

TECHNOLOGY ENHANCED HYDROGEN

White hydrogen carbon footprint assessment

January 2022

TEH₂



STRICTLY CONFIDENTIAL

EXECUTIVE SUMMARY

Naturally occurring reserves of 'white' hydrogen present a very interesting opportunity to produce hydrogen in a highly efficient process, combined with very low greenhouse gas emissions



- Hydrogen (H₂) is a key enabler of the energy transition and has a wide range of applications in e.g. transportation, storage and chemical processes. Naturally occurring 'white' hydrogen may provide a low-carbon alternative to carbon and/or energy-intensive H₂ production methods
- With emissions of approximately 0.24 to 0.35 kg CO₂e/kg H₂, white hydrogen is at least 4x less-carbon intensive than green hydrogen, and 36x cleaner than blue hydrogen, for the test case based on Brazil. Furthermore, the energy efficiency is significantly better than current production methods. Net energy ratios show that white hydrogen is an energy source rather than an energy carrier – as for grey, blue and green hydrogen, more energy is needed as input than contained in the H₂ itself

The carbon footprint is mainly driven by factors such as methane leakage and filtration, yet remains low even in worst-case scenario models



- The carbon footprint of white hydrogen is dependent on well and production characteristics, as well as methane's global warming potential (as referred to by GWP-20 or GWP-100)
- Assumptions made for methane leakage, gas purity, well production volumes and filtration efficiency are based on expert insights and results in some data uncertainty. Carbon intensity can increase by 41% depending on modelling assumptions. Yet, even in the worst case scenario with decreased gas purity, higher leakage, and lower filtration efficiency carbon intensity remains low at ~ 0.35 kg CO₂e/kg H₂, still significantly lower than the next best alternative

Compared to other methods of hydrogen production, white hydrogen is a cleaner alternative as it requires hardly any production energy and has little methane leakage



- Alternative methods require energy intensive processes to produce hydrogen from natural gas (grey hydrogen) - where fugitive methane emissions are significant - and to perform carbon capture (blue hydrogen). White hydrogen however, is produced naturally via thermal processes deep in the earth's crust; it only needs to be collected from the reservoir, making it at least 36x more carbon-efficient.
- Producing H₂ from renewable energy (green hydrogen) is a cleaner alternative than blue/grey H₂ and more in line with the carbon footprint of white hydrogen, but still remains higher when evaluated over the entire life cycle of production. Furthermore, white hydrogen requires significantly less energetic resources in a like-for-like comparison, freeing up renewable energy for other applications

Source: MJ Hudson analyses

Low-carbon hydrogen production methods will be key enablers of the energy transition and expected to play a vital role in transportation, energy storage and chemical applications

Preamble

Beam is a UK and US-based international impact player. The company acquires, co-invests in and operates energy assets in an environmentally progressive manner, and focuses on transition technologies to deliver enhanced returns and minimum environmental impact.

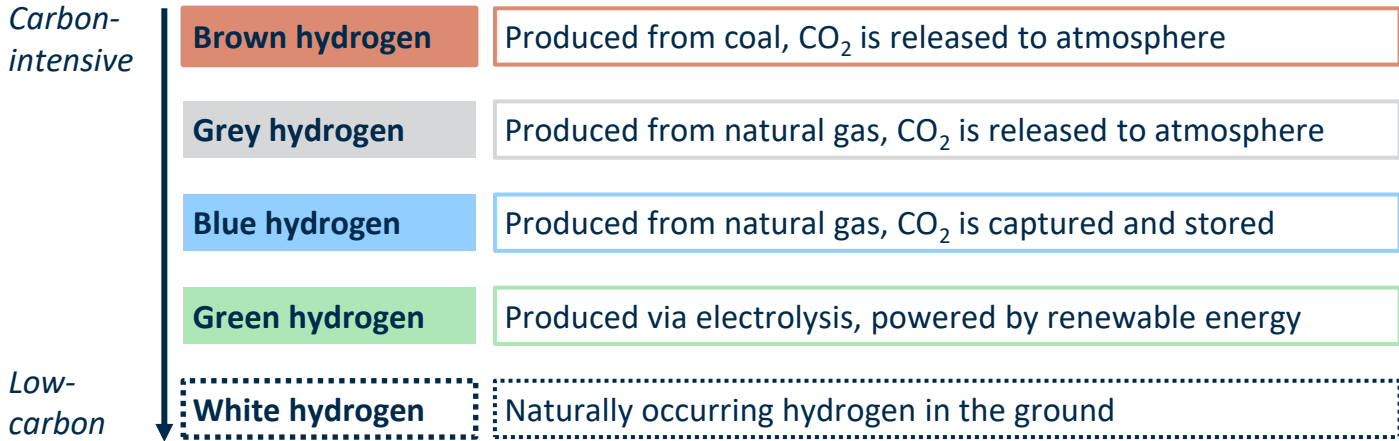
This report is aimed at providing a carbon footprint comparison of blue, green and white hydrogen production. We have been supported by MJ Hudson ESG & Sustainability to develop a carbon footprint estimation model of TEH's white hydrogen production. Benchmark carbon footprint data of other production pathways was based upon scientific literature. The results are summarised in this report.

