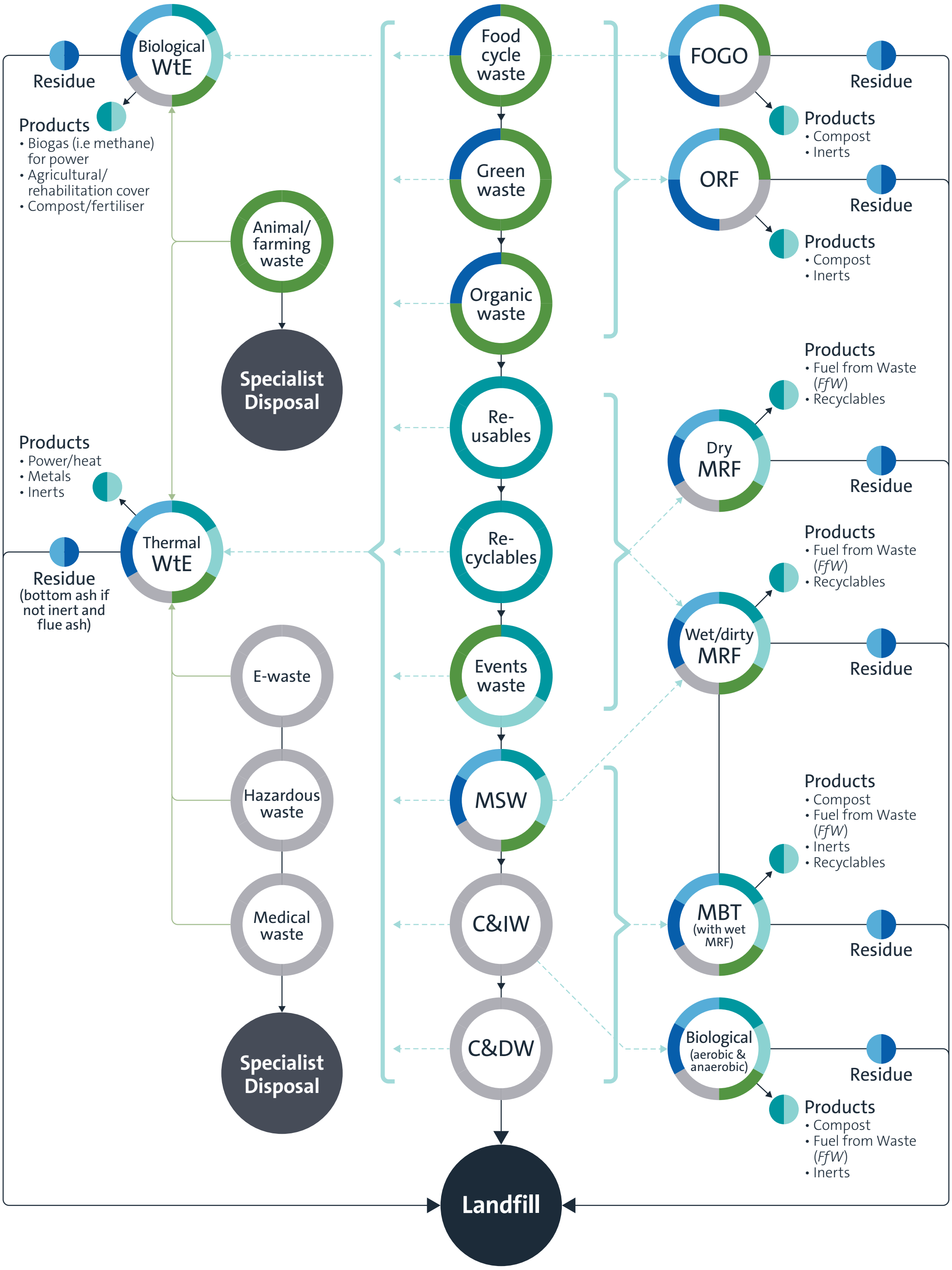
(f) Summary of waste streams and processing and treatment technologies, other than to derive hydrogen:

Figure 2 outlines the types of waste that arise (including those with an organic fraction) and how they may be processed and treated other than to derive or to produce hydrogen.

