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Exhibit No.: UCAN-08

Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, (2023).

Hydrogen Ladder Version 5.0

So my lovelies, here it is: Version 5.0 of the Hydrogen Ladder!



MICHAEL LIEBREICH

OCT 20, 2023



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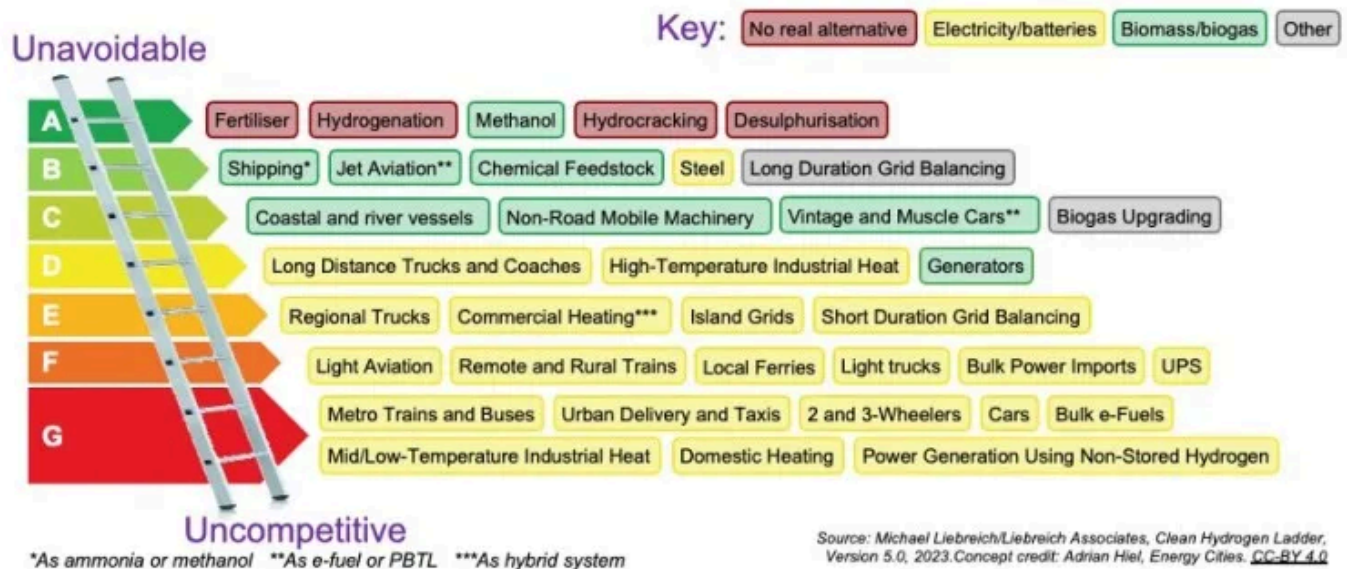


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Hydrogen Ladder 5.0

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This is the **first major update** since Version 4.1 in August 2021. I have been meaning to produce a new version for some time, but frankly I have been amazed at how well 4.1 held up. My **thanks** to everyone who has used the Ladder, amplified it, and given me feedback. This is a **collective effort**, and I hope Version 5.0 stimulates as much discussion as Version 4.1.

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Overview

The Hydrogen Ladder is my attempt to synthesise *all* the information known to me about *all* the factors driving technology uptake across *all* sectors of the economy in *all* countries of the world. Not ambitious at all!

What the Hydrogen Ladder is designed to do is to show how likely it is that any proposed use case ends up being a significant user of hydrogen (perhaps via one of its derivatives) ***in a decade or so, say 2035***. That doesn't mean it's game over, the transition has happened, it just means it is absolutely clear by then that hydrogen is either the answer, or a major answer, to decarbonizing that use case.

In other words, it looks forward to a time after the current firehose of subsidies has subsided to affordable proportions, after there has been enough time for a bit more tweaking of technologies, after the emergence of supply chains, after a bit of familiarity has grown in the project finance sector, and so on.

As for what the rows mean, here's how I think about them:

- A - no alternative (though this does not mean the use case is growing)
- B - decent market share highly likely
- C - some market share likely
- D - small market share plausible
- E - niche market share possible

- F - niche market share in some geographies possible
- G - the Row of Doom

The Hydrogen Ladder is **not all about efficiency**, as its detractors claim. It does not include information about market size. It does not include information about speed of adoption. It does not include information about relative emissions reduction per kg of hydrogen or kWh of electricity. I leave it to others to add that information to the discussion.

Conversely, it does take into account **cost, safety, convenience, critical mineral availability, co-benefits, externalities** like air pollution, **geopolitics, human behaviour** and - underlying it all - **thermodynamics, physics, chemistry, other sciences** and **economics**.