Source: IEA

A brief introduction to hydrogen

- Hydrogen is an energy carrier for transportation, energy backup/storage or chemical applications like green ammonia production. Yet, hydrogen's potential as a widespread low-carbon energy carrier poses challenges, as production currently is carbon intensive.
- Currently, global hydrogen is almost entirely supplied from fossil fuels, with **6% of global natural gas** and **2% of global coal** going towards hydrogen production. This makes hydrogen responsible for 830 Mtonnes CO₂ per year, roughly **2% of global emissions**.
- **Cleaner pathways** to produce hydrogen will become increasingly important as the role of hydrogen in a net-zero future according to the IEA is considerable and it is expected that the EU's hydrogen strategy for a climate neutral Europe will further propel clean hydrogen initiatives

Hydrogen production pathways



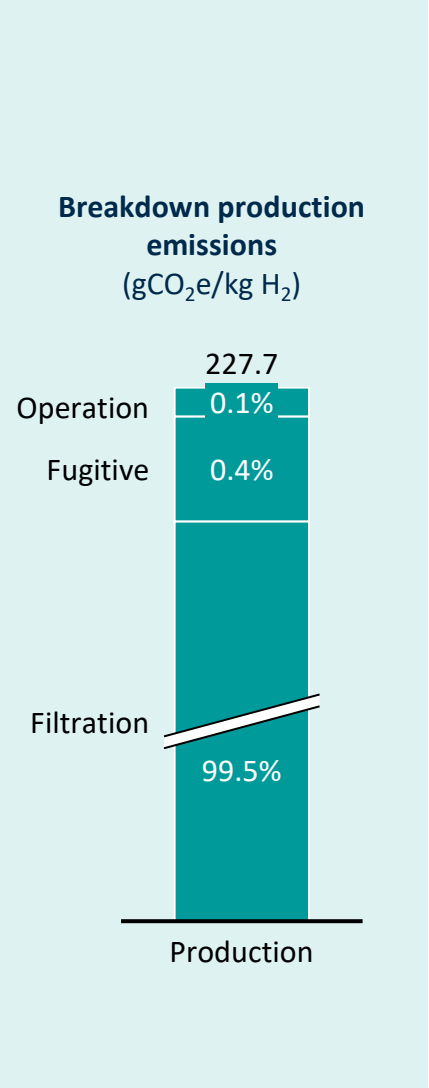
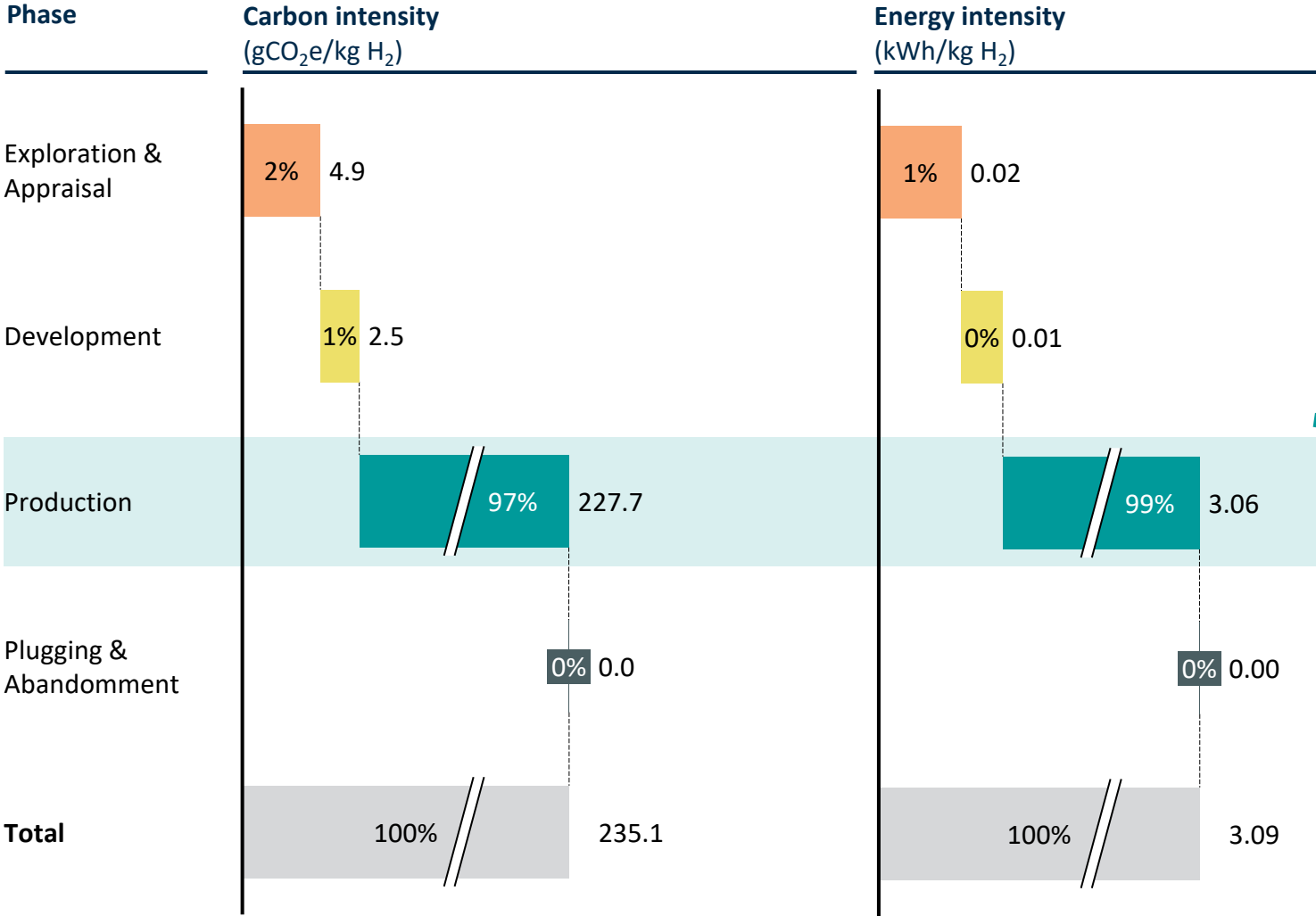
The carbon footprint model takes a value chain-based approach to estimate the carbon footprint during different phases of white hydrogen production