Figure 2:



WtE	Waste-to-Energy plant
MBT	Mechanical and Biological Treatment Facility
MRF	Material Recovery Facility
ORF	Organic Recovery Facility
C&IW	Commercial and Industrial Waste
C&DW	Construction and Demolition Waste
FOGO	Food organic / Garden organic facility

🟩 Reusable
🟩 Recyclable
🟩 Organic fraction
⬜ Other
🟦 Contamination
🟦 Incompatibles
--→ Flow of waste
—→ Conditional/optimal flow of waste

1.7 FOR MUNICIPAL SOLID WASTE TWO DISTINCT SET OF POLICY SETTINGS ARE REQUIRED:

(a) GHG arising from waste in landfill:

In the absence of policy settings that mandate or support recovery of GHG emissions arising from landfill, GHG emissions will continue to arise from organic matter landfilled in existing landfills: as organic matter decomposes, in particular, putrescible organic matter, landfill gas arises (***LFG***), containing both CO_2 and CH_4 (and residual gases and contaminants). Both CO_2 and CH_4 are GHGs. Landfills are CH_4 hotspots, especially in the countries with waste management systems that continue to be developed.

There are policy settings that could be introduced to manage or to support the capture and collection of *LFG*. The challenge with CH_4 capture and collection as a *LFG* is that it is relatively inefficient, especially when installed in an established landfill. If *LFG* could be captured and collected efficiently from landfill, it would not however recover all of the *LFG* arising.

If a technology and process were to be devised that allowed the effective simultaneous capture and collection of CH_4 and the mining of waste from waste already in landfill, and subsequent treatment of that mined waste to derive synthetic gas, this would achieve a reduction of *LFG* (and as such GHGs) arising, and allow the production of hydrogen.

In countries with more developed waste management systems, the approach has been to retire and to cap existing landfills, to cease to develop new landfills and instead to develop waste processing and treatment facilities (so called alternative waste treatment (***AWT***) facilities), including waste-to-energy, mechanical and biological treatment, mechanical treatment and biological (including anaerobic) processing and treatment. (See **Chapters 1** to **4** of the ***Ashurst Waste Compendium***.) The use of these technologies still gives rise to GHG emissions.

(b) GHG that will arise if waste is landfilled:

In respect of the organic fraction in the waste stream that arises in the future, maximisation of recovery and collection of organic waste needs to occur. The waste recovered and collected then needs to be processed and treated in a way that avoids or minimises the release of GHG emissions from the point at which the waste arises to the point at which it is processed, including to produce hydrogen. It is important to note that this does not mean that the most appropriate outcome will be to derive or to produce hydrogen from waste in all circumstances.