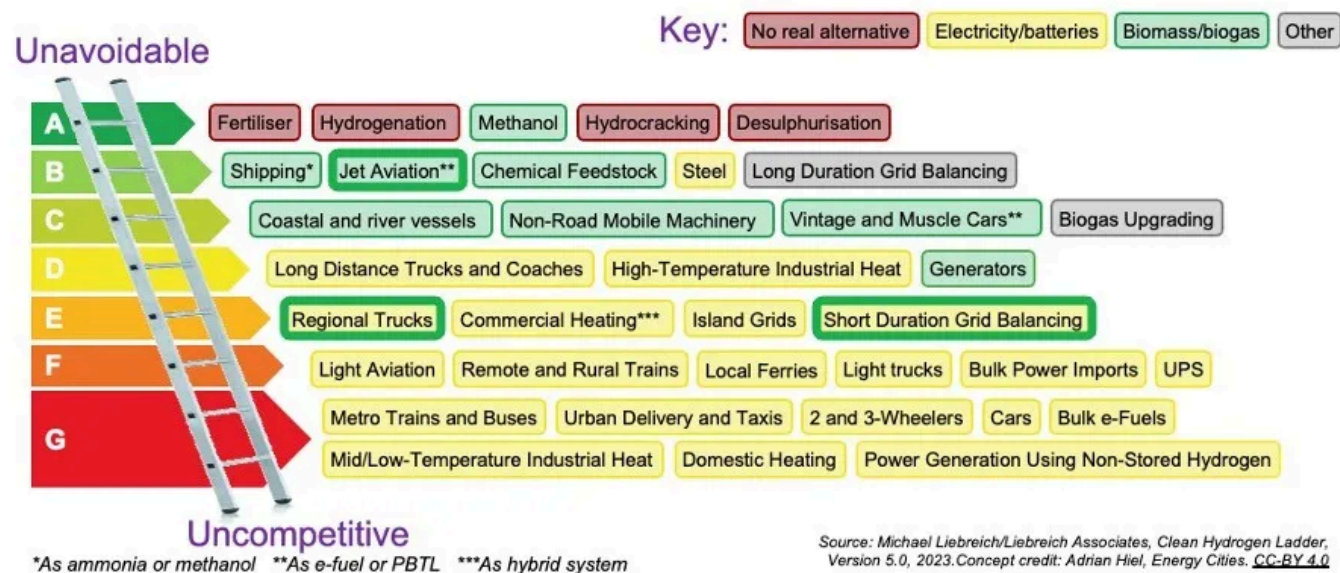
What has changed since Version 4.1? Three use cases have moved up and six have moved down. I have refined the wording for five use cases, combined five others into two, and added four new use cases. Some of these changes have been driven by market developments over the past two years; most of them, however, are the result of my own learning during that time – in particular about industrial and space heating and how hard it is to transport hydrogen – or by the need to clarify wordings or definitions.

The key messages of the Ladder remain unchanged: there are better and worse use cases for hydrogen; in the majority of cases there are cheaper, safer and more convenient zero-carbon alternatives; synergy between use cases (the Hydrogen Economy / Hydrogen Society / Swiss Army Knife view of the world) will not be enough to float all hydrogen boats; and since we should expect clean hydrogen supply to be limited for many decades, we should focus our efforts and public money on use cases on the top rows of the Ladder.

Promotions

Three uses cases have been promoted: **Jet Aviation, Regional Trucks** and **Short Duration Grid Balancing**.

Hydrogen Ladder 5.0 – Promotions (3)



Three promotions since Version 4.1

Aviation used to be split into Long-Haul (formerly Row C), Medium-Haul (formerly Row D), Short-Haul (formerly Row E) and Light (formerly Row F), but that made things too complicated. What has become clear is that anything that currently uses jet fuel is going to continue to do so, hence the newly combined use case **Jet Aviation**.

Although bio-based pathways look like offering the cheapest route to zero-carbon aviation, because of limited feedstock availability there is a very high chance that hydrogen will find some sort of role, hence Jet Aviation is a B. That is a promotion because it's higher even than Long-Haul Aviation was in Version 4.1.

The exact pathway by which hydrogen will find its way into jet fuel could be in the form of a pure e-fuel (i.e. using carbon captured from the air) or, as [Professor Rob Miller and I agreed is more likely when he was my guest on Cleaning Up](#), via Power and Bio to Liquid (PBTL) i.e. using biological carbon combined with green or pink hydrogen.

Anything with a piston currently, plus a whole new slew of VTOLs and STOL aircraft, will go electric, so Light Aviation remains way down the ladder on Row F.

