The true face of hydrogen

How robust definitions and chain of custody systems can help unmask fossil hydrogen in disguise

ecos

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About ECOS

ECOS - Environmental Coalition on Standards is an international NGO with a network of members and experts advocating for environmentally friendly technical standards, policies and laws. We ensure the environmental voice is heard when they are developed and drive change by providing expertise to policymakers and industry players, leading to the implementation of strong environmental principles.

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Contents

Executive summary

How to make sure hydrogen is truly green

In the recent years, hydrogen has evolved from a mere feedstock in the chemical and refining industry to, as some will put it, a key to decarbonising our energy system. Indeed, hydrogen made from renewables will play a crucial role in the transition to clean energy[1] – but we should be realistic about its role. Hydrogen is not a silver bullet.

In order to truly contribute to decarbonisation, hydrogen must have as low a climate impact as possible. Eventually, it should be produced from renewables only. Unfortunately, most of the hydrogen produced today is still very carbon-intensive[2] - with electrolysis covering a mere 4% of all hydrogen produced in the EU.

Many companies are exploring production routes that are less carbon-intensive. These are not fully renewable and therefore still far from an ideal solution. This is why **it is necessary to establish strong definitions to mark the difference between renewable and non-renewable hydrogen**, and within the latter **to differentiate between hydrogen with low and high climate impacts**.

Our paper will first focus on **what defines renewable, as well as non-renewable low-carbon hydrogen**, looking at the climate impacts to be considered and what 'renewable' and 'low-carbon' really mean.

Once we conclude that our hydrogen is renewable, or non-renewable yet low-carbon at source, **we need to track it across the supply chain so that it remains so**. This can become tricky: once produced, we cannot tell apart hydrogen from different sources – it has become an energy commodity. Hydrogen from wind looks the same as hydrogen from fossil gas, and is usually mixed in the same transport system, such as pipes.

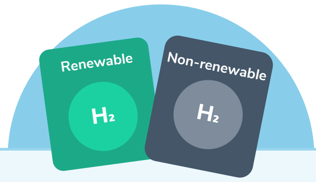
To make sure that hydrogen sold as renewable or low-carbon really qualifies as such, we need robust systems to track and trace molecules across the value chain. As hydrogen becomes more and more widespread, public administrations (and standard-makers) in many parts of the world are faced with this very question – how to track renewable and low-carbon hydrogen, so that it does not become a fossil fuel in disguise?

The good news is that there are several systems to track hydrogen particles across the supply chain. We call them **chain of custody systems**. Chains of custody match inputs, outputs and their associated characteristics as they move through each step. In the case of hydrogen, this means we can identify if hydrogen supplied to customers can be reasonably attributed to renewable sources.

Our paper goes on to **identify the most appropriate chain of custody model to track and trace renewable and non-renewable low-carbon hydrogen throughout the supply chain**.

Following a molecule of hydrogen throughout the whole supply chain is not simple. We have to rely on estimations. How much so depends on the type of distribution. For example, when trading hydrogen across continents, it is usually conveyed as a liquid derivate in large cargo ships – in this case, tracking each shipment is a logical solution. On the other hand, when hydrogen is traded within a region, it usually remains a gas and is conveyed via pipes or trucks – in that case, tracking each molecule becomes much harder, so reliable estimates will be needed.

Key recommendations

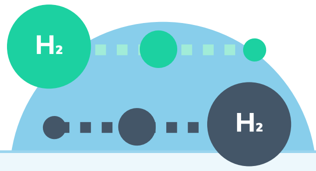


The true face of hydrogen: defining renewable and non-renewable low-carbon hydrogen

For hydrogen to contribute to the decarbonisation of hard-to-electrify sectors, a number of conditions must be met:

- **Production:** in the long run, hydrogen must be produced via electrolysis based on electricity from additional renewable sources, as this route has the lowest life cycle carbon impact. In the meantime, the climate impact of other production routes must be kept to a strict minimum.
- **Strong definitions:** any definition of hydrogen must take all the life cycle climate impacts into account. The definition of 'renewable hydrogen' may only cover hydrogen produced with the lowest life cycle climate impact[3]. The definition for 'non-renewable low-carbon hydrogen' must set a strict upper limit for its life cycle climate impacts[4].

A loose definition would allow hydrogen with significant life cycle climate impacts to still find its way to hard-to-decarbonise sectors, which, in turn, would jeopardise the full decarbonisation of these sectors by 2050.



Unmasking hydrogen: appropriate chain of custody models to track and trace hydrogen

There is no one-size-fits-all when choosing the right chain of custody model. Whether hydrogen is shipped as gas or as liquid determines which chain of custody model can make the most trustworthy claims.

- For **gaseous hydrogen** (domestically produced), a **strict mass balance system** is the most appropriate model, which should be reflected in EU legislation.. Such a system will be robust if it allows aggregating physically connected pipelines only, and as long as the share of renewable hydrogen is proportionally allocated to all end-users.

- For **liquid hydrogen** (imported), **segregation is the most appropriate mode**l as it allows for building a dedicated supply chain for this type of renewable energy carriers. However, mixing derivates from less sustainable sources should be prevented at every step of the logistic chain. **Identity-preserved systems** are an option for batches coming from a single source and kept away from other types of hydrogen at each step of the logistics chain

Book and claim systems (Guarantees of Origin) and loose mass balance systems allow a transfer of attributes from renewable and low-carbon hydrogen to high-carbon hydrogen or - even worse – fossil fuels, and **set the door wide open to greenwashing**.

Importantly, no chain of custody system should facilitate the blending of hydrogen in natural gas, as this will lock in fossil gas in our energy system.

The true face of hydrogen

Getting definitions right

Hydrogen can only play a role in decarbonising hard-to-electrify sectors as long as it does not contribute to climate change itself. The way it is defined must take all life cycle climate impacts into account, and not merely the ones related to production.

Hydrogen defined as 'renewable' should have the lowest life cycle climate impacts possible. It needs to be renewable energy based, and must not present any negative impacts. These may occur when hydrogen production is not backed by additional renewable energy consumption, or when it is not synchronised with the renewable energy production, meaning that energy needs to be supplied by other, carbon-intensive routes, in order to carry out the electrolysis processes[5].

Unfortunately, today we produce hydrogen faster than we produce new renewable energy. As a consequence, other, non-renewable hydrogen production paths are used, and definitions for other types of hydrogen are being developed, such as 'low-carbon hydrogen'.

It is imperative that the definition of these non-renewable hydrogen types cover all life cycle climate impacts as well. Moreover, strict thresholds should be set to limit these impacts.

