STANDARDS RESEARCH

Advanced Classification of Hydrogen

Life Cycle Assessment and Beyond

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Executive Summary

Globally, the production and use of hydrogen are increasingly considered as central to the fulfillment of sustainable development goals. Hydrogen has the capacity to meet the demands for heat, power, and transportation, with fewer emissions of greenhouse gases and other air pollutants compared to traditional fossil fuels, and with reduced reliance on non-renewable resources. It can also sustain new economic development and employment opportunities that are consistent with a low-carbon future. However, the extent to which hydrogen contributes to these benefits differs widely depending on how it is produced, distributed, and used. Furthermore, users of hydrogen may value different aspects and impacts of its supply chain according to the sustainable development goals they prioritize (e.g., climate action, human health, or access to decent work), which can vary by community.

Currently, there is no formal system for classifying hydrogen supplies according to the sustainable development attributes of their supply chains. The absence of a common definition to which both suppliers and consumers of hydrogen can refer could result in market confusion, which could in turn inhibit the adoption of hydrogen systems. This could slow the pace of decarbonization that the use of hydrogen may otherwise advance.

Identification schemes that focus on promoting hydrogen supplies that have very low levels of carbon-intensity (CI) over their lifecycles, from production to distribution to point-of-sale, are emerging around the world. However, the requirements of some of these schemes exclude certain supplies of hydrogen based on their source feedstock, which narrows the scope of hydrogen supplies that can be beneficially scrutinized. Informal systems of colour coding hydrogen have emerged in response to the demand for hydrogen identified by a broader set of feedstock options, but the inherent imprecision and random assignment of colours in this approach risks further market confusion.

It is essential to develop a formal system for classifying all types of hydrogen to support commercial growth between suppliers and consumers, both regionally and internationally, and to help achieve sustainable development goals. The tools for conducting a lifecycle assessment (LCA) are well-developed and rely on standard methods and definitions. These standards can support a new classification system. Moreover, the implementation of durable, successful classification systems in other sectors offers guidance on best practices for communicating complex information in simplified formats.

Not only would an internationally accepted hydrogen classification system support market development but it may also complement government policies and regulations. In many national and regional jurisdictions around the world, the promotion of hydrogen is becoming a focus of decarbonization and economic development objectives. However, between these jurisdictions, policy support for hydrogen can be subjected to a variety of definitions and conditions. A common classification system could facilitate compliance and commerce, especially among neighbouring and trading jurisdictions.

The landscape scan conducted for this report included a review of policies impacting the market for hydrogen classification systems by jurisdiction, a review of LCA methods applicable to hydrogen supply chains, and an analysis of selected classification and consumer information systems developed by both industry and government and successfully embraced in other sectors. This report also presents insight gathered from stakeholders and experts through one-on-one interviews. The results of this landscape scan informed the following guidance on designing a hydrogen classification system:

- A hydrogen classification system's purpose should be to disclose basic information to hydrogen consumers about the essential sustainable development characteristics of production pathways;
- Data sources and LCA methodology used under a hydrogen classification system should reference a global standard to generate consistent, comparable CI values;
- Information communicated under a hydrogen classification system should be presented objectively and backed by transparency about data sources and methods of evaluation; and
- Top-line communication about a hydrogen classification system should strive for simplicity.

"According to the International Energy Agency, with strong growth in demand, the use of hydrogen could prevent up to 60 gigatonnes of carbon dioxide (CO_2) emissions between 2021 and 2050."

1 Introduction

Classification systems facilitate commerce among suppliers and consumers of products and commodities by creating a singular definition of the item being exchanged. Without classification systems, confusion can arise about exactly what is being produced and sold and how it should perform relative to buyers' expectations. The resulting uncertainty can impede commercial activity, particularly during the early stages of new market development when trust in unfamiliar products and services has yet to be developed. Hydrogen is currently facing such a challenge.

The use of hydrogen is being actively promoted by many governments around the world as an important part of their climate change plans. Nations that are party to the Paris Agreement have committed to working together to keep global temperatures from rising by more than two degrees Celsius above pre-industrial levels [1]. Fulfillment of this goal requires substantial and rapid decarbonization of their respective economies by 2050. According to the International Energy Agency, with strong growth in demand, the use of hydrogen could prevent up to 60 gigatonnes of carbon dioxide (CO_2) emissions between 2021 and 2050, representing 6% of total cumulative reductions in greenhouse gas (GHG) emissions under their Net Zero Emissions Scenario [2]. The Hydrogen Council, an initiative led by CEOs from nearly 150 multinational corporations, estimates that hydrogen can abate approximately 80 gigatonnes of CO_2 by 2050 and 730 megatonnes by 2030, which is more than the combined total annual CO_2 emissions of the United Kingdom (UK), France, and Belgium [3].