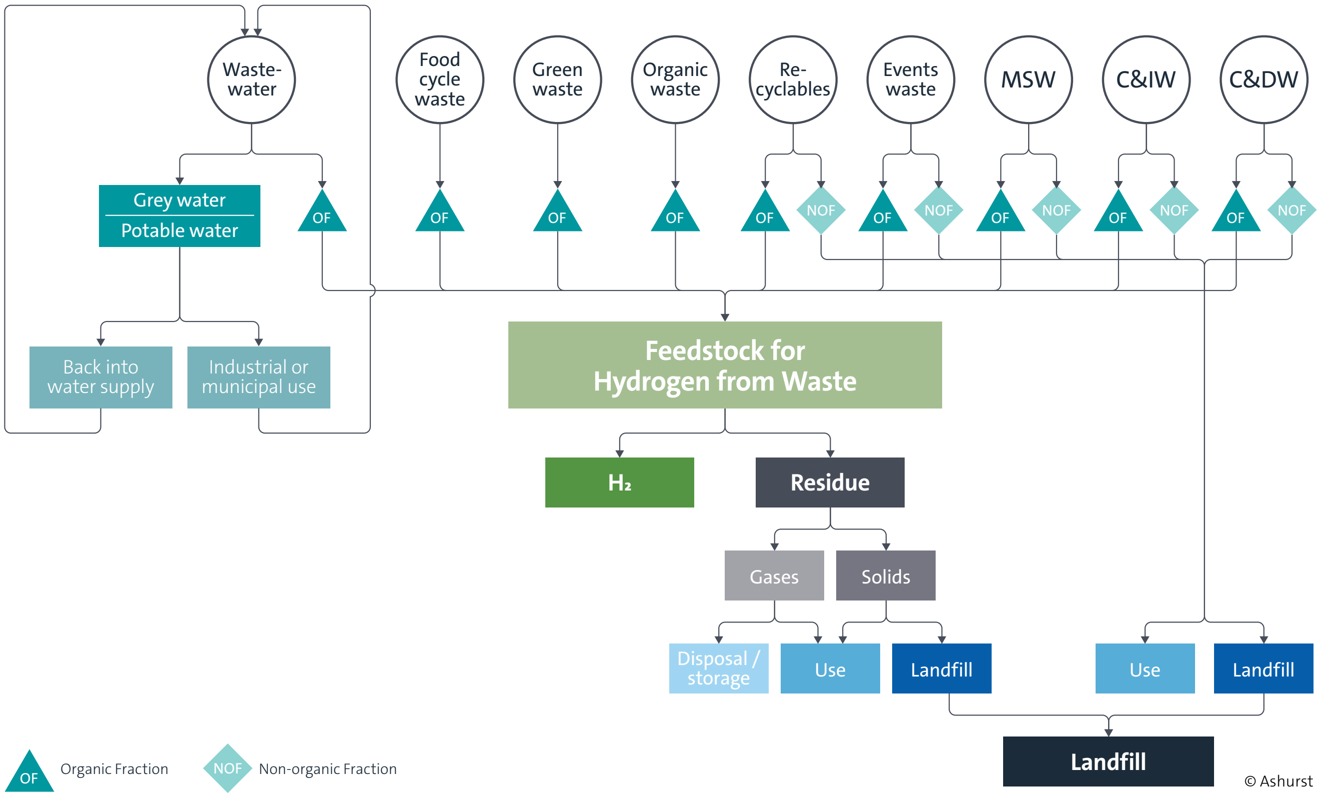
If municipal solid waste or residual material arising from the processing and treatment of municipal solid waste, or other organic material that is putrescible, is landfilled it will decompose and give rise to *LFG*.

As noted in **Section 1.7(a)**, in countries with developed waste management systems these policy settings are in place, and have been used for many years. The success of these policy settings is relative to the use of landfill: GHG emissions still arise, but positive benefits for the environment are achieved, including the pasteurisation of organic matter (diverted from landfill) for other purposes (including in *AFOLU*, including rehabilitaiton), the recovery of recyclable materials (including cardboard and paper, glass, metals, and plastics), in some instances, to derive high or higher net-calorific fuels to provide renewable fuel for high-heat temperature industrial processes (including for the purposes of the production of clinker as part of cement production) or as fuel for use in waste-to-energy facilities.

(c) Summary of waste streams and hydrogen from waste:

Figure 3 outlines the sources of organic fraction from wastewater and waste that may be used as feedstock to derive or to produce hydrogen from waste.

Figure 3:



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1.8 FOR WASTEWATER THERE IS ONE POLICY SETTING AND LIKELY TWO TECHNOLOGIES:

(a) Anaerobic Technologies:

If cost was not a relevant consideration (or stated another way, if money was no object), the policy settings for wastewater would be straight-forward: all wastewater would be subject to anaerobic digestion to derive CO_2 and CH_4 arising from the wastewater, which would derive biogas, and oxidise it, or that biogas would be reformed and scrubbed to produce biomethane for pipeline gas or that biogas, as synthetic gas, would be reformed to produce hydrogen, in each instance capturing and storing CO_2.

All anaerobic technologies (including co-digestion[6]) require feedstock that is homogenous. If feedstock from mixed sources is used it is likely to require blending / mulching. For anaerobic digestion technologies, cost has always been the most relevant consideration (or stated another way, affordability and value for money are the key considerations), as such, at least for the time being, biological technologies tend to be more expensive. Thermo-chemical technologies are less sensitive to the characteristics of the wastewater (or any solid waste with which wastewater is mixed to achieve co-digestion) used as feedstock.

(b) Thermo-chemical Technologies:

As noted in **Narrative Boxes 1** and **3** and in **Section 1.10**, thermo-chemical technologies exist (used to achieve gasification or pyrolysis) that can use both wastewater sludge and other solid waste as feedstock to derive synthetic gas from which hydrogen may be derived.