Hydrogen production paths

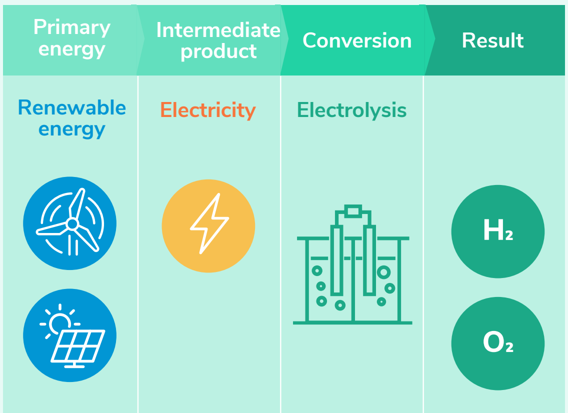
Hydrogen cannot be mined or extracted from the earth – it is produced by the breaking up of hydrogen-rich molecules. This can be done in several ways, each taking different molecules as a starting point and applying different conversion techniques. Below, we present an overview of the different production paths.

Renewable electricity-based electrolysis

Electrochemical splitting of water (H_2O).

1 kg of hydrogen requires the input of:

- 10 to 22 kg of water
- 50 MWh of electricity



Life cycle greenhouse gas emissions

Wind	0.3 – 0.88 kg CO_2/kg H_2
Solar	1.0 – 2.21 kg CO_2/kg H_2

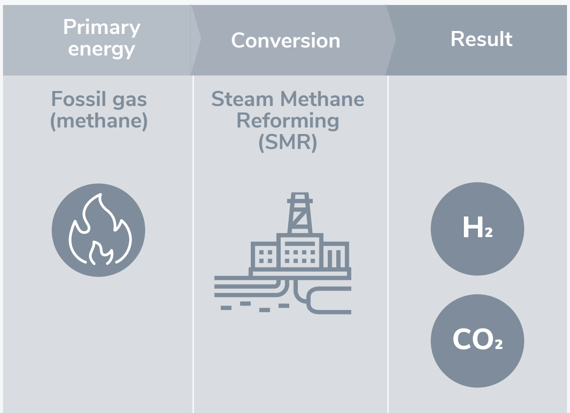
The source of electricity determines the carbon-intensity of hydrogen. Hydrogen is fully renewable if the electrolysis process is supplied with electrons from additional renewable sources, such as solar panels or wind farms.

Steam Methane Reforming (SMR)

It chemically splits natural gas (methane mainly) by adding high-temperature steam (800 to 900°C).

1 kg of hydrogen requires the input of:

- 16 kg of water



Life cycle greenhouse gas emissions

Fossil gas	11 – 14 kg CO_2/kg H_2

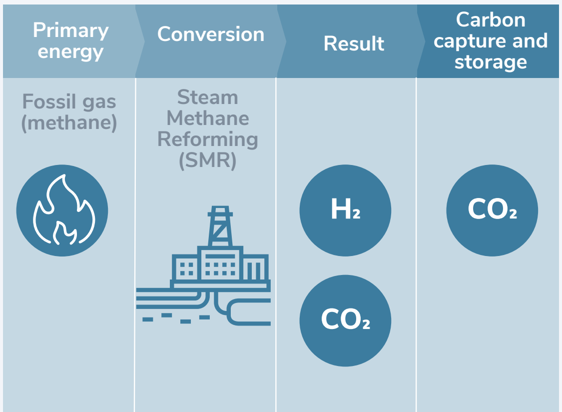
The SMR generation process alone emits up to 10 kg CO_2 per kg of hydrogen.

Upstream methane leaks during the extraction and transportation of methane increase the carbon intensity of SMR-generated hydrogen.

The SMR method is currently the most common route to produce hydrogen.

Steam Methane Reforming with carbon capture

Captures the CO_2 at the end of the Steam Methane Reforming process.



Life cycle greenhouse gas emissions

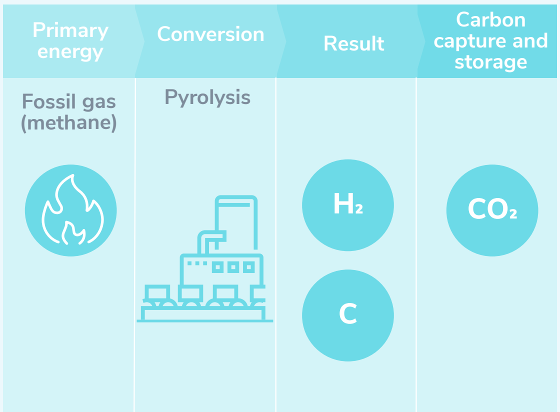
Fossil gas 1.5 – 6.5 kg CO_2/kg H_2

The extent of the carbon impact reduction depends on the carbon capture efficiency (currently limited to 90%)[6] and whether the captured CO_2 is stored permanently and removed from the atmosphere.

There is no compensation for the carbon impact provoked by upstream methane leaks.

Pyrolysis of methane

Methane is split at a high temperature (up to 1100-1200°C) in the absence of air into hydrogen and solid carbon.



Life cycle greenhouse gas emissions

Fossil gas 6.1 – 6.5 kg CO_2/kg H_2

This process generates solid carbon instead of CO_2 as a by-product, which is much easier to capture. The carbon must be used in products with a long life cycle to prevent its reentry into the atmosphere.

Does not compensate for the carbon impact from upstream methane leaks.

Climate impacts of hydrogen: the full picture

The use of hydrogen should aim at supporting the decarbonisation of hard-to-electrify sectors only. To do so effectively, however, the different climate impacts of hydrogen must be kept to the very minimum, and none of them should be ignored. The different production paths of hydrogen vary considerably in terms of life cycle climate impact. The overview above indicates the whole life greenhouse gas emissions, determined by Life Cycle Assessment studies[7].

For Steam Methane Reforming, for instance (see Figure 1[8]), the life cycle climate impact includes the direct emissions from the process in which methane is split into hydrogen and CO_2, and the emissions from the combustion of natural gas to bring the process to the desired temperature (Scope 1 emissions according to the GHG protocol).

The life cycle climate impact also includes emissions from the electricity production and supply (Scope 2 according to the GHG protocol). To complete the picture, we must also add emissions from the compression and transport of natural gas from the sources to the hydrogen plant, as well as the fugitive methane emissions occurring during the transport of natural gas (Scope 3 according to the GHG protocol).