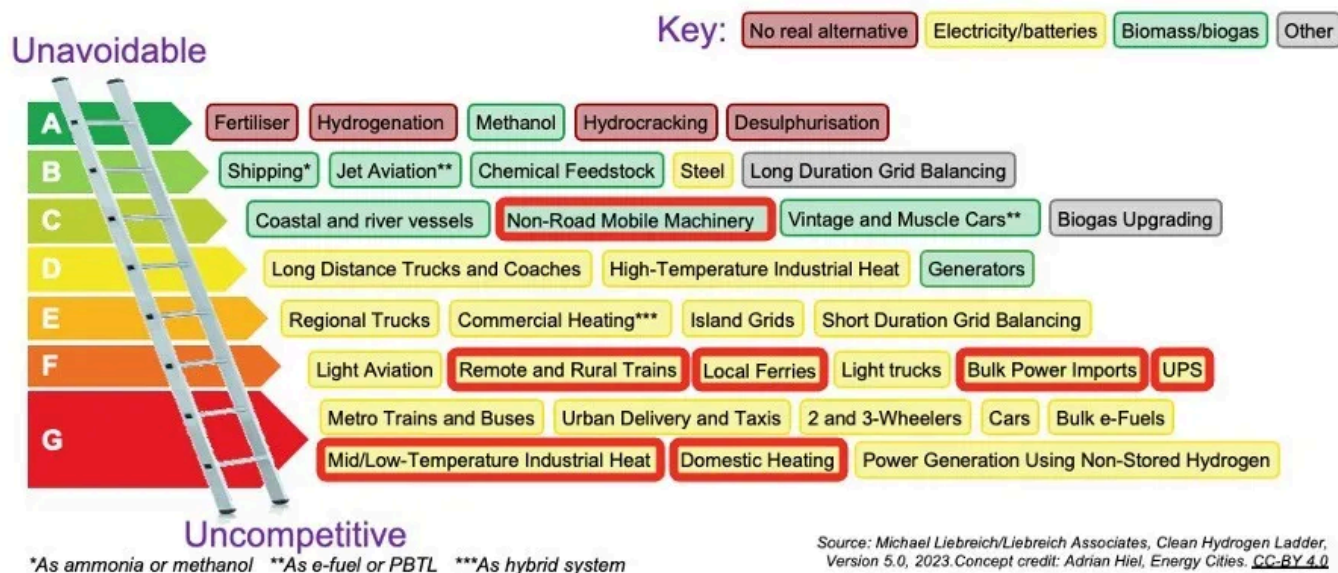
Regional Trucks has been promoted to Row E from Row F, and **Short Duration Grid Balancing** also to Row E from Row G. Both are essentially piggybacking on other use cases higher up the Ladder: if we do see Long-Distance Trucks and Coaches (Row D) using hydrogen, some Regional Trucks might use the same refuelling infrastructure; and if there is Long-Duration Storage using hydrogen or one of its derivatives, we might see the same projects participate to some extent in Short Duration Grid Balancing.

Demotions

Seven use cases have been demoted between Version 4.1 and 5.0: **Non-Road Mobile Machinery**, the **Remote Trains** part of what is now Remote and Rural Trains, **Local Ferries**, **Bulk Power Imports** (formerly Clean Power Imports), **UPS**, **Mid/Low-Temperature Industrial Heat** and **Domestic Heating**.

Hydrogen Ladder 5.0 – Demotions (7)

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Seven demotions since Version 4.1

Non-Road Mobile Machinery is demoted to Row C. I'm sorry, Lord Bamford, I love that you have built an internal combustion engine that runs on hydrogen, but who is going to buy it? It takes 16 to 18 tube trailer deliveries of hydrogen to replace one delivery by diesel tanker, and I just can't get my head around the logistics or safety of

hydrogen-in-a-forest or hydrogen-on-a-construction-site. As for mining, even your friend Andrew Forest's Fortescue Metals Group has embarked on the process of electrifying mining trucks. So I don't rule it out, but I have curbed my enthusiasm.

Remote Trains goes down two to Row E and is combined with Rural Trains. By the time a railway is so remote or rural it can't be electrified, it is such an edge case that the economics of switching it to hydrogen won't make sense either. It is worth noting that India has already electrified over 90% of its broad-gauge routes.

Local Ferries are demoted to Row F – for the same reasons that there will be no Remote and Rural Trains, there will be no local hydrogen ferries.

Uninterruptable Power Supplies (UPS) was on Row E but has been demoted to Row F. Batteries are getting so cheap, and they don't need constant checking, maintenance and refilling, so it's now really hard to see why you go to the brain-ache of a hydrogen UPS. If you need really long-duration UPS, there are new low-cost battery chemistries ideal for 7-14 days, and who knows, one day flow batteries might finally happen.

Bulk Power Imports, formerly Clean Power Imports, moves from Row E to Row F. What we are talking about here is where a country or region with demand for clean power imports it from a country or region with a surplus. In particular I am thinking here of Japan's intention to fire its huge coal fleet with imported ammonia, which it calls "co-firing" even though co-firing is only one step towards the required end point of 100% ammonia.

Over the past two years I have done a LOT of work on the economics of transporting hydrogen and its derivatives, which I summarised in a piece for BloombergNEF entitled [The Unbearable Lightness of Hydrogen](#).

My conclusion is that as long as the source country is within cable and pipeline range – i.e around 5,000 kilometres – then generating a diversified mix of wind and solar power, firming it with a modest amount of batteries, and sticking it in an HVDC cable, easily beats the *full-system* economics of importing power by turning it into hydrogen, putting it in a hydrogen pipeline and then regenerating power.

For distances over 5,000 km, hydrogen can be transported only in the form of a derivative like ammonia, e-methane or e-methanol. Liquid hydrogen in a ship is not going to be a thing because... physics. Here, however, the economics of making it and then turning it back into electricity at the destination are worse than practically any form of local clean electricity generation, even if it creates a requirement for some long-duration storage.

This is because the local clean electricity can be used in real time for most of the year, and expensive long-duration storage is only needed cover only a minority of the time. If, on the other hand, you commit to using an imported hydrogen derivative 100% of the time just because it is not always windy and sunny, your economics are dead.