Narrative Boxes 3 and **4** provide a high-level summary of thermo-chemical technologies and the terminology applicable to them.

(c) What a difference a year makes! What has changed?

What has changed in the last 12 to 15 months or so is the recognition that wastewater and waste and biogas / synthetic gas are suitable feedstock for the derivation / production of renewable hydrogen, and there is a "line of sight" to market for that renewable hydrogen.

As such anaerobic and thermo-chemical technologies now compete on the basis of the possible production of renewable hydrogen.

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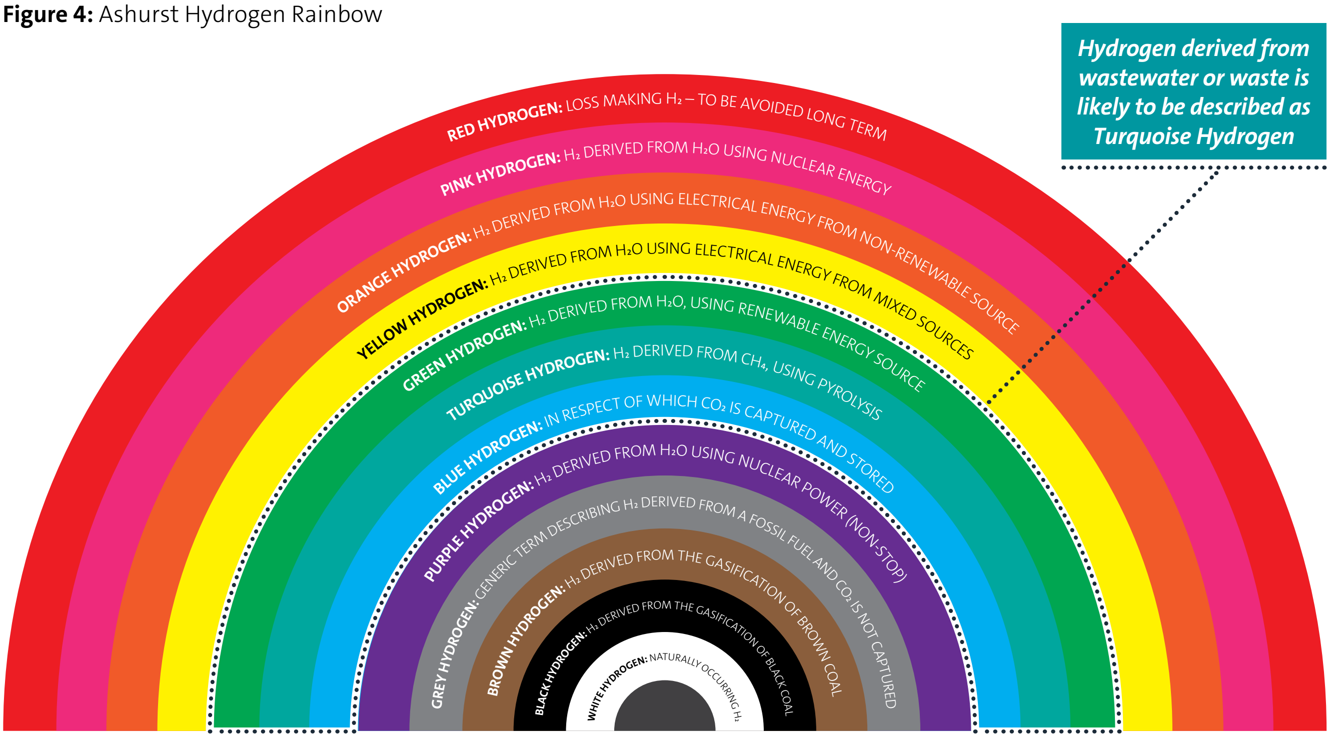
[6] It is possible to use both wastewater and waste as a feedstock using a co-digestion technology.