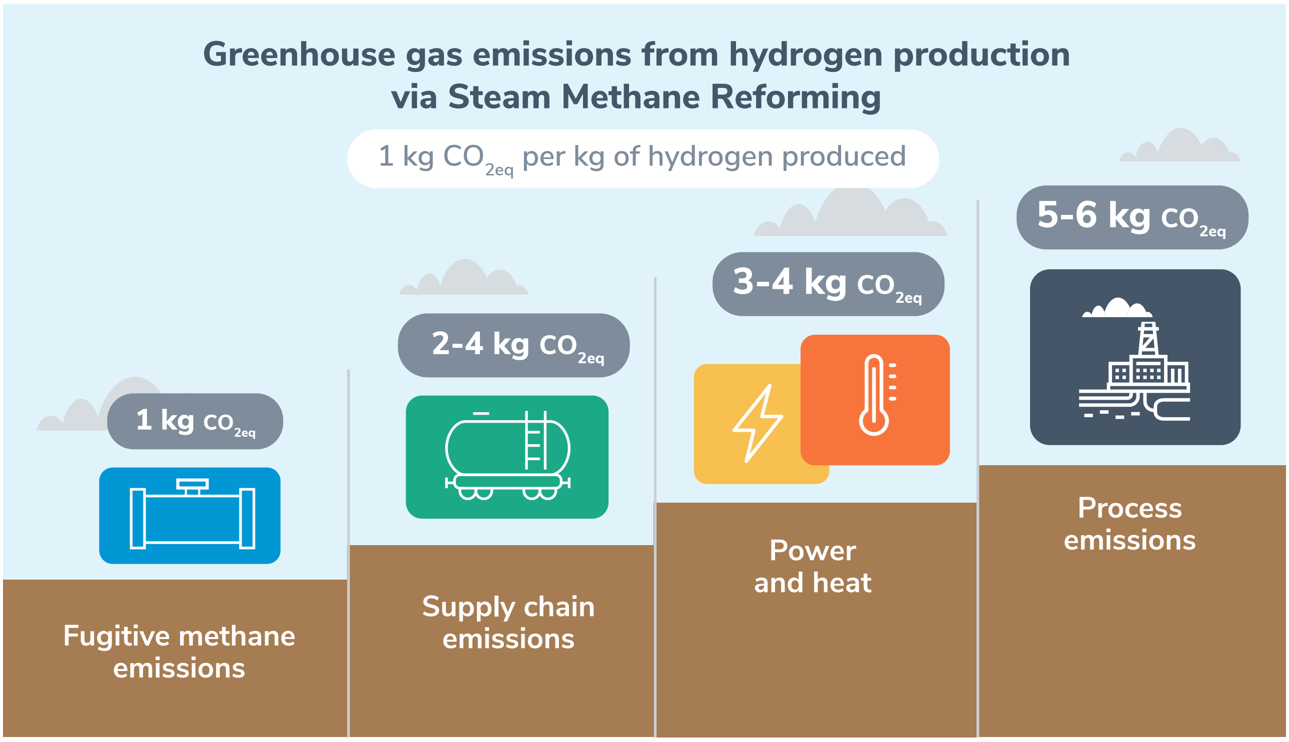


Figure 1 Sources of the greenhouse gas emissions of hydrogen production of Steam Methane Reforming

For hydrogen produced via electrolysis, the main source of greenhouse gas emissions originates from the production of electricity itself. Sourcing electrons from renewable electricity, such as wind and sun, minimise these emissions.

However, sourcing electricity from the grid may have negative side effects, which must be well controlled. Electrons should not be obtained from existing renewable electricity sources and the electrolysis process should be synchronised with the electricity production – with electrolysers operating only when this electricity is generated. Otherwise, more carbon-intensive electricity sources are used, and drive up the greenhouse gas footprint of hydrogen.

Renewable hydrogen according to EU rules

The production path referenced in the EU definition of 'renewable hydrogen' is electrolysis, supplied with renewable electricity, see Delegated Act on rules for the production of RFNBO[9], which is the hydrogen production path with the lowest life cycle climate impacts.

The EU definition of 'renewable hydrogen' also takes all life cycle climate effects into account.

To ensure that the electricity used to produce renewable hydrogen is truly renewable and to avoid that more carbon-intense electricity sources supply the electrolysers, additional rules apply:

- The deployment of electrolysis capacity must go hand in hand with the deployment of new renewable electricity generation capacity.
- Renewable hydrogen must be produced at times (the same hour) and in places (the same bidding zone) where renewable electricity is available.

To assess the greenhouse gas emissions savings from renewable hydrogen[10], the EU Renewable Energy Directive[11] put forward a methodology, which takes the full life cycle climate impacts into account: the greenhouse gas emissions from the energy input, from hydrogen production, its transportation and distribution, the end-use of the fuel, as well as from carbon capture and geological storage.

The Gas Directive – under revision at the time of writing – instructs the Commission to adopt similar Delegated Acts to specify the methodology for assessing greenhouse gas emissions savings from non-renewable low-carbon fuels.

The existing methodology for renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels should be maintained **as the model for specifying the methodology for assessing greenhouse gas emission savings from low-carbon fuels**. The hydrogen market in Europe is developing fast, so it is key to provide clarity about this methodology as soon as possible. Furthermore, **the necessary Delegated Acts need to be adopted within 6 months of entry into force of this Gas Directive**.

Low-carbon hydrogen

The only right definition the EU can set

As stated in the Hydrogen Strategy, the priority for the EU is to develop renewable hydrogen production capacity – a goal we strongly support. However, the Hydrogen Strategy also mentions low-carbon hydrogen as a transitional fuel in the short- and medium-term. But low-carbon hydrogen is still non-renewable hydrogen and its deployment should not stand in the way of the deployment of fully renewable hydrogen.

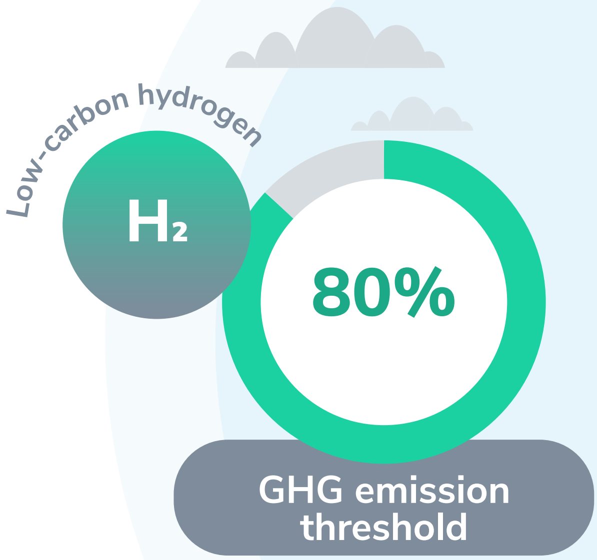
The Gas Directive defines a fraction of the non-renewable hydrogen as 'low-carbon hydrogen' or 'hydrogen the energy content of which is derived from non-renewable sources, which meets a greenhouse gas emission reduction threshold of 70%'[12].

The benchmark to compare the greenhouse gas emissions is the fossil fuel comparator, whose climate impact is set at 94 gCO_{2eq}/MJ[13]. This definition aims to cover hydrogen produced via Steam Methane Reforming with carbon capture or produced via electrolysis supplied with non-renewable low-carbon electricity.

Yet, to ensure that 'low-carbon hydrogen' really has a low environmental impact, **the GHG emission threshold should be set at 80%, compared to the fossil fuel comparator, which corresponds to 18.8 gCO_{2eq}/MJ or 2.26 kg CO_{2eq}/kg H_2**.

Setting the threshold at this level is entirely feasible and aligns well with existing legislation. In fact, this threshold will already enter into vigour in 2026 for biofuels, bioliquids and biomass fuels, used for the production of electricity, heating and cooling in installations starting operation from 1 January 2026. Meeting this threshold is technically feasible by controlling the upsteam leaks of methane (≤ 0.3%) and the carbon capture and storage rate (≥ 83% where current technology can meet 90%)[14].