The commercial success of hydrogen is a matter of global importance, and its contribution to climate stabilization relies on accelerating market adoption. However, there is currently no simple way to distinguish different supplies of hydrogen according to sustainable development characteristics, including climate action. This is a problem because the key driver of market interest in hydrogen is its capacity to advance environmental, social, and economic indicators of change, tangibly and significantly.

Most of the GHG emissions associated with fossil fuels occur at the very end of their supply chains, usually when the fuels are combusted. In contrast, hydrogen combustion generates no (or very few) emissions that contribute to climate change or air pollution. Most emissions associated with hydrogen occur in the earlier links of its supply chain, during its production, conditioning, and delivery to market.

If hydrogen was produced in only one way, consistently using a single type of feedstock and process, then the emissions occurring upstream of its point-of-use would be of similar magnitude regardless of the system of supply. This is analogous to the production of gasoline, diesel, and aviation fuels, most of which are similarly derived from crude oils via the application of common principles of refining. However, hydrogen can be sourced from a diverse array of feedstock materials, ranging from renewable to non-renewable, that use radically different production technologies that rely on different forms of energy, including electricity, heat, sunlight, or a combination thereof. The GHG emissions associated with each different hydrogen production process can be different from another by an order of magnitude [4].

Without information about the emissions occurring upstream of its point-of-use, hydrogen consumers can only guess at the degree to which their purchase is actually contributing to their decarbonization goals. This matters because market demand for "green power" is growing, as demonstrated by the emergence of energy retailers, such as Bullfrog Power in Canada, who specialize in the supply of renewable energy to grid-connected electricity consumers [5]. Buyers receive certificates representing the input of wind, solar, and run-of-the-river power to the grid. This suggests that customers care about the impacts of their energy choices upstream of the point-of-use. More broadly, the unabated coal-fired power generation in Canada is currently governed by Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations (SOR/2012-167) [6]. Given the evidence that the public cares about what energy sources are tapped for electricity, the sources of hydrogen are expected to be similarly scrutinized.

The need to differentiate supplies of hydrogen according to feedstock source and production process has already driven the creation of an informal classification system, which uses colours to distinguish types of hydrogen production. However, this colour-coding system has not been formally standardized and can vary between different sectors and markets. A common interpretation of the colour codes is [7]:

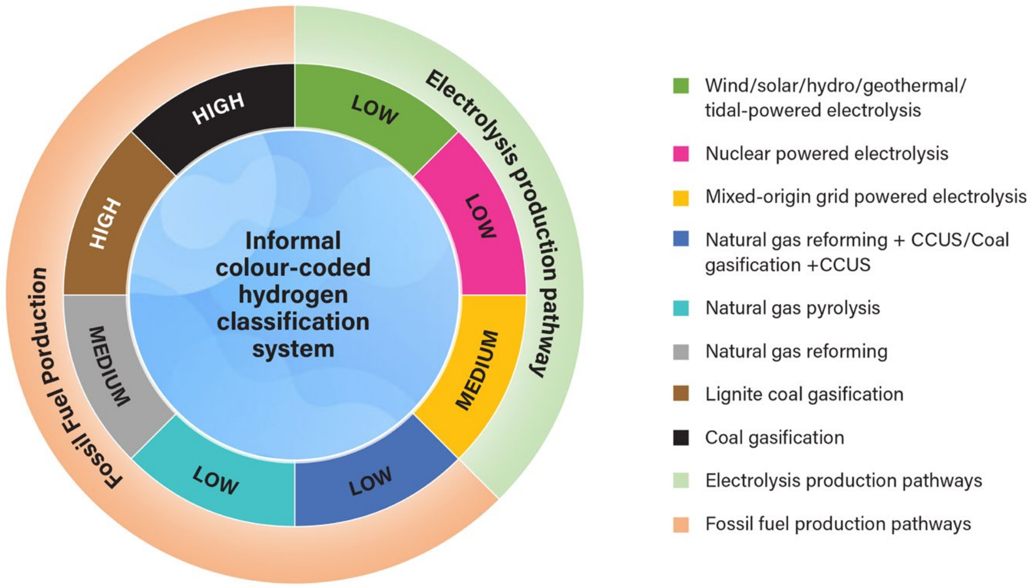
- **Green hydrogen:** Hydrogen produced by electrolysis using renewable electricity (i.e., green power). The colour green also sometimes refers to the use of biomass as a renewable source of hydrogen, extracted through gasification, or water electrolysis via biomass-fired power.
- **Pink hydrogen**: Hydrogen produced by water electrolysis using nuclear power.
- **Yellow hydrogen:** Hydrogen produced by water electrolysis using electricity supplied from transmission grids energized by a mix of different power sources.
- **Blue hydrogen:** Hydrogen produced from natural gas through methane reforming processes (e.g., steam methane reforming, autothermal reforming), where most of the by-product CO_2 is kept from entering the atmosphere by methods of carbon capture, utilization, and storage (CCUS).
- **Turquoise hydrogen:** Hydrogen produced from natural gas using pyrolysis methods and technologies, whereby the carbon in methane precipitates out as solid carbon-black material.
- **Grey hydrogen:** Same as blue hydrogen but without CCUS. Despite the release of CO_2 in its production, grey hydrogen is associated with fewer GHG emissions over its entire lifecycle than diesel.
- **Brown hydrogen:** Hydrogen produced via gasification of lignite coal, which contains higher concentrations of hydrogen than purer ranks of coal.
- **Black hydrogen:** Hydrogen produced via gasification of coal containing lesser concentrations of hydrogen than lignite coal. Processing this feedstock traditionally releases the most amount CO_2 per unit of hydrogen produced.