1.9 ASHURST HYDROGEN RAINBOW

Figure 4: Ashurst Hydrogen Rainbow



Definitions

Red Hydrogen	A reference to the fact that "early doors" hydrogen projects tend to be loss making
Pink Hydrogen	H_2 produced by splitting of H_2O using nuclear power as the electrical energy source
Orange Hydrogen	H_2 produced by splitting of H_2O using electrical energy from a non-renewable source
Yellow Hydrogen	H_2 produced by splitting of H_2O using electrical energy from mixed energy sources
Green Hydrogen	H_2 produced by splitting of H_2O using electrical energy from renewable electrical energy (REE), no GHG emissions on production or oxidation (use)
Turquoise Hydrogen	H_2 produced from thermal splitting of natural gas (form of pyrolysis) to produce "carbon black" (including CO_2), giving rise to GHG on production and oxidation (use)
Blue Hydrogen	Grey or Brown (or Black) hydrogen but CO_2 captured permanently using CCS / CCUS: logically, the means of production does not matter as long as CO_2 captured and stored
Purple Hydrogen	H_2 produced from steam arising from nuclear power generation
Grey Hydrogen	H_2 produced with fossil fuel as the feedstock, including from natural gas, coal and oil (but most often and typically natural gas), using established processes
Brown (or Black) Hydrogen	H_2 produced from coal
White Hydrogen	H_2 arising naturally on earth
Renewable Hydrogen	H_2 produced without any fossil fuel, but may not be GHG free if any carbon feedstock is used (biomass / biofuel)
Clean Hydrogen	Blue Hydrogen, Green Hydrogen and Turquoise Hydrogen, and possibly including Low-Carbon / Renewable-Carbon Hydrogen, and including any hydrogen produced using a bio-logical process in which GHG is captured
Cleaner Hydrogen and Nearly Clean	Blue Hydrogen produced using renewable energy and hydrogen produced using nuclear steam or nuclear power
Blue Ammonia	NH_3 produced from Blue Hydrogen, CO_2 arising captured permanently using CCS / CCUS, and with the Blue Hydrogen combined with N extracted from any source, and on oxidation (use), NO_X arise
Green Ammonia	NH_3 produced from the combination of Green Hydrogen and N extracted from the air using electrical energy from a REE, the process requiring high temperature, and on oxidation (use) NO_X emissions arise
Turquoise Ammonia	NH_3 produced from the combination of Turquoise Hydrogen and N extracted from any source using any energy source, the process requiring high temperature, and on oxidation (use), NO_X arise

1.10 WHAT COLOUR IS THE HYDROGEN DERIVED FROM WASTEWATER AND WASTE

The Ashurst Global Towards Net-Zero Emissions team has previously hazarded the view that there is a space in the Ashurst Hydrogen Rainbow toward light turquoise for hydrogen produced using gasification technologies, and possibly a lighter shade of turquoise if hydrogen is derived from renewable sources using a pyrolysis technology with the carbon arising (including CO and CO_2) captured in solid form. If renewable energy is used to provide any electrical energy required to derive or to produce the hydrogen there is an argument for a very light shade of turquoise.

In the ordinary course, Turquoise Hydrogen is hydrogen that is derived from CH_4 in the form of natural gas using pyrolysis and renewable energy: see the first article in ***The Shift to Hydrogen (S2H2): Elemental Change*** series, entitled ***Why H2? Why Now?***

If the CH_4 derived from wastewater or waste as a synthetic gas from an entirely renewable source, i.e., is derived from a waste stream that does not contain any hydrocarbon material (including any plastic) or other material that cannot be regrown or otherwise renewed, the hydrogen is more than likely to be categorised as renewable hydrogen.

Whether or not hydrogen derived from wastewater or waste is clean hydrogen will depend on the GHG emissions intensity of the technology used to derive the renewable hydrogen: Blue, Green and Turquoise Hydrogen are all regarded as clean hydrogen.

As a general statement, thermo-chemical technology involves an exothermic reaction to fossil fuel (coal, natural gas or gas) or organic material, to produce hydrogen, but which does not result in oxidation / combustion of the feedstock. The colour of the hydrogen produced will depend on the feedstock used, the source of energy used to fire or to power the process and the GHG intensity of the production of that hydrogen.

As will be apparent from this feature so far, the hydrogen produced using wastewater or waste is renewable hydrogen.