It is also worth mentioning that the threshold is 2.26 kg CO_{2eq}/kg H_2, in line with limits set by the United Kingdom (2.4 kg CO_{2eq}/kg H_2)[15] and the USA (Tier 2: 2.5 kg CO_{2eq}/kg H_2)[16]. Aligning with these thresholds will therefore facilitate international coherence.



Chain of custody models

Ensuring full transparency for hydrogen

Hydrogen supply chains

The case for segregation

Hydrogen should have a low life cycle carbon impact when produced – but not only at that stage. It must also keep its low life cycle carbon impact as it is transported to the consumer. This is determined by the shipping method used: from the production unit to the final user.

Currently, the bulk of hydrogen production occurs at the site where it is processed afterwards. For large quantities, there is a direct and unique pipe between the production site and the consumer. Small batches of hydrogen are transported on the road using specialised gas trucks. In both cases, hydrogen from a single source reaches the consumer.

Sometimes, dedicated hydrogen pipelines provide some (petro)chemical industries with hydrogen. However, as hydrogen production expands and gradually replaces fossil gas, natural gas grid operators are also exploring the construction of dedicated hydrogen pipelines – or repurposing parts of their natural gas grids into hydrogen ones. New and repurposed pipelines will distribute hydrogen from various sources, with different levels of life cycle carbon impact.

For transport purposes, hydrogen should always have its own dedicated pipes. The intention to add hydrogen to natural gas (and its transport pipes) – also known as blending – is unacceptable. In theory, this practice aims to partly decarbonise the fuel supply but, in order to be compatible with current systems using pure natural gas, only up to 10% of hydrogen can be added to the blend[17]. This means that fossil gas would remain the lion's share of the blend, **locking in fossil gas in the energy system**.

Even more worrying, the massive use of hydrogen in blending would eat into the supplies needed in applications that actually make sense. Let's examine what it would take if we replaced 10% of the natural gas currently consumed in the EU with renewable hydrogen. If that happened, the EU would need to produce more hydrogen from renewable energy than it foresees by 2030 in its Hydrogen Strategy. The EU would also need to channel all of its production into blending – and it still would not be enough to reach 10% of today's gas consumption. Meanwhile, the applications for which hydrogen is a viable solution would be left without supplies[18].

Not all hydrogen consumed in a territory will be produced domestically. The European Union, for instance, sets a target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of renewable hydrogen imports by 2030[19]. Distant countries with a high potential for renewable energy, such as Oman, Namibia or Chile, come forward as hydrogen producers, not only for Europe but also for other parts of the world.

Shipping hydrogen over such long distances poses particular challenges, however. Hydrogen gas has a low density; it would require large ships and/or a lot of shipments to transport significant amounts overseas. Hydrogen can be liquified to increase its density, but that would require a very low temperature (-253 °C).

An alternative approach is to convert hydrogen into other molecules, such as ammonia, methanol or synthetic natural gas (methane)[20], which are much easier to ship. These hydrogen carriers can be distributed in Europe in bulk carriages or via pipelines. Some of these carriers may be reconverted to gaseous hydrogen and mixed with hydrogen from other sources. Synthetic natural gas, though, will be blended with fossil natural gas and will delay its phase-out.

Batch freights are the best options to ship renewable and low-carbon hydrogen separately from non-renewable hydrogen – but are unsuitable to convey the large amounts that will be needed. Pipelines can convey large volumes of hydrogen – but should be dedicated to hydrogen only. **Blending hydrogen with natural gas must be avoided as it would destroy the sustainable nature of renewable and low-carbon hydrogen completely.**

The hydrogen logistic chain determines whether renewable and low-carbon hydrogen can retain its nature. Hydrogen infrastructure should be designed and built around that idea.

Logistic chains need to be able to, first and foremost, segregate renewable hydrogen from its non-renewable counterpart. Then, within the non-renewable fractions, low-carbon hydrogen and high-carbon hydrogen must also be segregated. This will allow for better guarantees to the end-consumer that the delivery is in fact renewable or low-carbon.