The above definitions are visually presented in Figure 1.

As shown in Figure 1, the colour codes do not map to unique hydrogen feedstocks. For example, blue and turquoise hydrogen both represent natural gas as a feedstock, but are associated with different levels of GHG emissions. Furthermore, green and pink hydrogen map to different sources of electrical energy inputs but share similarly low levels of GHG emissions.

The fact that this colour-coded hydrogen classification system exists, albeit informally, demonstrates that suppliers and consumers want to differentiate hydrogen by *more* than just GHG emissions. There are already standard methods for determining the lifecycle GHG emissions of fuels and materials (i.e., emissions occurring over the entire supply chain of the product and at its point-of-use), including hydrogen, that are in

Figure 1: Informal colour-coded hydrogen classification system. Low, medium, and high designations represent carbon-intensity of the hydrogen colour. Based on colour definitions in [7]



widespread use. Beyond GHG emissions, the market appears to value other attributes of the hydrogen supply chain, which raises the following questions:

- What other attributes of supply chains matter within new markets for hydrogen beyond GHG emissions?
- Why are feedstocks important enough to define hydrogen by colour?
- Why has a colour-coded system of classification emerged, instead of more detailed descriptions that can convey more information with greater precision?

This report presents the findings of an investigation guided by these questions. It provides a scan of the landscape shaped by the emerging market for hydrogen as a fuel and an agent of decarbonization, and discusses the perceived needs of suppliers and consumers for a more effective method for classifying hydrogen. Finally, it provides guidance on the development of a hydrogen classification system, informed by best practices in lifecycle assessment (LCA) and consumer information systems.

Put simply, the attributes of hydrogen delivered to a customer are the attributes of its supply chain. Without a formal classification system for hydrogen that readily expresses the sustainable development characteristics of its supply chain, the development of new hydrogen markets may be impeded by uncertainty and confusion over precisely what is being traded. This could put ambitious global decarbonization goals at risk. The development of a formal classification system for hydrogen can create shared clarity between producers and consumers on the attributes that are most important to the market, which can enable the commercial exchange of hydrogen to grow unimpeded.

2 Methodology

The objective of this report is to inform the development of a classification system for distinguishing hydrogen according to the GHG emissions associated with its production pathway, as well as by other important sustainable development attributes from the user perspective. Ideally, such a system would be sufficiently accurate and comprehensive to facilitate meaningful comparisons among hydrogen supply options yet balanced against the need for simplicity and expediency in consumer and stakeholder decision-making.

Pursuant to the objective, four distinct elements of research and analysis were conducted:

- A jurisdictional scan of existing and developing **policies related to the carbon-intensity (CI)** and supply chain characteristics of hydrogen supplies;
- A review of prevailing **methods for estimating the CI** (i.e., a measure of GHG emissions associated with a product's supply chain) of hydrogen produced and delivered to consumers, and differences among those methods;
- An assessment of **best practices in consumer information systems** and product labelling relating to human health and environmental attributes, including a review of hydrogen certification programs; and
- A synthesis of criteria, principles, and preliminary concepts, based on the findings of the research, that should be considered in the development of industry-led standards for hydrogen classification systems.