Narrative Box 3: Generic Thermo-chemical technologies and residual material arising

Gasification	thermal treatment within 420-700 degrees Celsius range achieving degradation
Pyrolysis	thermal treatment with 700-900 degrees Celsius range achieving disintegration
Plasma	thermal treatment at around 1,500 degrees Celsius to achieve molecular disassociation
Gasification Tar	residual material after gasification of waste, which may have uses in road construction
Pyrolysis Bio-char	residual material after pyrolysis of waste, may be used to rehabilitate soils or as fertiliser
Plasma Slag	residual material after plasma treatment of waste, may be used as raw material for building materials

Narrative Box 4: Terminology relating to Electro and Thermo-Chemical Technologies

Thermo-Chemical hydrogen production process (*THPP*)	application of heat to fossil fuel (coal, natural gas or oil or organic material to produce hydrogen)
Steam Methane Reform (*SMR*) to derive hydrogen	a *THPP* using steam to derive CO and CO_2 and hydrogen from natural gas feedstock
partial oxidation to derive hydrogen	a thermal process using heat and controlled / limited oxygen to derive CO and hydrogen
Water Shift Reaction (*WSR*)	a thermal process using heat (steam) to separate CO and H_2 if *THPP* technology is used
Electro-chemical hydrogen production	application of electrolysis (electrical current) technology to H_2O to split into H_2 & O, incl. alkaline electrolysis (***AE***), polymer electrolyte membrane or proton exchange membrane (***PEM***) and solid oxide electrolyser cell (***SOEC***)
Gasification to derive hydrogen	a *THPP* using heat and no, controlled or limited oxygen to derive CO and CO_2 and hydrogen from coal (brown or black) or organic fraction of waste
syngas or **synthetic gas**	a mixture of gases derived from *THPP*: • H_2 and CO if coal gasified to produce H_2; • CH_4 if organic fraction of waste is gasified to produce H_2; and • H_2 and CO and CO_2 if plastic alone is gasified to produce H_2.

Section 2 – From Wastewater and Waste to Energy Carrier to Oxidation

2.1 BACKGROUND ON HYDROGEN:

In continuing progress towards net-zero emissions, hydrogen, as an energy carrier[7], has emerged (or to some, "re-emerged"[8]), as an energy carrier to displace energy carriers derived from fossil fuels. Hydrogen as an energy carrier (or energy vector) is the focus of hydrogen in this *H24I* feature. Hydrogen as an energy carrier can be stored, and future Ashurst publications will cover storage, as part of a *S2H2* article on CCS / CCUS and hydrogen storage.

Displacement of fossil fuels has two elements: production of an energy carrier and the use (or oxidation) of that energy carrier. While the use of hydrogen (whatever its colour) is GHG free[9], the production of hydrogen may not be. For hydrogen to be GHG free, or carbon neutral, from source of feedstock to point of ultimate use, it needs to be Green Hydrogen, or Blue Hydrogen or Turquoise Hydrogen with all of the CO_2 and CO captured and stored permanently.

2.2 ENERGY CARRIERS COMPARED: PRODUCTION OF HYDROGEN FOR USE AS A FUEL:

Given that hydrogen can be used to displace most fossil fuel derived energy carriers, it is helpful to understand how hydrogen compares to those energy carriers. **Table 2** outlines the comparative heating values of hydrogen compared to CH_4, natural gas, motor spirit, diesel, and crude oil. As will be apparent, in terms of useable energy in each fuel, hydrogen provides greater heating value by mass than fuels derived from fossil fuels.

Table 2: Comparison of Heating Values by Mass and GHG emissions

Fuel	**Heating value MJ/kg (HHV[10] and LHV[11])**		**Heating value Btu/lb (HHV and LHV)**		**Estimated CO_2 emissions arising on combustion of fuel, i.e., final use**
	HHV	**LHV**	**HHV**	**LHV**	
Hydrogen (H_2)	142	120	61,125	51,630	H_2O in warm air (warm vapour)
Methane (CH_4)	55	50	23,811	21,433	53 kg per GJ or 117 lbs per MMBtu
Natural gas	51	47	22,450	20,250	55 kg per GJ or 120 lbs per MMBtu
Motor spirit (gasoline/petrol)	46.5	43.5	20,000	18,700	70 kg per GJ or 157 lbs per MMBtu
Diesel fuel (inc. bio-diesel)	45.7	42.7	19,675	18,400	74 kg per GJ to 161 lbs per MMBtu
Crude Oil	45.5	43.5	19,580	18,350	73 kg per GJ or 159 lbs per MMBtu

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[7] H_2 is the most common element in the universe (it is estimated that 75% of the elemental mass of the universe is H_2). H_2 needs to be captured by gravity to provide the mass to allow to nuclear fusion in stars or to form compounds with other elements.