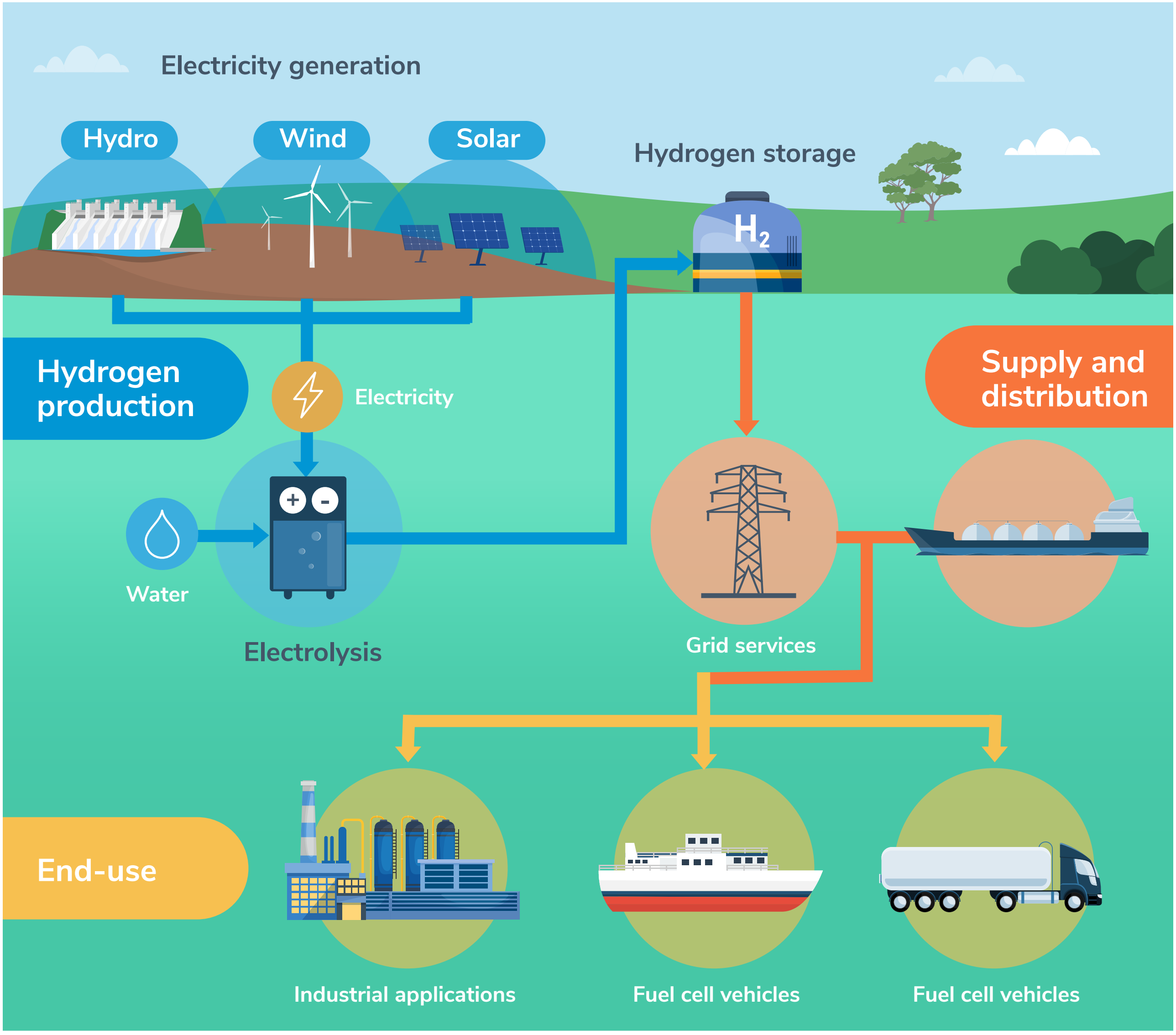


Figure 2 Own analysis based on Australian Hydrogen Roadmap

Chain of custody models

Dedicated hydrogen grids should be designed to supply hard-to-electrify sectors only. To develop such networks, we need credible systems to track and trace renewable and low-carbon hydrogen, especially when such hydrogen is mixed with that of less sustainable origin.

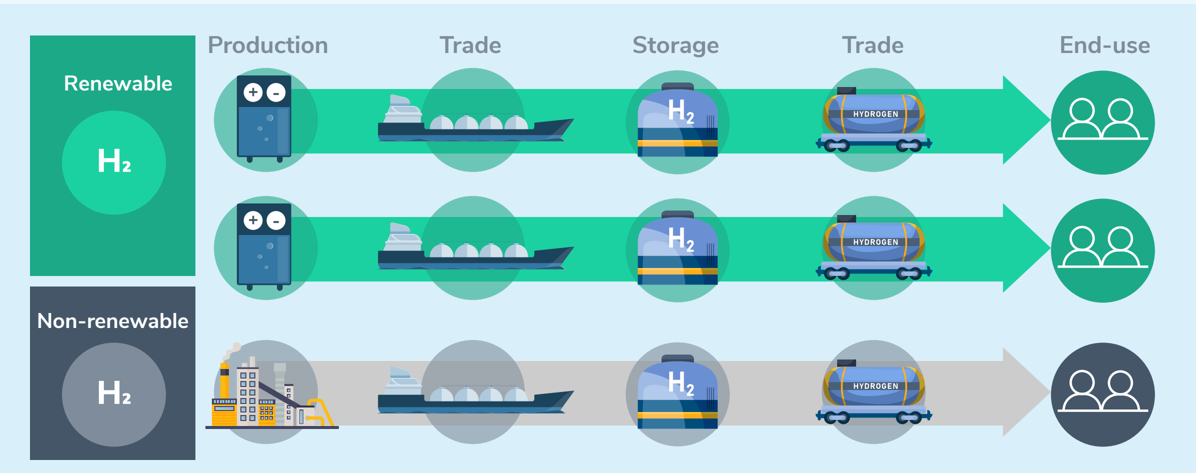
There are many systems used to determine the origin of energy commodities along the supply chain, as well as properties such as GHG emissions, or other environmental or social impacts. They are called 'chain of custody' models. They define how a product and its associated characteristics are matched throughout the value chain until it reaches the final user. Chain of custody models are instrumental in ensuring that hydrogen is renewable in origin and channelled towards priority end-users.

According to the different levels of physical product traceability, there are five categories of chain of custody models. Below we go on to explain how they work in the case of hydrogen, and how they are linked to the claims made about the renewable origin of hydrogen.

Model 1 Identity-preserved

Identity-preserved systems keep a batch of products from a specific origin entirely separate from other batches from different origins across the entire supply chain, even if all batches comply with the same (sustainability) criteria.

According to this system, renewable hydrogen from production site A may not be mixed with renewable hydrogen from production site B, let alone with non-renewable hydrogen from any other production site.



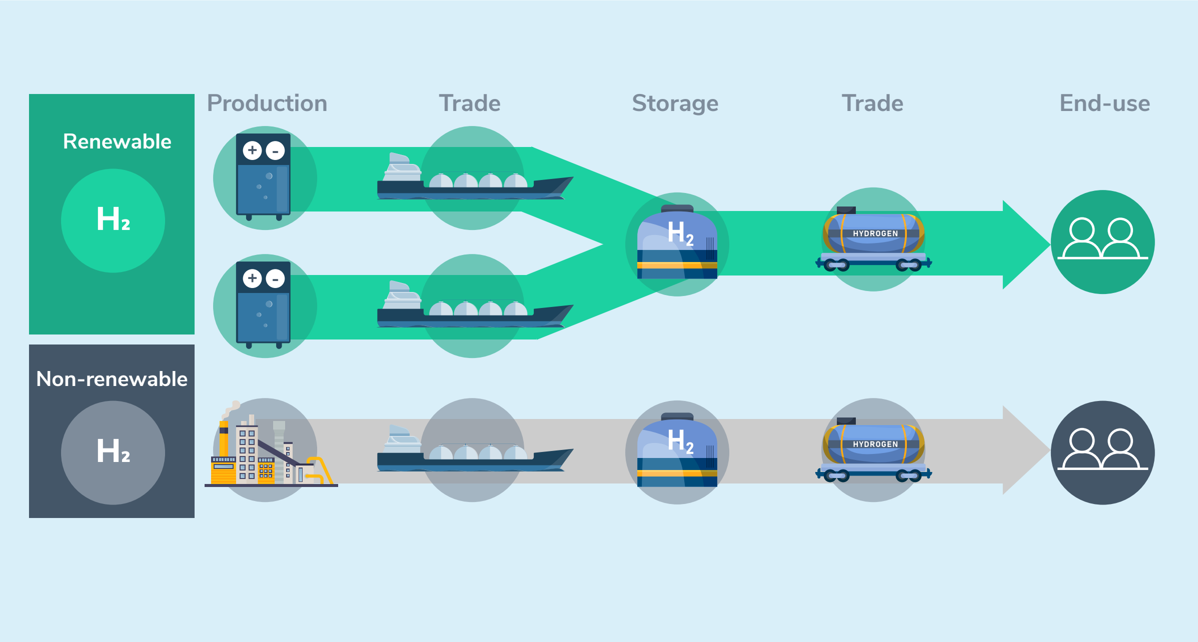
Because of the separated treatment, the identity-preserved system is the most rigorous with regards to the traceability of products. The product, its characteristics and associated documentation can be traced back to a single point of origin. The system, however, entails high costs due to the specific logistics requirements.

Identity-preserved systems can monitor small batches of renewable hydrogen shipments in gas trucks. If the hydrogen is transported via pipelines, there must be a single and direct connection between a specific hydrogen production unit and the hydrogen offtake point.

Model 2 Segregation

Segregation systems allow products that comply with (sustainability) criteria from one source to be mixed with compliant products from another source. Still, they do not allow the physical mixing of compliant and non-compliant products at any of the steps of the supply chain.

Renewable hydrogen from production site A may be mixed with renewable hydrogen from production site B, but not with non-renewable hydrogen from any other production site.