It's important to note that this does not mean there won't be hydrogen imports – where hydrogen is needed for a use case further up the ladder it may well be imported (but only by pipeline or as a derivative, nothing else makes sense).

The only reason that Bulk Power Imports isn't on the Row of Doom, Row F, is that there may be cases where the only way to import power to a market is via a physical commodity – perhaps some islands which can't be connected to the mainland by cable, who knows – I can't think of any examples but I'm keeping an ever-so-slightly open mind.

The other big demotions relate to heating. **Domestic Heating** was on Row F, but as 45 reports reviewed by Jan Rosenow have unanimously concluded, backed up by the IEA's latest [Net Zero Roadmap](#), there is essentially no role for hydrogen in heating.

Mid/Low Temperature Industrial Heat also used to be on Row F but, in the light of progress on high-temperature heat pumps, there is no longer any rationale for industrial heat and steam up to 200C to be provide by anything other than a heat pump.

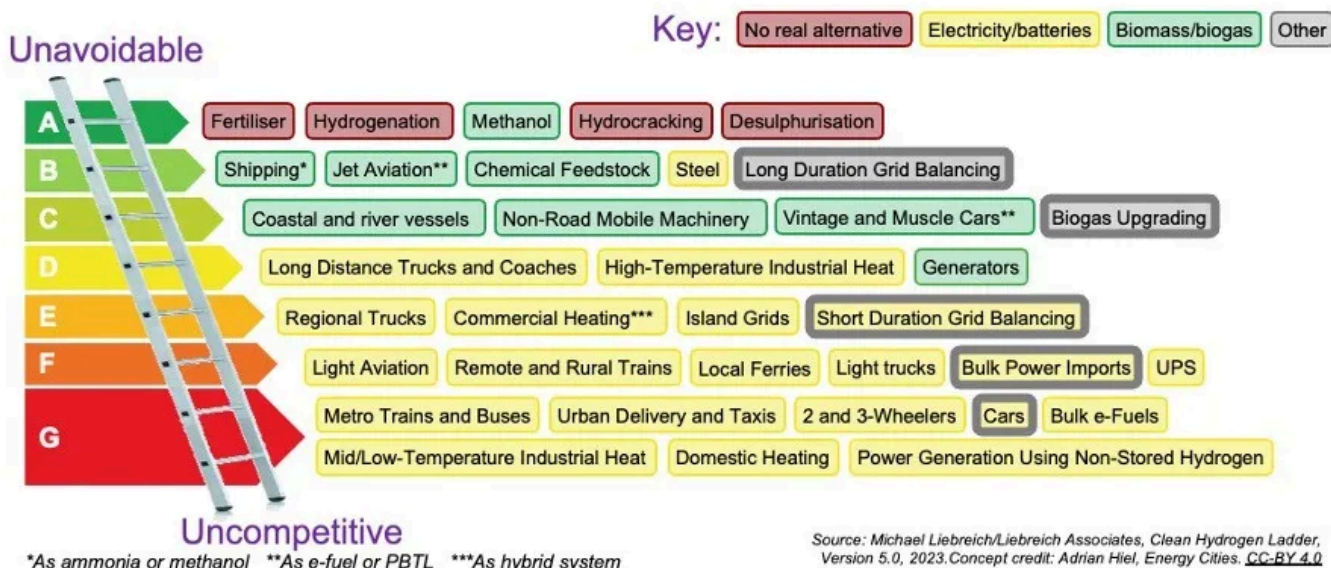
The balance between three promotions and six demotions is probably a pretty good indicator of how my views of hydrogen have hardened over the last two years.

Wording changes

The whole purpose of the Hydrogen Ladder is to help deliver a simple summary of a huge amount of information and analysis. In five cases, I have refined or changed wordings in order to clarify the exact use cases to which the ladder refers.

Hydrogen Ladder 5.0 – Wording changes (5)

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Five use cases have been reworded in the interest of clarity

I renamed Long Duration Storage as **Long Duration Grid Balancing** in order to enhance the Ladder's focus on use cases. Storage is not a use case per se, it is one way among several of meeting a particular type of energy demand. By "long duration", I mean anything over about two days. Anything under that is now called **Short Duration Grid Balancing** and is on Row E.

What was formerly called Local CO2 Remediation is now called **Biogas Upgrading**, but the intent is the same. Biogas produced by anaerobic digestion is a mix of methane and CO2. Instead of venting the CO2, as often happens currently when there is no local demand, we are likely to use locally-produced hydrogen to upgrade it either to methane, methanol or another PBTL fuel. Non-fossil carbon is going to be much more valuable in the future, as the absurd valuations put on DAC companies attests.