Phases	Exploration & Appraisal	Development	Production	Plugging & Abandonment
Description of activities	<ul style="list-style-type: none"> Investigating presence of hydrogen resources and drilling wells for testing gas characteristics and volumes Main emissions arise from fuel combustion to power the rig machinery 	<ul style="list-style-type: none"> Drilling production wells and installing on site-processing facilities Main emissions arise from fuel combustion to power the rig machinery 	<ul style="list-style-type: none"> Recovering hydrogen from production wells and filtrating hydrogen from other gasses Main emissions arise from electricity consumption to power the filtration system 	<ul style="list-style-type: none"> Plugging of a well by filling up with cement at the end of its lifetime, and restoring the site Main emissions arise from fuel combustion to power the plugging machinery
Calculation method	<ul style="list-style-type: none"> Drilling emissions are calculated by estimating rig fuel use per day Fugitive emissions assume a methane leakage factor Model based on Brazil for electricity grid emission factor 	<ul style="list-style-type: none"> Drilling emissions are calculated by estimating rig fuel use per day Fugitive emissions assume a methane leakage factor 	<ul style="list-style-type: none"> Operational emissions are estimated using electricity use per day Filtration emissions are estimated using electricity use per kg H₂ Fugitive emissions assume a methane leakage factor 	<ul style="list-style-type: none"> Plugging emissions are calculated by estimating the plugging machinery fuel use per day Cement embodied emissions are calculated by estimated using well diameter and well plug length
Model assumptions	<ul style="list-style-type: none"> Discounted over lifetime Drilling: <ul style="list-style-type: none"> 2 exploratory wells á 40 days of drilling per well 10 rig operational hrs/ day Fugitive: <ul style="list-style-type: none"> 1% CH₄/ kg gas-mix 0.3% CH₄ leakage / kg CH₄ 	<ul style="list-style-type: none"> Discounted over lifetime Drilling: <ul style="list-style-type: none"> 40 days of drilling per well 10 rig operational hrs/ day Fugitive: <ul style="list-style-type: none"> 1% CH₄/ kg gas-mix 0.3% CH₄ leakage / kg CH₄ 	<ul style="list-style-type: none"> Calculated per kg H₂ Operations <ul style="list-style-type: none"> 30 years lifetime of well 3,000 kg gas / day Filtration <ul style="list-style-type: none"> 98% H₂ gas purity 3 kWh per kg H₂ for filtration system 	<ul style="list-style-type: none"> Discounted over lifetime Well parameters <ul style="list-style-type: none"> 0.1 m well diameter 100 m cement plug length Plugging <ul style="list-style-type: none"> 7 days of plugging 30 litres machinery fuel use / day

Source: MJ Hudson white hydrogen carbon footprint model, Beam Earth data

The main emissions arise during the production phase and result from filtration of white hydrogen, yet are still limited to 0.24 kgCO₂e/kg hydrogen