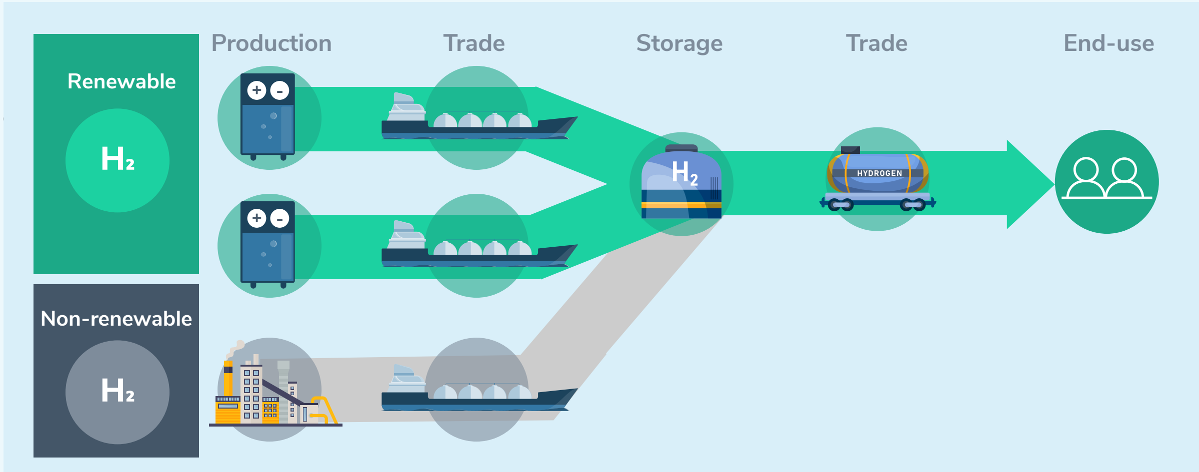


While remaining stringent in terms of traceability, the segregated system is more flexible and less costly to operate than the identity-preserved system.

Segregation can track shipments of small batches of renewable hydrogen in gas trucks. For hydrogen transported via pipeline, the pipeline should only convey renewable hydrogen, possibly produced in multiple units.

Model 3 Controlled blending

Controlled blending chain of custody models allow mixing products that comply with (sustainability) criteria with non-compliant ones. However, the physical segregation of compliant products is maintained until the final point of blending or mixing for a specific batch. Also, the mixing of compliant and non-compliant products is controlled and recorded, so that it is possible to track the amount of compliant content in the final mix.



Controlled blending can be used for shipments of batches containing both renewable and non-renewable hydrogen. It is less suited for hydrogen transported via pipeline. Tracking gas mixtures in a pipeline can be challenging, especially if the offtake profiles by some hydrogen customers vary considerably in time.

Model 4 Mass balance

Mass balance systems are used for supply chains in which products that comply with (sustainability) criteria are mixed with products that do not. This is done before products are delivered to the end-consumer.

Mass balance systems take into account both the production process itself, and the inputs and outputs that happen along the way. Over a predefined period of time, the total amount of compliant product leaving the supply chains and delivered to the end-consumers must be equal to the amount added to the supply chain. Different units can be used to determine this share: mass, volume, energy content, number of moles.

For example, in order to sell 1 GWh of renewable hydrogen to a steel factory over a month, a supplier must add the same amount to the supply chain within that month. The origin of the actual molecules delivered to the factory is not necessarily renewable.

There are many possible variants in mass balance systems. The main variables are:

- **The size of the system** in which compliant products and non-compliant products are mixed.

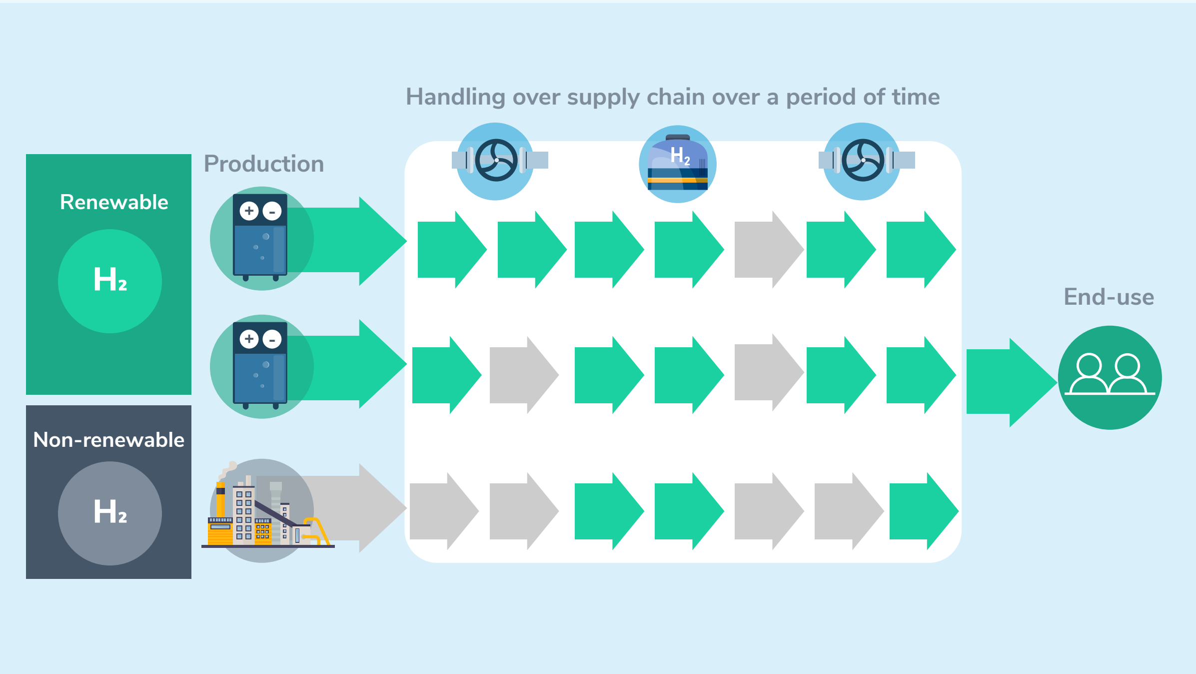
  The size of the system can vary considerably. It may be a single gas truck in the case of small batches of hydrogen, a particular pipeline, or a country's whole hydrogen pipeline network. The system could even comprise all hydrogen pipelines of an entire continent, without the pipelines being interconnected. This would allow a concrete pipeline containing gas-powered hydrogen to deliver energy certified as 'renewable'.

- **The timespan used** to verify the composition of the output versus the input (is the mass balance made over a month, a quarter, a year?). For instance, the timeframe for balancing biofuels in the EU may not exceed 3 months[21].

- **How compliant claims are linked to deliveries**. There are two options:

  - **Proportional:** all end-consumers receive products containing an equal share of compliant product. For example, every client receives hydrogen that is, say, 20% renewable. This option tries to reflect the real share of the compliant product in the energy supplied.