[8] Some may recall the term hydrogen economy coined in the early to mid-2000's, and that it disappeared along with "dot com" boom. In the context of the abatement of GHG emissions, the "hydrogen economy" was seen as an ideal outcome. The impetus at that time was to produce a cheap fuel.

[9] Strictly, this is not the case: on combustion, H_2 oxidises in the presence of O to produce water vapour, and water vapour is a GHG. Water vapour is not however considered to be an anthropogenic GHG that has contributed to climate change because its presence in the atmosphere has not been subject to increase as a result of human activity.

[10] **Higher Heating Value** (or Gross Calorific Value or Gross Heating Value) of an energy carrier is the quantity of heat energy derived from a stated mass of the gas or liquid on its combustion, including the latent heat of vaporization of H_2O.

[11] **Lower Heating Value** (or Net Calorific Value or Net Calorific Value) of an energy carrier is the quantity of heat energy derived from a stated mass of the gas or liquid on its combustion, not including the that latent heat of vaporisation of H_2O.

2.3 USEABLE ENERGY PER KG:

The key measure used in respect of hydrogen is **kWh per kilogram**: 1 kg of hydrogen comprises 33.3 kWh of useable energy, 1 kg of motor spirit comprises 12 kWh of useable energy, and 1 kg of natural gas comprises 13 kWh of useable energy. By mass, hydrogen has more than 2.7 the useable energy of an equivalent mass of motor spirit, and more than 2.5 the useable energy of an equivalent mass of natural gas.

2.4 DISPLACING FOSSIL FUELS:

For hydrogen to displace energy carriers produced from fossil fuels, which it could do in theory, it will be necessary for the production costs of hydrogen to be competitive with motor spirit and natural gas. At the moment, they are not competitive with the cost of motor spirit and natural gas at either the point of production or point of use. At point of production, CCS / CCUS costs increase production costs for Blue Hydrogen and renewable electrical energy and electrolyser costs give rise to higher costs of production for Green Hydrogen. From the point of production to the point of use, new capital costs have to be incurred, and amortised, in respect of equipment, transportation vehicles and vessels, and infrastructure (including storage, transportation and hydrogen refuelling infrastructure). These increase the costs of delivered hydrogen to the point of use.

2.5 DELIVERY AT POINT OF PRODUCTION:

The headlines from *Hyzon* and *Raven SR* are all about the production costs. If the headline low estimated costs are achieved, the production of hydrogen from the organic fraction in waste will change the dynamics, allowing the use of hydrogen as a energy carrier to compete with motor spirit and natural gas, and BEVs. If the hydrogen produced is then stored at the point of production, and the users of the hydrogen refuel at the point of production, the assumed dynamics of hydrogen, as an energy carrier, will be reset for both production and delivery.