Information was gathered in three phases through secondary and primary modes of research:

- **Secondary research** (Phase 1). This involved a comprehensive review of published literature, publicly accessible reports, and government communications on the topics identified above (CI-focused policy, LCA methods for hydrogen, and consumer information systems). More than 70 sources of information were reviewed, and are included in the References section.
- **Primary research** (Phase 2). This involved direct engagement with hydrogen sector stakeholders and experts. Key findings emerging from the secondary research in Phase 1 informed (and were incorporated into) an interview guide, which was circulated to a diverse array of individuals and organizations, most of whom accepted the invitation to be interviewed. Fifteen individuals were interviewed, each representing one of the following aspects of the hydrogen supply chain and areas of expertise:
  - Hydrogen producers and marketers;
  - Hydrogen distributors;
  - Hydrogen users;
  - Hydrogen equipment manufacturers and system builders;
  - Government stakeholders;
  - Hydrogen industry associations; and
  - LCA model developers and users.
- Collectively, the interviewees provided an international spectrum of perspectives, participating in interviews from their locations in Canada, the United States (US), and Europe, and some having active interest in each of these regions, as well as in markets in Asia.
- The interview guide is provided in Appendix A. It consists of 20 discussion points across the following three themes:
  - CI of hydrogen supply chains and LCA models;
  - Beyond CI, other important attributes of hydrogen supply chains; and
  - Consumer information systems.

The project concluded with Phase 3, in which the project team considered the findings of the secondary and primary research and developed a set of recommendations to guide the development of a hydrogen classification system should the industry choose to respond to the need and the opportunity. Prospectively, a hydrogen classification system emerging from this process could be further developed into a standard if it is embraced by producers and users as an effective tool for expediting commerce and supporting the growth of new hydrogen markets around the world.

3 Jurisdictional Scan of Policies Affecting Hydrogen Production and Supply Chain Attributes

The jurisdictional scan conducted for Phase 1 of this report found that a range of policies have already been established or are being considered in jurisdictions around the world to promote a transition away from the reliance on fossil fuels and toward the adoption of alternatives that have one or both of the following characteristics:

- They advance sustainable development goals, which can be economic, social, and environmental in nature; and
- They create fewer GHG emissions compared to the fuel being displaced, thus contributing specifically to decarbonization goals.

The scope of sustainable development goals identified under a given policy can be quite broad. In 2015, the United Nations (UN) established 17 interlinked objectives called the UN Sustainable Development Goals, which are shown in Figure 2 and span the domains of poverty, justice and equality, and climate action [8].

In contrast with the breadth of issues covered by the UN Sustainable Development Goals, the promotion of alternative fuels tends to focus more narrowly on climate action, although it can also stimulate economic growth and create new employment opportunities. Achieving decarbonization in the context of fuels or other commodities usually relies on one or both of the following strategies:

- **Fuel switching:** A specific alternative fuel (or fuels) is identified and, on the basis of its desired attributes, a mandate requiring its use is set or an incentive is offered by government. Typically, the attribute of primary interest is lower GHG emissions associated with the fuel's production or end use. One example is the required blending of renewable fuels into fossil fuels, such as a regulated blend rate of 5% bioethanol in gasoline sold at vehicle refuelling stations in Canada [9]. Another example is an economic incentive to support the conversion of gasoline engines in vehicles to operate on natural gas instead [10]. A mandate or incentive for the purchase of an electric vehicle (EV) is another type of fuel-switching policy that reduces GHG emissions (substantially if the electricity is sourced from low- or zero-emitting power sources).
- **CI reduction:** The overall GHG emissions associated with the production, distribution, and use of one unit of a given fuel (often measured by energy content) is considered the CI of that fuel. Regulations or incentives can be used to motivate a reduction in fuel CI over a defined period (usually several years). To provide flexibility in compliance with a mandate, regulated parties are usually permitted to:
  - reduce the CI of the incumbent fuel sold in a jurisdiction; or
  - add fuels that are less carbon-intense to a mix of fuel products sold in a jurisdiction, thus reducing the overall *average* CI of all fuels sold therein.

As an example of the latter, a fuel retailer may add EV charging stations to a retail forecourt. The lower CI of the electricity sold to EV customers offsets the higher CI of the gasoline sold. Alternatively, a natural gas distributor may procure biogas to blend into its supply, thereby reducing the CI of the heating fuel delivered to customers (the methane in biogas is the same as in natural gas, except it is biogenically sourced and not fossil-based). Such policy frameworks also permit the sale of credits by alternative, low-carbon fuel producers to regulated, traditional fuel suppliers to facilitate their compliance with a CI mandate.