  - **Free allocation:** a share of consumers receives fully compliant products only. In our example, 20% of the customers receive fully renewable hydrogen; the remainder receive molecules not marketed as renewable. This option misleads the end-consumer, and it does not stimulate the hydrogen supply chain to move towards a fully renewable future.

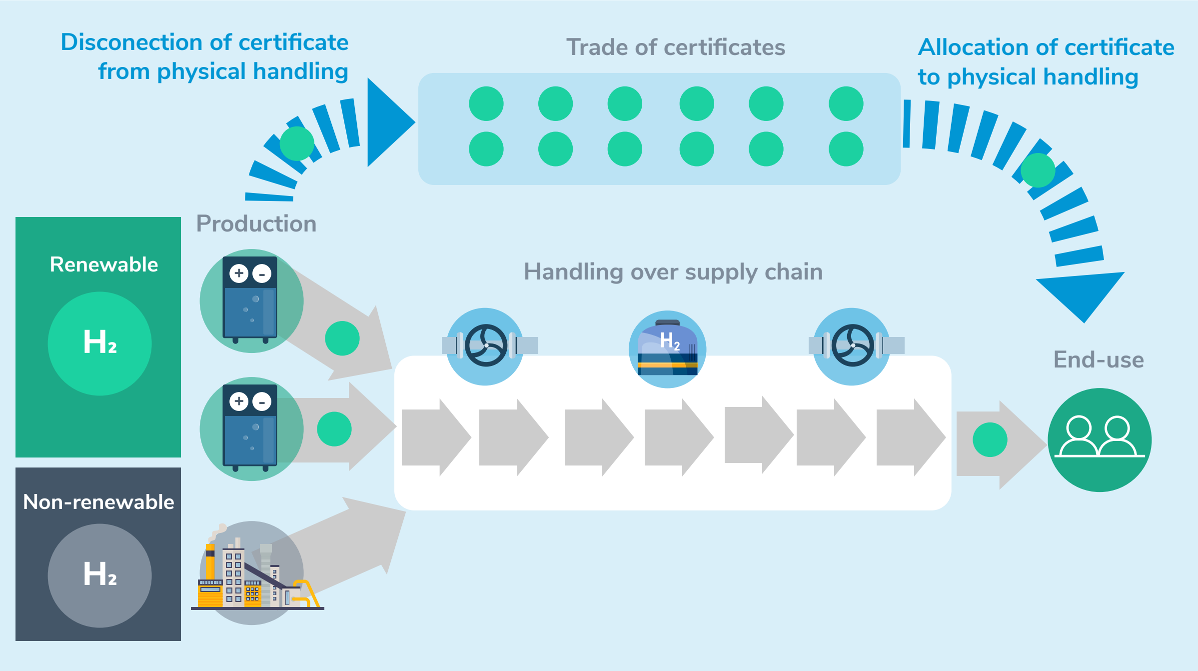


Model 5 Book and claim

Book and claim systems do not consider supply chains but markets. Any physical connection between the flow of the goods and their claimed characteristics is lost.

For goods produced following specific environmental requirements, a certificate is issued claiming associated environmental characteristics. Certificates are then detached from the physical goods they actually correspond to, and freely traded (often via an online platform). Certificates can be bought to claim the associated environmental characteristics corresponding to the amount of goods produced following the specific set of environmental requirements.

Controlled blending chain of custody models ensure that the end-product contains a well-monitored proportion of certified content, allowing specific end-use claims to be made.



One infamous example of a book and claim system is the Guarantees of Origin (GO) system: the model used to track and trace renewable electricity from source to customer in the European Union. This system has many shortcomings, as we showed in our 2020 briefing[22].

Since the GO is detached from the physical flow of electrons, buying it is not a synonym for purchasing renewable electricity. This becomes even more illogical when there is no common infrastructure: a consumer in any EU member state can buy a GO from Iceland even if the electricity grid of Iceland is not connected to continental Europe.

Moreover, the general public often confuses the nature of the electricity produced in their country (as specified by issued GOs) with the nature of the electricity consumed (purchased GOs). This is especially true in countries with a high share of renewables in their electricity mix, which often sell their GOs to other states. Even after electricity has lost its renewable nature (GOs are sold), the general public still perceives their country as a producer of renewables.

Finally, the GO system failed to fulfil its promise of fostering additional renewable energy production. The bulk of the GOs is delivered by installations already functioning well before the Renewable Energy Directive entered into force, such as hydro dams and waste incinerators.

We strongly believe that the origin of hydrogen should be tracked using the model that best reflects the true nature of the molecules delivered in each case. This way, consumers will be more likely to trust claims linked to ‘renewable hydrogen’ as part of a sustainable energy system. The next section focuses on how to pick the best option in the case of hydrogen.

How to choose the right model for hydrogen?

Renewable hydrogen is still scarce and tracing systems are in their infancy. Yet, as the market for hydrogen grows, so will production and trade. Meanwhile, grades of non-renewable hydrogen are being defined, such as 'low-carbon hydrogen' defined by the EU. That is why there is a growing interest worldwide in discussing the legal basis of hydrogen tracing.

Choosing the right chain of custody system when conveying hydrogen is set to become more and more critical. An illustrative example of market growth can be found in recent announcements made by the EU. In 2022, the bloc set a production target of 10 million tonnes of renewable hydrogen as well as an import target of 10 million tonnes of renewable hydrogen by 2030[23]. Each of these volumes represents 10% of all the natural gas consumed in the EU27 in 2019[24].

Chain of custody models should fulfil several missions. Namely, the chosen model must:

- allow for telling apart renewable hydrogen from its non-renewable counterpart at the gate of the consumer;
- prevent natural gas blends, as they destroy the sustainable nature of renewable hydrogen;
- enable hard-to-electrify sectors to be prioritised.

Based on these prerequisites, Table 1 assesses the different models of Chains of Custody discussed for tracking and tracing renewable hydrogen along the supply chain.

	Chosen chain of custody model				
	Identity preserved	Segregation	Controlled blending	Mass balance	Book and claim
Type of supply chain	Batch	Batch / Single pipeline	Batch / Single pipeline	Batch / Multi-pipeline network	Multi-pipeline network
It is dedicated for transporting hydrogen	✓	✓	✓	✗	✗
It prevents blending with natural gas	✓	✓	✓	✗	✗
It guarantees which production unit has produced the delivered H_2	✓	Partly	Partly	✗	✗
It guarantees whether H_2 physically delivered is renewable	✓	✓	Partly	Partly	✗
It channels H_2 into priority uses first	✗	✗	✗	✗	✗

Table 1 Assessment of different chain of custody models to track and trace renewable hydrogen in the supply chain

When choosing the right chain of custody model, we must first consider which supply chain will be needed to convey renewable hydrogen to end-consumers. Domestically produced hydrogen might go through a very different supply chain than the imported one. While the former will be transported as gas in pipelines, the latter may arrive as a liquid. The choice between gas and liquid form has implications on which chain of custody is the most suitable.

Gaseous hydrogen: mass balance

Domestically produced hydrogen usually remains in its gas form, and transported via grids. Currently, the hydrogen grid consists of isolated, not interconnected pipelines. However, in the future, some hydrogen pipes are likely to be interconnected. While the renewable hydrogen supply chain builds up, multiple sources working with different technologies will feed hydrogen with varying life cycle climate impacts to the grid, serving multiple end-consumers.