I renamed Clean Power Imports to **Bulk Power Imports** to emphasise that this refers to the importation of hydrogen or a derivative simply to meet the normal power

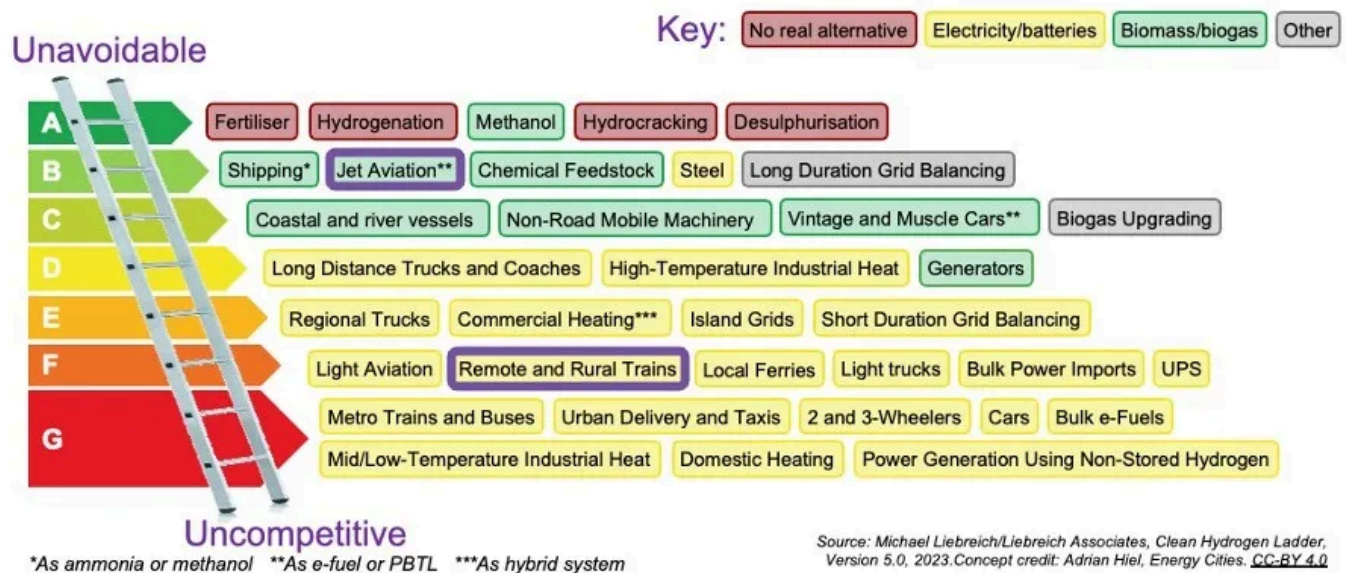
demand of an economy – not to sit in long-duration storage waiting to provide back-up power. I am thinking in particular of Japan's plans to import ammonia and use it first to co-fire coal-fired power stations, and ultimately to fire them with pure ammonia.

H2FC Cars have been renamed as plain **Cars**. In part this is to focus the Ladder on use cases, in part to acknowledge that in the past two years there has been increased talk about hydrogen cars using internal combustion engines rather than fuel cells, as though that would be the magic that would make them suddenly beat out EVs (it won't).

Use cases combined

Five use cases have been combined into two. Short, medium and long-haul aviation have become **Jet Aviation**, as described above. And Remote Trains and Rural Trains have become **Remote and Rural Trains**.

Hydrogen Ladder 5.0 – Use cases combined (5 to 2) Liebreich Associates

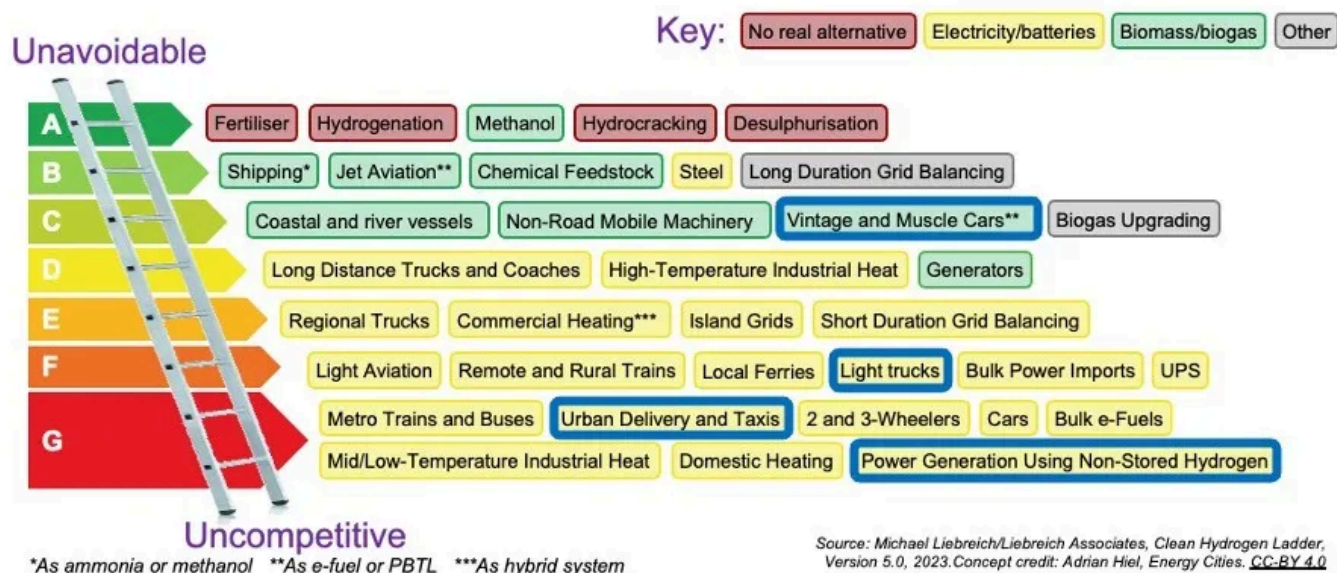


Five use cases have been combined into two for simplicity

New or partially new use cases

Version 5.0 includes five new use cases: the Muscle Car part of **Vintage and Muscle Cars**, **Light Trucks**, the Taxis part of **Urban Delivery and Taxis**, and **Power Generation Using Non-Stored Hydrogen**.