Figure 2: UN Sustainable Development Goals

Hydrogen can be implicated in either of the strategies described above. A policy may directly press for the use of hydrogen in a certain fuel-switching application or it may indirectly incentivize the adoption of hydrogen. In Section 4, the methods for calculating CI values (particularly for hydrogen) will be explored in more depth.

The following terms are frequently used when discussing decarbonization and calculating CI in the context of fuels:

- **Lifecycle:** The entire cycle of a product beginning with **production**, which includes the collection of raw materials and feedstocks needed for synthesis and manufacture, moving to **distribution**, which includes transport from production facilities to users, and ending with **use**, which includes the generation of any waste and by-products of use.
- **Low-carbon fuel**: A fuel that over its lifecycle emits fewer GHG emissions than the fuel it is displacing. The lifecycle CI of a fuel is the typical measure by which a fuel is compared and is either designated low-carbon or not.
- **Pathway:** A unique series of supply chain links that define the fuel delivered to the customer according to its production process. Crude oil refined into diesel for use in a truck is one example of a pathway. Biomass gasified into a synthesis gas that is then condensed and hydrotreated to produce synthetic diesel for the same truck is another. Both fuels are chemically equivalent, but they emerge from different pathways and have different CIs due to the net emissions over their respective lifecycles.
- **LCA model:** A numerical model that quantifies one or more distinct attributes of a pathway. Certain LCA methods (and some specific LCA models) are referenced in policy as the prescribed tool for calculating the CI of fuel pathways. For example, the regulation for California's Low Carbon Fuel Standard (LCFS) requires use of the CA-GREET3.0 LCA model to measure compliance [11], and the Fuel Life Cycle Assessment Model (Fuel LCA Model) is identified as a CI calculator for use under Canada's Clean Fuel Regulations [12]. In both cases, the regulating authorities administer the LCA models and maintain currency of the data inputs.

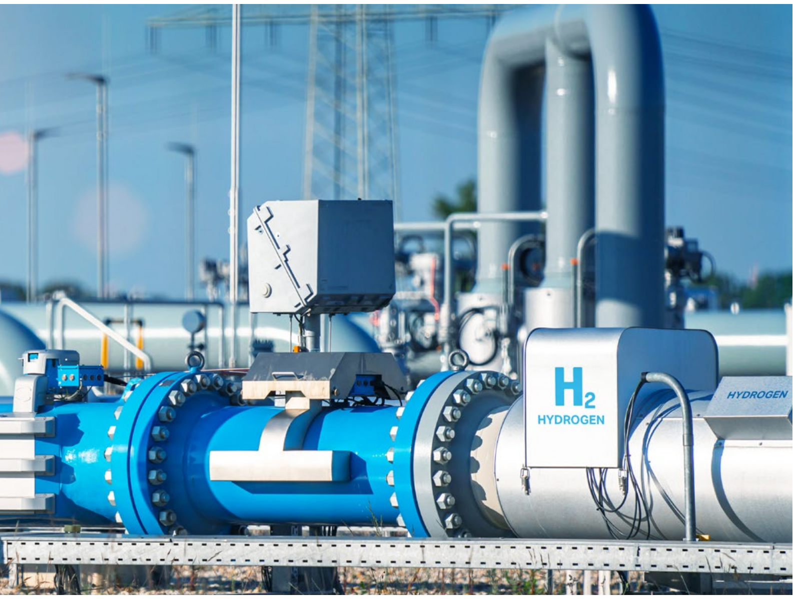
For context, the CI of gasoline and diesel sold in North America are often calculated to be approximately 100 grams of carbon dioxide-equivalent per megajoule (gCO_2e/MJ), whereas hydrogen produced by electrolysis using passive renewable power, such as from wind turbines, would approach 0 gCO_2e/MJ [13]. If the lifecycle calculation encompasses fabrication, installation, and maintenance of the turbines, then the CI might be a few grams higher, but this is disregarded in most models as being outside the boundaries of analysis. These details are explored further in Section 4.

Sections 3.1 through 3.8 summarize the policies with the most relevance to hydrogen as a pathway to decarbonize energy systems, and in some cases, as a chemical agent used to decarbonize manufacturing processes. These policies were identified through a scan of the following jurisdictions that have public declarations to promote hydrogen as part of their sustainable development or climate action plans:

- Canada
- United States
- Mexico, Central America, and South America
- European Union
- Australia and New Zealand
- China, India, and Japan
- The Middle East and Africa

The jurisdictional scan was organized around three general research queries:

- What is the stated purpose of an identified policy instrument (e.g., regulation, code, or standard) within a given jurisdiction, and is hydrogen implicated directly or indirectly?
- How do the policy instruments work? That is, who is targeted or obliged to comply, how is compliance fulfilled, and are any specific LCA models or tools referenced?
- Do the policy instruments make any special provisions for hydrogen?