This layout of the hydrogen grid inevitably leads to a mixture of hydrogen from different origins within the grid. When hydrogen arrives at the gate of the end-consumer, it will be impossible to indicate which source the hydrogen originates from, nor will it be possible to claim that the delivered hydrogen is renewable. At best, we will be able to indicate the share of renewable hydrogen within the delivered mix.

Since tracing every single batch of hydrogen in a pipe is nearly impossible, we need to rely on estimates – but they must be as good an approximation as possible. To that end, **strict mass balance systems** are the most suitable Chains of Custody models. Only this way can we make credible claims about the share of renewable hydrogen in the delivered mix.

To be credible, the mass balance system should proportionally allocate the fraction of renewable hydrogen within the supply chain to all end-consumers equally. The system must not allocate all the renewable hydrogen in the mix to a share of end-consumers only. In short, we should avoid a situation when a few consumers are supplied with supposedly '100% renewable hydrogen', while other users of the same grid are sold unbranded molecules.

To determine this share, all inputs of renewable and non-renewable hydrogen must be monitored over a set period of time. The shorter that period, the more accurate the declared percentage of renewables in the mix will be.

Moreover, a given mass balance system should be restricted to physically connected pipeline systems – where hydrogen can freely flow. Mass balance systems should not allow aggregating the hydrogen flowing in not interconnected pipelines. This would allow for artificial transfers of renewable hydrogen between pipelines, opening the door to unjustified claims.

It should be noted, however, that a strict mass balance system does not prevent a producer of renewable hydrogen from receiving a premium from end-consumers who choose to pay more for renewable hydrogen. But this premium can only guarantee the production of a corresponding quantity of renewable hydrogen, not its physical delivery to the end-consumer.

Less strict mass balance systems – those allocating the renewable share to selected end-consumers only and/or covering not interconnected pipelines – do not allow to make credible claims about the quantity actually delivered.

This is even more the case for book and claim systems, which do not consider physical supply chains but markets. To illustrate, the Guarantee of Origin system for electricity allows Iceland to export the renewable nature of the electricity it produces to continental Europe even when it is not possible to export the electricity itself, as there is no power line conecting Iceland with the rest of Europe.

Liquid hydrogen: segregation & identity-presevered

Hydrogen is likely to be imported across continents in the form of liquid derivatives. This makes it much easier to transport it long distance, using ships, rail or even pipelines[25].

Cargos might be supplied by one production site, considering the magnitude of renewable hydrogen projects in exporting countries. In Oman, for instance, a renewable hydrogen project was announced in May 2021, consisting of 25 GW of onshore wind and solar PV capacity[26]. It aims to produce over 1.8 million tonnes of renewable hydrogen and up to 10 million tonnes of green ammonia per year[27].

Consequently, segregation and even identity-preserved models might be applicable as chain of custody systems for liquid hydrogen carriers. In the case of **segregation**, renewable hydrogen carriers from various sources may be mixed, but mixing with similar hydrogen carriers from a non-renewable source would not be allowed. **Identity-preserved** is stricter: concerned cargos must be kept separate at every step of the supply chain.

Mass balance systems are less strict than segregation as they allow fully renewable hydrogen carriers to be mixed with non-renewable ones. As the supply chains for international liquid-state carriers need to be developed virtually from scratch, it is better to create a dedicated supply chain for renewable hydrogen carriers immediately, opting for systems allowing for fully renewable hydrogen distribution.

Unlike gas hydrogen, liquid hydrogen carriers such as ammonia are incompatible with natural gas. Their physical and chemical characteristics prevent blending with natural gas by default. The exception is synthetic natural gas, which has the same properties as fossil natural gas, and the import of which will delay the phase-out of fossil gas.

Whether hydrogen is shipped as gas or as liquid determines which Chain of Custody model can make the most trustworthy claims.

For **domestically produced hydrogen** (usually conveyed as gas), a **strict mass balance system** is the most appropriate model. 'Strict' means proportional allocation, a short time period to make the balance and covering interconnected pipelines only.ww

For imported hydrogen (usually shipped as a liquid), **segregation is the most appropriate model** as it allows for building a dedicated supply chain for this type of renewable energy carriers.

Guarantees of Origin systems should not even be considered, as they allow to greenwash fossil gas as renewable.

Chain of custody systems
The right choice the EU must make

The EU applies two chain of custody systems to track and trace renewable energy:

- **Guarantees of Origin** – a book and claim system – for renewable electricity
- **Mass balance systems for biofuels,** bioliquids and biomass fuels

When revising the Renewable Energy Directive in 2018 (RED II), the EU called to extend the Guarantees of Origin system to cover renewable gases, which includes biomethane and hydrogen[28]. Following that call, European standardisers are reviewing standard EN 16325 – Guarantees of Origin related to energy, with the aim to include hydrogen in its scope.

However, as the current negotiations on the revision of the Renewable Energy Directive (RED III) progress, we can observe a positive shift in the approach: from relying fully on Guarantees of Origin, to using mass balance systems for tracking and tracing renewable and low-carbon fuels[29].

According to the latest proposal seen by the authors, both systems will coexist:

- Art 19 of the RED on Guarantees of Origin for energy from renewable origin states: "Member States shall ensure that a guarantee of origin is issued in response to a request from a producer of energy from renewable sources including gaseous renewable fuels of non-biological origin such as hydrogen";
- While a new article 31a obliges the European Commission to set a base to enable the tracing of liquid and gaseous renewable fuels and recycled carbon fuels. The article adds: "The interconnected gas system shall be considered to be a single mass balance system."

The mass balance system seems to prevail as Guarantees of Origin will need to be transferred to this database when registering a consignment of renewable fuels in the Union database.

The Commision's proposal for the revision of the Gas Directive also seems to confirm the preference for a mass balance system for low-carbon fuels, although it does state that guarantees of origin still need to be used to disclose the share of renewable gas purchased by the final customers[30].

The European Union now must complete this shift. To ensure that claims about the true nature of the delivered hydrogen are trustworthy – renewable or, if non-renewable, low-carbon – additional requirements are needed:

- The **Union Database should be used as the sole system for tracking and tracing renewable hydrogen and hydrogen derivates**.
- This database should only **apply the mass balance system to interconnected segments of the gas system**. The transfer of characteristics of hydrogen and derivates between segments of the gas system that are not interconnected should not be allowed.
- **The mass balance system should be used proportionally**. All connected end-consumers must receive information about the real share of renewable hydrogen in the hydrogen mix they are supplied with. Free allocation must not be allowed: renewable or low-carbon hydrogen must not be distributed to a share of end-consumers only.
- **Characteristics of renewable hydrogen and derivates should be revoked if it is blended with natural gas**. If not cancelled, renewable or low-carbon attributes may be transferred from hydrogen to natural gas. This would disguise the fossil nature of natural gas and lead to greenwashing, which is unacceptable.

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