Hydrogen Ladder 5.0 – New or partially new uses (4)



Four new use cases have been added since Version 4.1

The former Vintage Cars use case now reads **Vintage and Muscle Cars**. The reason for the change is not because Muscle Cars (by which I mean high-end sports cars and super-cars) will be a major market for hydrogen – precisely the opposite. I wanted to emphasise that e-fuels for land transportation are going to be a niche market. Down on Row G you'll still find see Bulk e-Fuels – that's the e-fuels the general population might put in their cars, only they won't because they will always be too expensive.

Another new use case is **Light Trucks**, on row F. Don't worry, I am not warming to hydrogen cars – they are still on Row G (renamed from H2FC cars) and frankly, given the uptake of the Ford F150 and the attractiveness of the Rivian (I'm not going to make any comment about Tesla's extraordinarily ugly Cybertruck), I think light trucks too will eventually go fully electric. However, I do acknowledge that for the foreseeable future there are usage patterns – such as regularly towing a trailer or motor home over long distances, where EVs will struggle for range. And if a vaguely decent hydrogen fuelling network for Long-Distance Trucks and Coaches is built before battery energy

densities double again, it is possible some light truck drivers might use it. One to watch.

My favourite new use case, going straight in at Row G, is **Power Generation using Non-Stored Hydrogen**. It shouldn't even be necessary to say that making green hydrogen and then immediately using it to generate electricity, without capturing the value of time-shifting via storage, is utterly absurd, given the 70% cycle losses involved.

It's not really a use case in the true sense – that would be **Destroying Exergy**, but only STEM wonks would understand. When I produced Version 4.1 it never crossed my mind that anyone would think it made sense to create green hydrogen and then immediately use it to generate electricity.

Now, however, two groups of people are trying to do exactly this. First, IRA grifters. The IRA contains such generous carrots-on-carrots subsidies that Power Generation with Non-Stored Hydrogen looks like a profitable business. Second, the gas industry in the UK and other countries is lobbying heavily to blend hydrogen into the gas transmission or distribution grid. If you do that, a large proportion of it is routed straight to power stations and immediately burned to produce power – returning just a fraction of the energy used in making it, at huge and delivering miniscule emission reductions at a vast cost per TCO_{2e}.

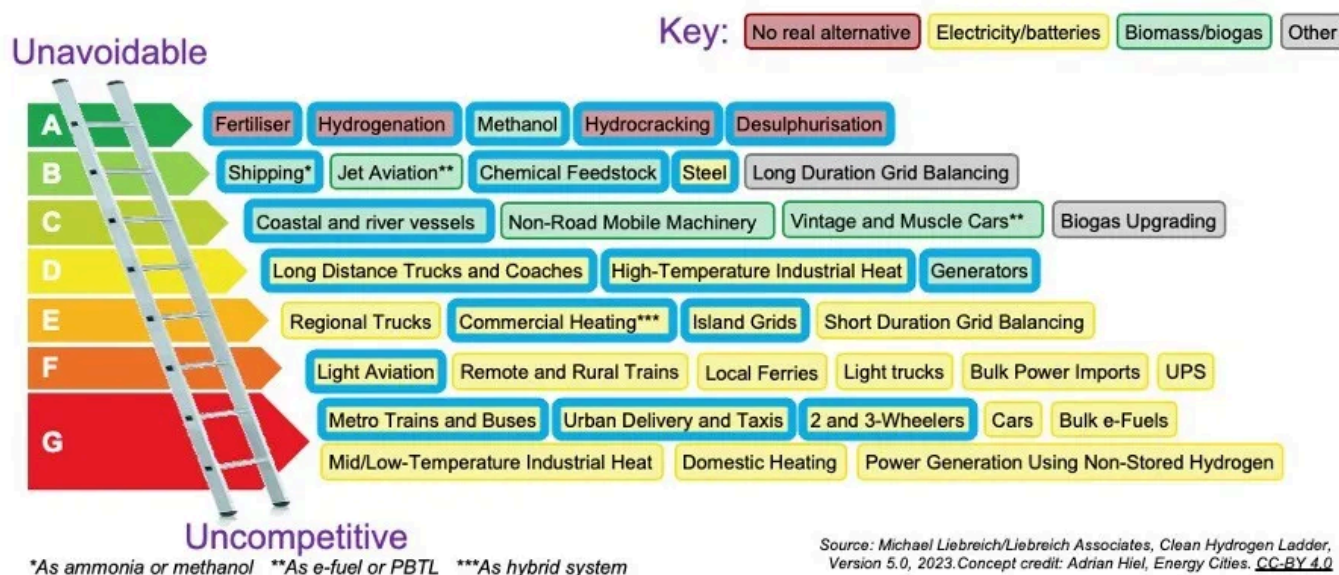
I have [explained elsewhere](#) that power curtailment would need to reach around 80% before it makes sense to blend hydrogen into the gas grid rather than use electricity to heat via a heat pump. Global average curtailment right now is around 2%. At some point I will write up that analysis and publish it here.