White hydrogen lifecycle carbon and energy footprint (GWP-100)

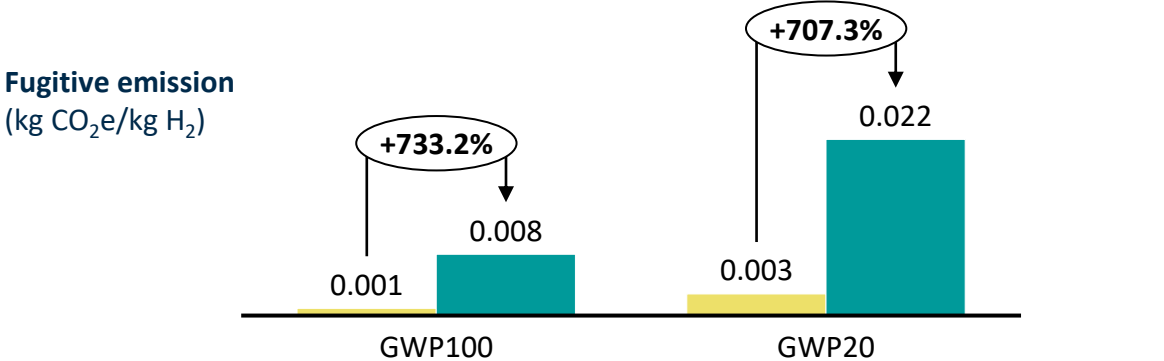
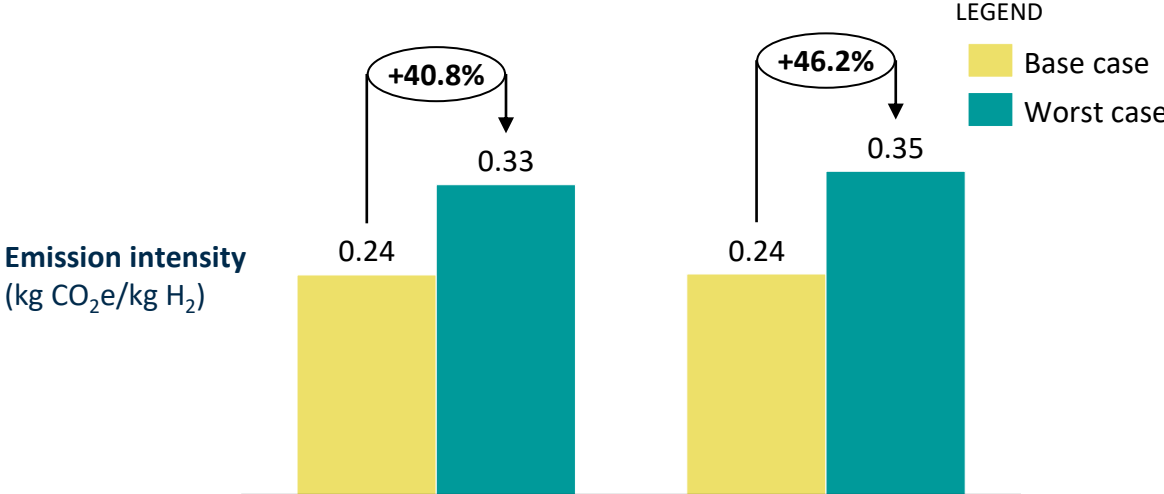


Note that energy & carbon emissions for Exploration & Appraisal, Development, Plugging & Abandonment are divided by the total hydrogen production over the lifetime's asset (30 years). Source: MJ Hudson white hydrogen carbon footprint model, Beam Earth data

In a scenario with increased methane leakage, reduced gas purity and production, emissions rise by 41% to 0.33 kg CO₂e/kg hydrogen