"Aside from CI, no policy in Canada promotes or restricts hydrogen by its supply chain attributes."

3.1 Canada

The federal government and several Canadian provinces have produced hydrogen vision and strategy documents that broadly assess the potential for new hydrogen systems to contribute to decarbonization and generate new economic opportunities. Some include aspirational targets, but none obligate parties to undertake hydrogen initiatives. Accordingly, there are no regulatory requirements that specifically promote hydrogen production or use in Canada, but there are regulatory frameworks under which hydrogen is encouraged along with other low-carbon fuels. Under these policies, the less carbon-intense the supply chain, the more value the hydrogen has as a means of compliance. Aside from CI, no policy in Canada promotes or restricts hydrogen by its supply chain attributes.

3.1.1 Clean Fuel Regulations

Canada's Clean Fuel Regulations (SOR/2022-140), also known as the Clean Fuel Standard, were developed to support the goals of the Pan-Canadian Framework on Clean Growth and Climate Change, which was adopted in 2015 by the federal government and most of the provinces and territories [14]. A centrepiece of the framework is carbon pricing, which is considered necessary to fulfill Canada's pledge under the Paris Agreement to reduce its GHG emissions by 40% to 45% below 2005 levels by 2030. However, the proposed carbon pricing schedule was not potent enough to deliver this scale of reductions from distributed sources of emissions, such as vehicles, so a clean fuel standard was proposed to progressively reduce the CI of all fuels, based on an LCA, supplied to users in Canada [15]. After a period of consultation and regulatory development, the Clean Fuel Regulations [16] were implemented in 2022.

The Regulations reference an LCA model developed by Environment and Climate Change Canada (ECCC) called the Fuel LCA Model [17], which is freely available to the public. It comes populated with data that generates CI estimates for a range of fuel pathways, including hydrogen. This allows users to select from a predetermined list of CI values that match their fuel, or to use their own data inputs to evaluate a unique fuel pathway of interest.

Under the Regulations, the permissible limit on the CI of fuels sold by obligated parties in Canada declines year over year (i.e., the practice becomes progressively stricter over time). Currently, the regulation requires the CI levels of fuels produced or imported for sale in Canada by suppliers to be at least 14 gCO_2e/MJ lower than in 2016. Fossil fuel suppliers are expected to reduce the average CI of their products through production efficiency improvements, increasing blends of renewable fuels, and using more renewable feedstock in their refining processes. Eventually, however, the Regulations are expected to require major transitions to alternative fuels with lower and lower CI levels.

Suppliers of fuels that are less than the regulated CI limit can register to earn credits, which can be traded to any supplier exceeding the threshold, thereby enabling them to comply with the standard in a given year. This credit trading mechanism is expected to resource new development of clean fuels. Most hydrogen pathways are expected to be promoted under the compliance schemes described above, along with low-carbon electricity and synthetic fuels (from both biomass and non-biological origins).

3.1.2 British Columbia's Renewable and Low Carbon Fuel Requirements Regulation

British Columbia (BC) was the first province to introduce a limit on the CI of fuels sold by producers and importers when it implemented its Renewable and Low Carbon Fuel Requirements Regulation (BC Reg. 394/2008) in 2010. It provides the model on which Canada's Clean Fuel Regulations were later based, and operates similarly in most respects. In 2023, the Regulation was amended and the required level of reduction in CI was adjusted to 30% below the pre-regulation average by 2030, to approximately 66 and 62 gCO_2e/MJ for diesel and gasoline, respectively [18].

BC's Renewable and Low Carbon Fuel Requirements Regulation is itself based on California's LCFS, which was developed in 2009 and is discussed in Section 3.2.3 [19].

Compliance strategies in BC's Regulation are the same as those in Canada's Clean Fuel Regulations, including credit trading. However, the BC Regulation allows the government to assign a limited number of credits to special projects that contribute to the Regulation's goal, which is to decarbonize transportation energy use within the province. Transportation activity contributes the most to BC's GHG emissions inventory, and the development of new, low-carbon fuel supply chains is a provincial priority. The assignment of credits having market value among regulated fuel suppliers has helped to fund the development of advanced clean fuel systems, including hydrogen infrastructure.