Unchanged use cases

Around two thirds of the use cases on the ladder have remained on the same row between Version 4.1 and 5.0.

Hydrogen Ladder 5.0 – Unchanged (18)

Liebreich
Associates



Two thirds of use cases have remained on the same row since Version 4.1: these 18 were entirely unchanged, some others were reworded or combined but stayed on the same row.

18 out of 35 use cases remained entirely unchanged; four more saw changes to wordings but remained on the same row. Of the five old use cases that were combined into two new ones, one (Rural Trains) remained on the same row.

So two thirds of the use cases in Version 5.0 (22 ½ out of 35) remained on the same row in Version 5.0. I think that is a testament to the robustness of Version 4.1 – and I hope Version 5.0 displays similar longevity.

Row A is entirely unchanged. It consists of the existing uses of hydrogen in our economy, the bulk of it used to make fertiliser or in fuel refineries. As of today, 99% of the nearly 100 million tonnes of hydrogen we use is produced from fossil fuels; it has to be cleaned up because it is responsible for just under 2.5% of current emissions. Although these use cases will shrink as we get smarter about fertiliser usage and fuel demand starts to decline, these are huge markets. They will probably grow more before they begin shrinking, and will be around for many, many decades, so we can't just ignore them. And there is no route to net zero that doesn't go through Row A.

Chemical Feedstocks – other than methanol (already represented on Row A) remain on Row B even though I'm not seeing growing excitement about making a broad range of synthetic chemicals from hydrogen. In fact, my Spidey-Sense tells me that bio-based chemical pathways are picking up more interest, so that use case may see a downgrade in the next version.

I was very tempted to demote **High-Temperature Industrial Heat**, because most of it is going to go electric, as I wrote recently in [a piece for BloombergNEF](#). The reason I didn't is that Row D is already pretty low considering that there are some energy-intensive use cases that are going to be hard to electrify so hydrogen might find a few havens.

Commercial Heating remained on Row E but gets a new footnote, noting that if hydrogen is used, it will be via a hybrid system. There is no rationale for the use of hydrogen in space heating other than to help deal with weather extremes that might otherwise overtax the power grid, but it will be cheaper to use hydrogen only when absolutely necessary, rather than get stuck using it all year, hence the need for a hybrid system.

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Reference Shelf I: Hydrogen Ladder Version 4.1

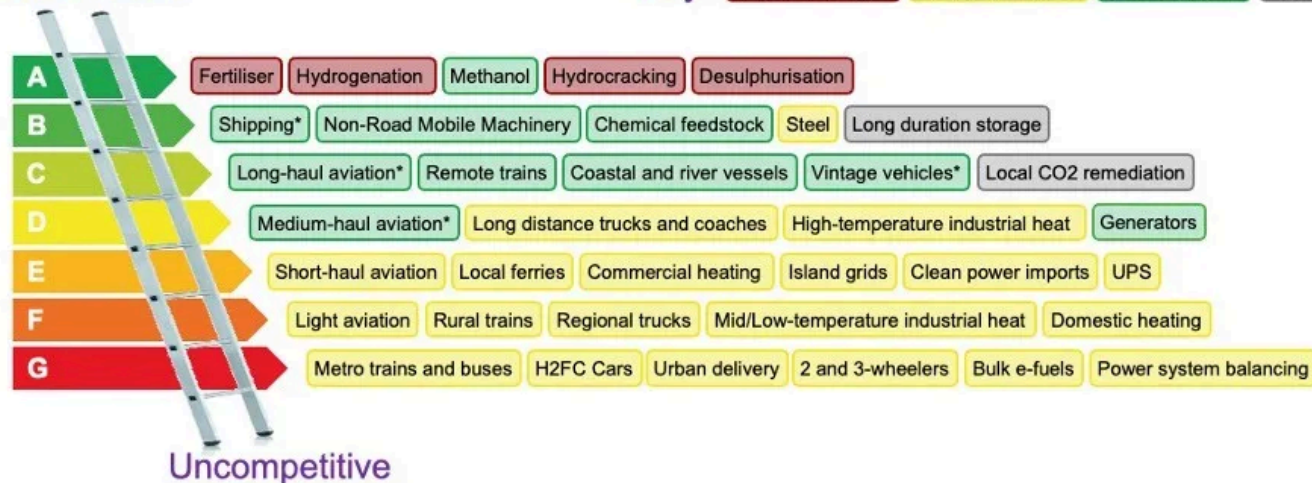
For your convenience, here's a copy of Version 4.1 of the Ladder. You can also still read [the original piece launching Version 4.1](#).