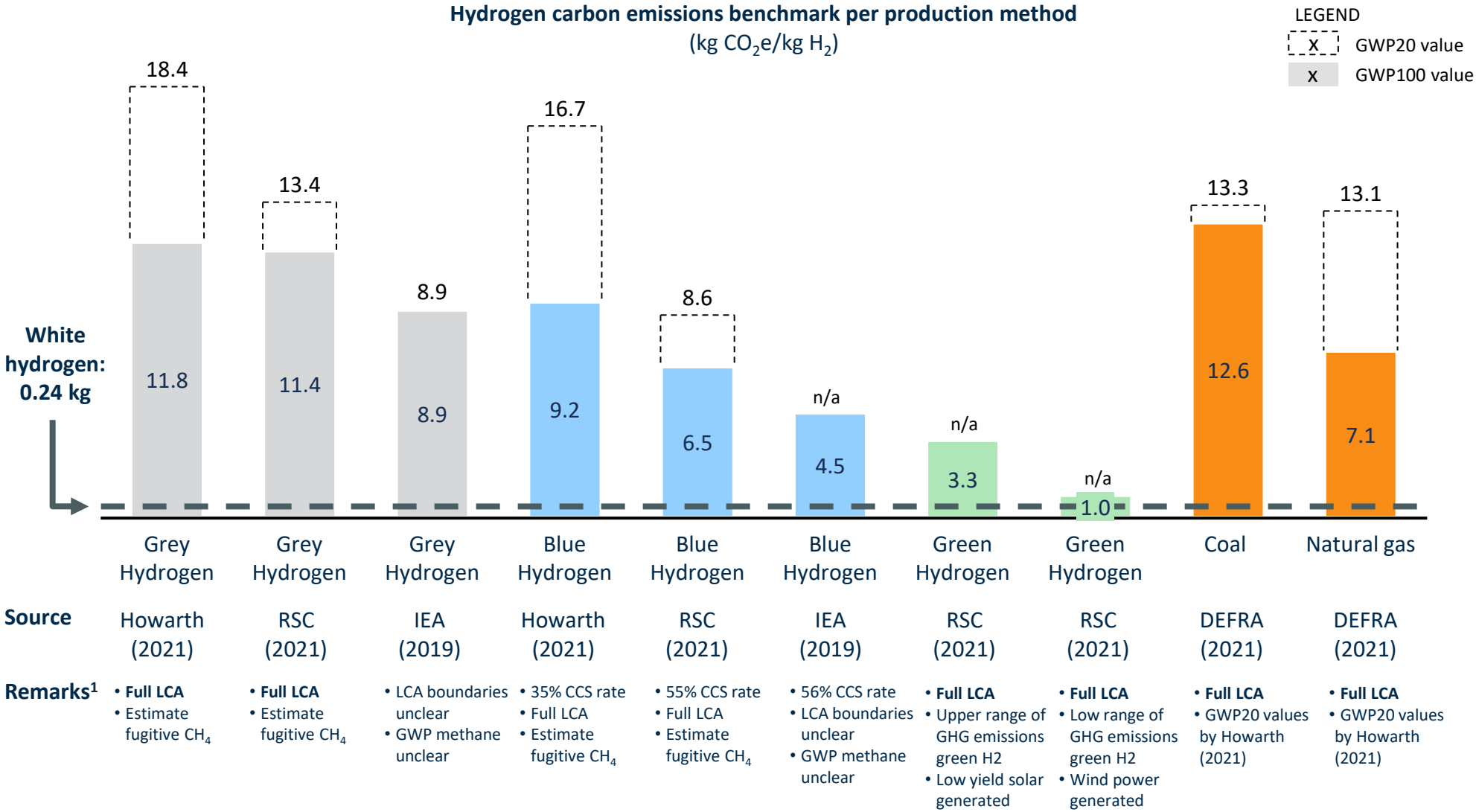
- The model is subjected to **certain insecurities related to the assumptions** that are made. Different scenarios are considered to account for these uncertainties.
- We considered both a **Base case and a Worst case** scenario. Within each scenario, different values related to key assumptions are used.
- Furthermore, a **distinction is made for GWP20 and GWP100 values** for both cases. These values present the global warming potential (GWP) of greenhouse gasses. GWP20 incorporates higher values for methane emissions than GWP 20.

	Base case	Worst case
Methane leakage (%)	0.3	0.8
Gas purity (%)	98	94
H₂ production (kg H ₂ /day)	2,940	2,700
Filtration electricity use (kWh/day)	3	4



Source: MJ Hudson white hydrogen carbon footprint model, Beam Earth data

The benchmarking study shows that the carbon footprint of white hydrogen is significantly lower than other hydrogen production pathways