In addition to regulating the CI of the fuel pool in BC, the Regulation sets minimum renewable content levels of 4% and 5% for diesel and gasoline, respectively. This helps to maintain a market for bio-based and renewable fuels, such as biodiesel and ethanol.

BC's Regulation prescribes the use of the GHGenius v4.03 LCA model [20], which predates the federal government's Fuel LCA Model, so there may be some minor differences in the output CI estimates. This highlights the issue of different regulations on CI levels in fuels using different models in different jurisdictions. However, if the methods of LCA modelling are consistent, the differences should remain minor.

Finally, as with Canada's Clean Fuel Regulations, BC's Regulation qualifies some hydrogen products as low-carbon fuels.

3.2 United States

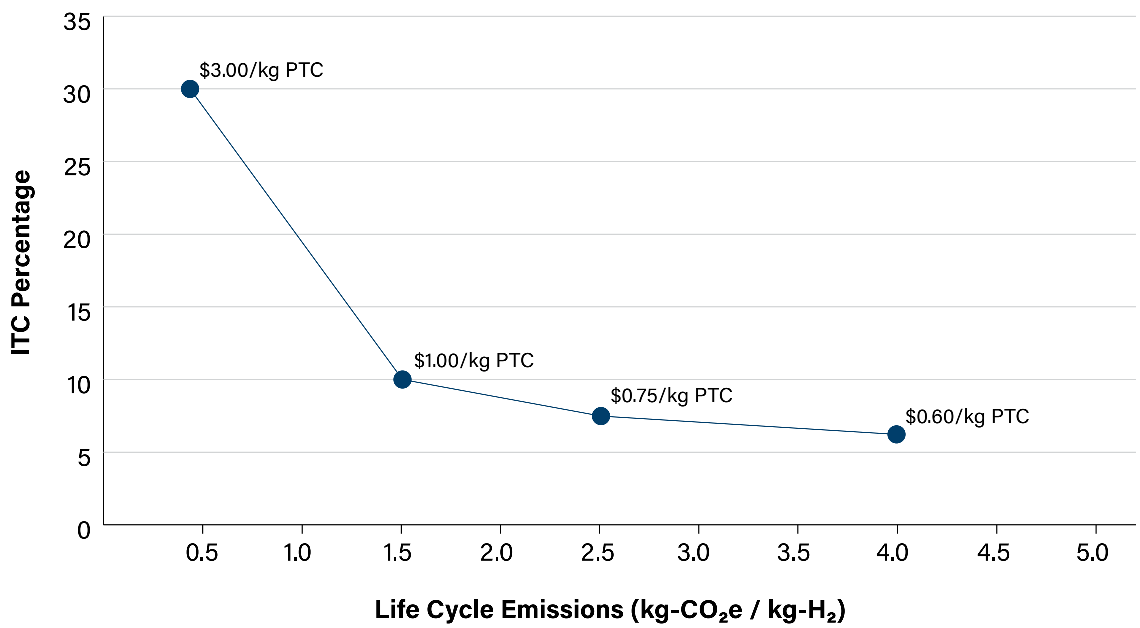
In the US, policy at the federal level and in some states (i.e., California) provides direct and indirect support for hydrogen on the basis of CI of supply, through regulation and through economic incentives. The most impactful of these policies are described in sections 3.2.1. through 3.2.3.

3.2.1 US Inflation Reduction Act, 2022

The US Inflation Reduction Act of 2022 (H.R.5376) authorizes nearly US$400 billion in federal spending on energy and climate change over a ten-year period, and represents the largest ever financial allocation to climate action [21]. It combines a wide array of clean energy tax credits under a single piece of legislation, including a subsidy for clean hydrogen production that scales according to the CI of the pathway.

As shown in Figure 3, the incentive can be realized by the hydrogen producer as an input tax credit (ITC) or as a production tax credit (PTC) [22]. The ITC subsidizes capital expenditure in new hydrogen production facility construction, while the PTC subsidizes the cost of hydrogen production. Both options are available to producers and each favours different circumstances, but the value of the implied subsidy is intended to be consistent.

Figure 3: Input tax credit (ITC) and production tax credit (PTC) schedule of US Inflation Reduction Act, 2022



The lifecycle GHG emissions of the hydrogen produced determine the level of incentive. Generally, electrolysis that is largely powered by renewable or nuclear power would qualify for a PTC of $3.00/kg, as would natural methane reforming coupled with CCUS of nearly all by-product CO_2. Respectively, this would correspond to green, pink, and blue hydrogen, according to the informal colour scheme described in Section 1. This incentive can be stacked with other incentives in the Inflation Reduction Act, including incentives for renewable power and CCUS, meaning that a hydrogen initiative could receive additional support if its supply chain includes these elements.