Hydrogen Ladder 4.1 – For reference

Liebreich
Associates

Unavoidable

Key: No real alternative Electricity/batteries Biomass/biogas Other



* Most likely via ammonia or e-fuel rather than H2 gas or liquid

Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 4.1, 2021. Concept credit: Adrian Hiel, Energy Cities. CC-BY 3.0

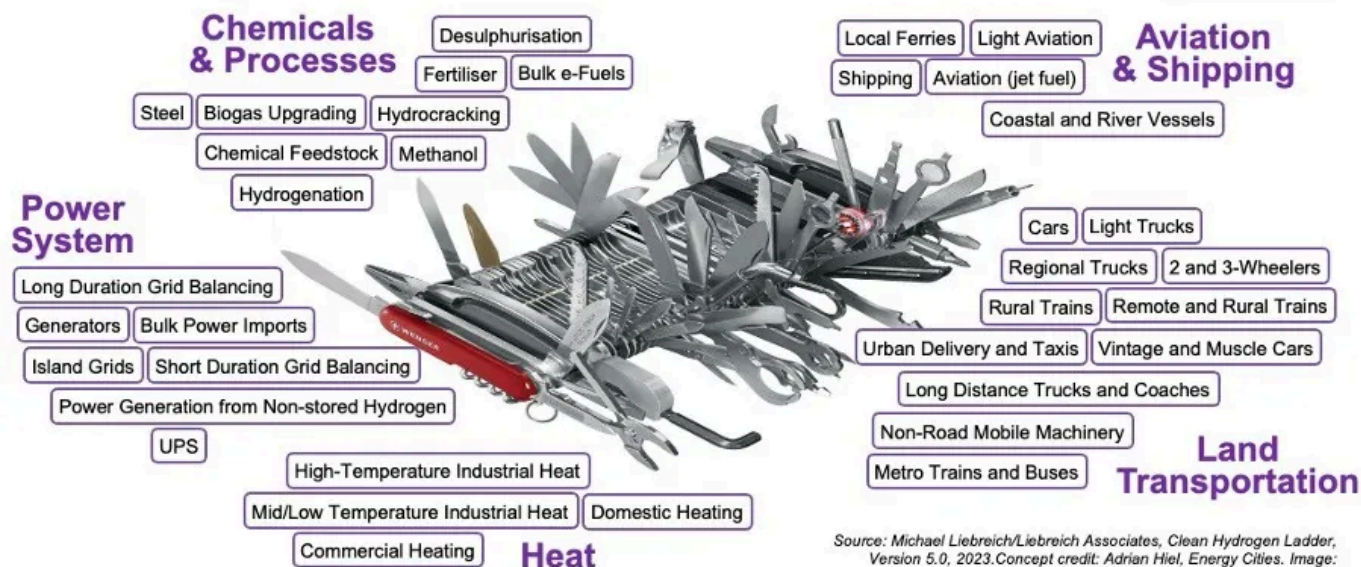
Version 4.1 of the Hydrogen Ladder served well for over two years, from August 2021 to October 2023

The rationale behind Version 4.1 is still relevant, particularly for the two thirds of use cases that have not changed in Version 5.0.

Reference Shelf II: Clean Hydrogen Swiss Army Knife

And here is an updated version of the famous Clean Hydrogen Swiss Army Knife. Just promise me that you won't use it to claim that hydrogen can and will do everything. The whole point of the graphic is to show how absurd it is to think hydrogen will do everything!

Clean Hydrogen Swiss Army Knife



Reference Shelf III: background reading, listening and watching

If you want more background on my thinking about hydrogen, here is a bit of background reading/listening:

- [Separating Hype from Hydrogen – Part One: The Supply Side](#) (BloombergNEF, October 2020)
- [Cleaning Up Audioblog - Clean Hydrogen: the Supply Side](#) (August 2021)
- [Separating Hype from Hydrogen – Part Two: The Demand Side](#) (BloombergNEF, October 2020)
- [Cleaning Up Audioblog - Clean Hydrogen: the Demand Side](#) (August 2021)
- [My keynote at the World Hydrogen Congress](#) (22 minute video, October 2022)
- [The Unbearable Lightness of Hydrogen](#) (BloombergNEF, December 2022)
- [Cleaning Up Audioblog - The Unbearable Lightness of Hydrogen](#) (December 2022)
- [Subsidies Everywhere All At Once](#) (Cleaning Up with Marco Alverà, May 2023)
- [Europe's Hydrogen Pusher](#) (Cleaning Up with Jorgo Chazimarkakis, February 2023)

Summary and licensing information

So, there you have it. I hope you enjoy poring over Version 5.0 of the Ladder as much as I have enjoyed producing it.

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If anyone wants to translate Version 5.0 of the Ladder into any other language, please feel free to do so, but again, only if you include a credit in the appropriate format and a link back to this page. If you send me a link, I'll include it here. My thanks again to those who translated 4.1 into German, Spanish and Japanese.

Feel free to make your own version – as long as you give credit in the approved format, include a link back to this page, and indicate the changes you made. You may not suggest that I endorse you or your use unless you have received my permission in writing. For more information, please read the [Terms and Conditions of the Creative Commons License](#).

As always, my thanks go to all of you who have engaged with the Ladder, contributed, and taught me so much. And, of course, to Adrien Hiel of Energy Cities, creator of the original graphic which I borrowed and, hopefully, enhanced!

Please be sure to provide plenty of feedback and - as long as I consider them in good faith - I'll do my best to answer your questions.