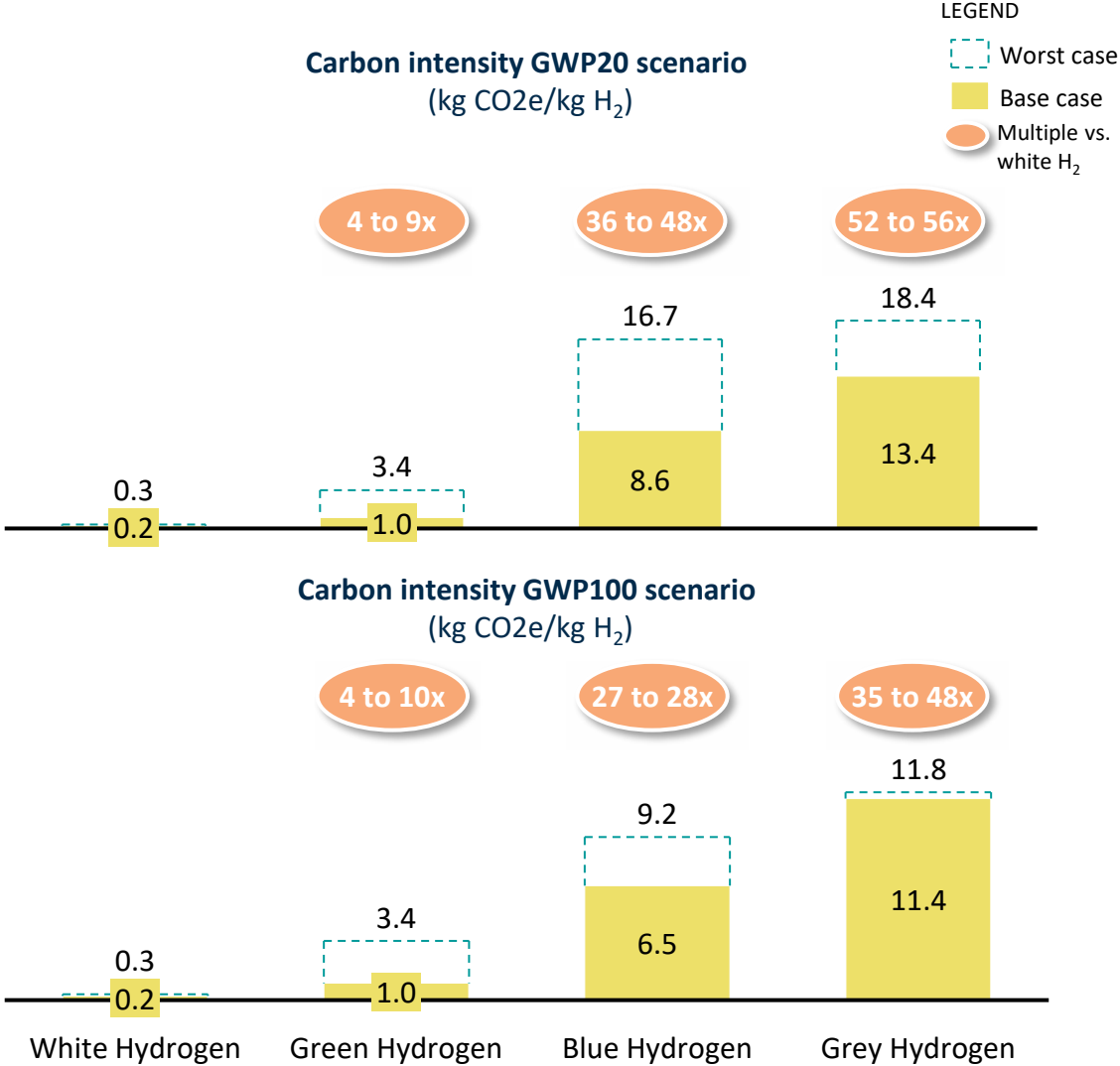
Source	Howarth (2021)	RSC (2021)	IEA (2019)	Howarth (2021)	RSC (2021)	IEA (2019)	RSC (2021)	RSC (2021)	DEFRA (2021)	DEFRA (2021)
Remarks ¹	<ul style="list-style-type: none"> • Full LCA • Estimate fugitive CH₄ 	<ul style="list-style-type: none"> • Full LCA • Estimate fugitive CH₄ 	<ul style="list-style-type: none"> • LCA boundaries unclear • GWP methane unclear 	<ul style="list-style-type: none"> • 35% CCS rate • Full LCA • Estimate fugitive CH₄ 	<ul style="list-style-type: none"> • 55% CCS rate • Full LCA • Estimate fugitive CH₄ 	<ul style="list-style-type: none"> • 56% CCS rate • LCA boundaries unclear • GWP methane unclear 	<ul style="list-style-type: none"> • Full LCA • Upper range of GHG emissions green H2 • Low yield solar generated 	<ul style="list-style-type: none"> • Full LCA • Low range of GHG emissions green H2 • Wind power generated 	<ul style="list-style-type: none"> • Full LCA • GWP20 values by Howarth (2021) 	<ul style="list-style-type: none"> • Full LCA • GWP20 values by Howarth (2021)

¹A full LCA indicates that emissions embodied in the production of materials e.g., solar panels, is also considered in the carbon footprint calculation.