Table 3: Principal current technology used to produce hydrogen from fossil fuels

Natural Gas to produce Grey Hydrogen	
• **Steam Methane Reform (SMR):** Steam (at 700/1000°C) at pressure (at 1 bar) is used to react with natural gas, in the presence of a catalyst (usually nickel) to derive hydrogen, carbon monoxide (CO) and carbon dioxide (CO_2) • **Water Shift Reaction (WSR):** CO and H_2O (as steam), in the presence of a catalyst (typically, iron or nickel) to derive further hydrogen, and CO_2 • **Pressure-Swing Absorption:** H_2 derived from SMR and WSR purified to produce pure hydrogen	$CH_4 + H_2O$ (as steam) $= CO + 3\ H_2$ $CO + H_2O$ (as steam) $= CO_2 + H_2$ (heat) CO_2 removal $= H_2$
• **Partial Oxidation:** Natural gas (or other hydrocarbon) at pressure is partially oxidised (in controlled oxygen environment) reacting to derive CO, hydrogen and CO_2 (and nitrogen if controlled air, not pure oxygen, is used) • **Water Shift Reaction:** CO and H_2O (as steam), in the presence of a catalyst (typically, iron or nickel) to derive further hydrogen, and CO_2	CH_4 + limited $O_2 = CO + H_2$ (heat) $CO + H_2O$ (as steam) $= CO_2 + H_2$ (heat)
Coal (brown and black) – to produce Brown or Black Hydrogen	
• **Gasification of coal:** Gasification (at 700 to 1000°C) of coal in a pressurized gasifier (i.e., a controlled oxygen environment) to derive gases, principally CO and H, and CO_2, in the form of synthetic gaseous mix (syngas). (This is a form of partial oxidation, used to derive coke.) • **Removal of impurities from syngas** • **Water Shift Reaction:** CO and H_2O (as steam), in the presence of a catalyst (typically, iron or nickel) to derive further hydrogen, and CO_2 • **Hydrogen and CO_2 separation:** if there is to be CCS / CCUS, the CO is dehydrated, and compressed to produce liquefied CO_2 at each stage of the process	CH (coal) + limited $O_2 = H_2O = CO + CO_2$ and H_2 $CO + H_2O$ (as steam) $= CO_2 + H_2$ (heat)
Blue Hydrogen from Brown or Black Hydrogen using Carbon Capture and Storage (CCS / CCUS)	
• Hydrogen and CO_2 separation, as part of production of Brown or Black Hydrogen • CO_2 prepared from injection into storage infrastructure (compressed or liquefied) and intermediate storage and carriage • CO_2 injection into storage infrastructure	It is important to note that while the technology to achieve CCS / CCUS exists, the application of the technology in global terms has been limited. As such, in addition to CCS / CCUS it is important to consider other uses for CO_2 derived from H_2 production

2.6 CURRENT PRODUCTION OF HYDROGEN:

As a generalisation, the technologies used to derive or to produce renewable energy from waste use an element, or a combination of the elements, of existing technologies (outlined in **Table 3**).

These technologies are different from the hydrogen technologies used to produce Green Hydrogen: Green Hydrogen is produced using water which contains no carbon, which is split into H_2 and O using an electrolyser. The electrolyser technologies may be categorised as liquid electrolyser (aka alkaline electrolysers), polymer electrolyte membrane or proton exchange membrane (PEM) and solid oxide electrolyser cell (SOEC) technology, with the electrolyser deriving the electrical energy required for electrolysis from a renewable electrical energy source.

2.7 HYDROGEN DERIVED AND PRODUCED FROM WASTE:

(a) Hydrogen from the organic fraction of waste:

As outlined above, there are a number of technologies that are variations on gasification and pyrolysis technologies. These technologies apply different high-heat temperature treatments to derive synthetic gas: essentially CH_4-rich synthetic gas is fractionalised to drive CO, CO_2 and H_2. Typically, H_2 molecules will comprise about 50% by volume of the derived gases. The derived gases are scrubbed and H_2 molecules are recovered. To those used to working on other waste projects, "wetter is better" because it indicates the presence of water (H_2O), and the presence of H_2O will increase the yield of H_2 molecules.

(b) Hydrogen from plastic:

As would be expected, it is possible to produce hydrogen from plastic (polymers): polymers are derived from hydrocarbons. There are gasification and plasma technologies that allow monomers, including H_2 molecules, to be derived from polymers. Deriving H_2 molecules from polymers may be regarded as another option for hydrogen production, but, (and it is a big but), the mass of polymers arising as plastic waste each year, and the percentage of those plastics that is collected means that deriving hydrogen from plastic as a separate feedstock (as distinct from unsegregated plastics as part of the municipal solid waste stream or as part of the commercial and industrial waste stream) while feasible seems less likely to achieve the scale in hydrogen production.

Section 3 – Conclusion

The momentum that has been achieved in the shift to hydrogen (as part of the broader progress towards net-zero GHG emissions) across a number of sectors in many countries over the last 12 months has been marked. The momentum appears to be increasing. While the momentum in the wastewater and waste sector has not been as marked as in other sectors, we expect a material increase in the momentum. This is not going to involve a straight and narrow path, but nor is it likely to involve a crooked an precipitous path – there is a clear path to the production of renewable hydrogen from wastewater and waste.

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