Source: Various academic studies (see above)

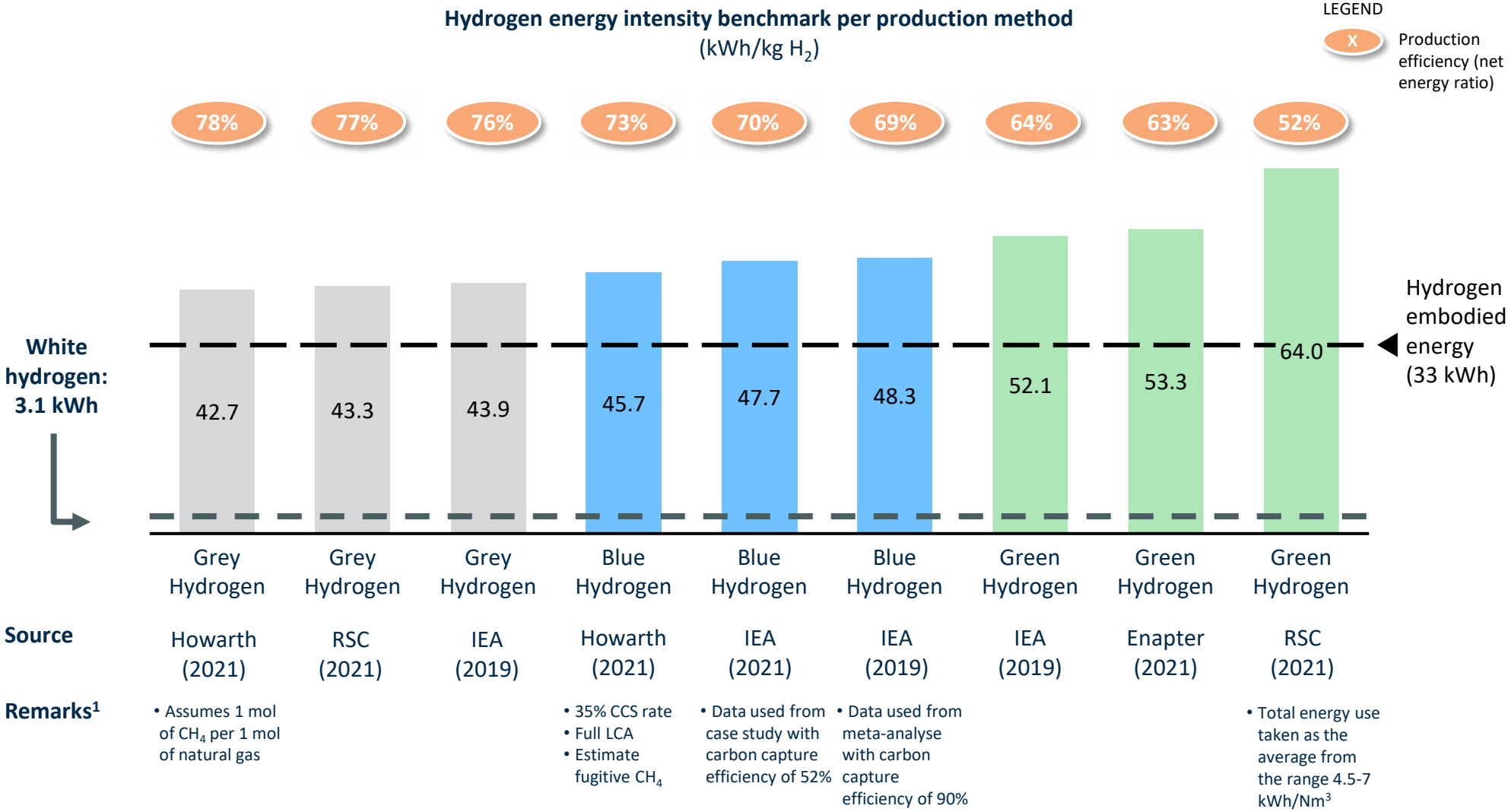
The analysis indicates that white hydrogen appears to be 4 to 56x less carbon intensive than other hydrogen production pathways, depending on alternative production method

- The production process of white hydrogen differs from significantly from green, blue and grey hydrogen and is therefore **less carbon intensive**:
 - Compared to grey and blue hydrogen, **no energy is required to produce the actual hydrogen from other fuel sources**, e.g. an SMR process in which natural gas gets heated with steam to form hydrogen. In white hydrogen, the hydrogen is produced via **naturally occurring subsurface geothermal processes** in the earth's crust and only needs to be collected
 - Compared to blue hydrogen, **no energy is required to power any carbon capture processes**, as no carbon dioxide is produced in operations
 - Furthermore, for grey and blue hydrogen, **methane leakage emissions are much more pronounced** compared to white hydrogen
 - Green hydrogen still has **indirect emissions** in the construction phase of renewables that result in carbon emissions
- As a result, white hydrogen is estimated to have a carbon intensity per kg hydrogen that is **4 to 56 times lower than alternative production pathways**, depending on comparison scope



Source: MJ Hudson white hydrogen carbon footprint model, Beam Earth data

The benchmarking study also shows that the energy intensity of white hydrogen is significantly lower than other hydrogen production pathways

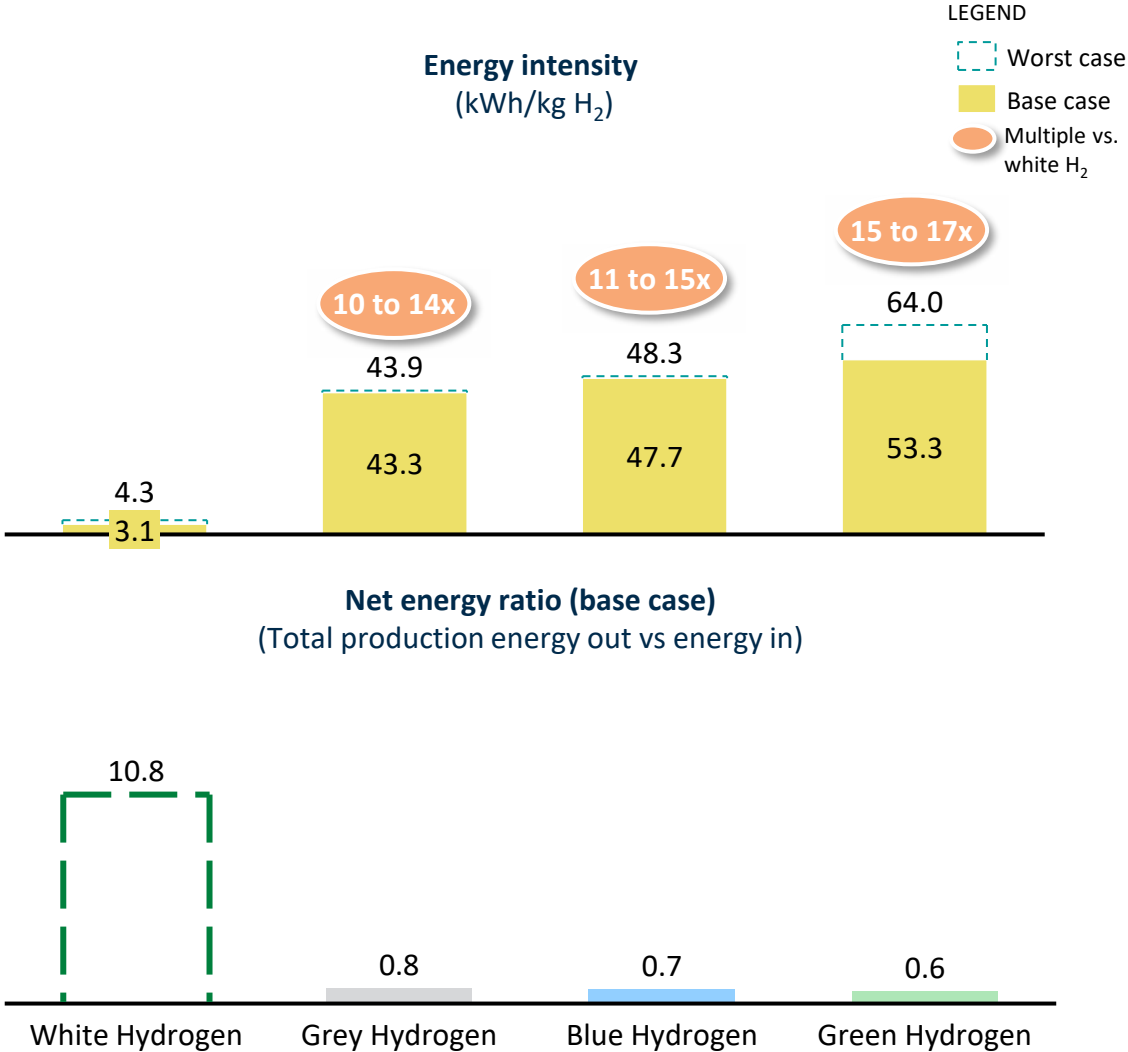


1) A full LCA indicates that emissions embodied in the production of materials e.g., solar panels, is also considered in the carbon footprint calculation.

Source: Various academic studies (see above)

The analysis shows that white hydrogen is an energy source instead of an energy carrier, delivering 11x more energy than needed in the production process

- The process for the production of white hydrogen is **significantly less energy intensive** than for grey, blue and green hydrogen. Similar reasoning applies for the differences between the energy intensities and the carbon intensities:
 - Compared to grey and blue hydrogen, no energy is required to produce the heat and pressure needed during the SMR process
 - Compared to blue hydrogen, no energy is required to power any carbon capture processes
 - Green hydrogen is primarily formed via electrolyzers, which are relatively inefficient and from an energy perspective need to 'start from zero' as the water used as feedstock carries no embodied energy
- As a result, white hydrogen is estimated to have a energy intensity per kg hydrogen that is **10 to 17 times lower than alternative production pathways**
- The white hydrogen production pathway can produce almost **11 times more energy than is consumed in the production process**, making white hydrogen an **energy source instead of an energy carrier**



Source: MJ Hudson white hydrogen carbon footprint model, Beam Earth data



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