Notably, the Inflation Reduction Act also requires that recipients of the subsidy comply with a prevailing wage and apprenticeship requirement, in accordance with hours and rates determined by the US Secretary of Labor. This points to a supply chain attribute that is not focused on climate action, but on employment and local economic development outcomes.

3.2.2 US Department of Energy Clean Hydrogen Production Standard

The US Department of Energy has released a guidance document for a Clean Hydrogen Production Standard (CHPS) [23], which was developed to support the implementation of the Infrastructure Investment and Jobs Act of 2021 (H.R.3684). The H.R.3684 Act is broadly intended to promote hydrogen produced from fossil fuels CCUS, hydrogen-carrier fuels (including ethanol and methanol), renewable energy resources (including biomass), and nuclear energy. The CHPS prospectively establishes 4.0 kgCO_2e/kgH_2 (i.e., per kilogram of hydrogen produced) as the upper threshold for hydrogen produced to qualify for support under the Act, and defines clean hydrogen as having a CI of less than 4.0 kgCO_2e/kgH_2. For calculating CI, use of Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (described in Section 4.2.1) is recommended.

Note that in both the Inflation Reduction Act and the CHPS, the CI of hydrogen relates only to the production of hydrogen and not the impacts of its distribution or use. The phrasing used to define this system boundary is "well-to-gate" (see Figure 7 in Section 7.2.2).

3.2.3 California's Low Carbon Fuel Standard

California's LCFS was implemented around the same time as BC's Renewable and Low Carbon Fuel Requirements Regulation, and they share many similarities. The LCFS requires a reduction in the CI of California's transportation fuel pool of 20% by 2030 from a 2010 baseline, with regulated targets set for each year that grow progressively stricter. The purpose of the LCFS is to support the overall climate change goals set forth in California's Assembly Bill 32 (i.e., a 40% reduction in GHG emissions by 2030 from 1990 levels) [24].

The LCFS prescribes the CA-GREET3.0 LCA model [11], which allows stakeholders to calculate and submit their fuel CI values to the California Air Resources Board (the state agency responsible for administering air quality and climate change programming, including the LCFS), or choose from a list of default CI values for common fuel pathways. Hydrogen is among the default fuel pathways. Compared to the diesel and gasoline baselines, hydrogen fuel CI values range from modestly lower to net-negative [25]. Net-negative CI values correspond to biogenic sources as waste-derived hydrogen, indicating that the production of hydrogen is associated with more GHG emissions reductions than just those of the fuel it displaces.

As with CI-based regulations in Canada, the LCFS considers the full lifecycle of the fuel, including production, distribution, and use.

3.3 Mexico, Central America, and South America

Hydrogen is generally recognized as both a low-carbon pathway and an economic opportunity by national governments in Mexico, Central America, and South America. In particular, the governments of Mexico, Costa Rica, Panama, and Argentina have identified hydrogen as strategically important. Formal communications tend to focus on technology and skill development, and the jurisdictional scan did not identify any policy measures that focus on the lifecycle attributes of hydrogen, including CI.

In its Energy Sectoral Program 2020-2024, Mexico's Ministry of Energy committed to exploring hydrogen as part of its efforts to make sustainable use of the country's energy resources [26]. Costa Rica and Canada have signed a memorandum of understanding to collaborate on developing hydrogen systems in the context of climate action [27]. Panama has released a Green Hydrogen Roadmap, which aims to position the country to become a regional hub for low CI hydrogen imports and exports [28]. Finally, Argentina has developed a 2030 National Low-Emission Hydrogen Strategy, which focuses on leveraging its natural energy resources, including renewable power for electrolysis, to produce low CI hydrogen for domestic use and international export [29].

3.4 European Union

The European Commission (EC) has implemented two complementary policy directives (the Renewable Energy Directive and the Fuel Quality Directive, described below) to increase the input of renewable energy throughout the European Union (EU) and to support the GHG emissions reduction goals of member nations. The directives are also intended to support the EU's Hydrogen Strategy, adopted in 2020 [30], and the REPowerEU Plan presented in 2022, which aims to rapidly reduce the EU's dependence on energy imports from Russia [31]. Hydrogen is identified as a foundational element of both policy objectives. The REPowerEU Plan calls for the EU to produce 10 million tonnes and to import 10 million tonnes of renewable hydrogen by 2030. The EC directives establish the international import requirements pertaining to the CI of hydrogen supplies and the sources of production.

3.4.1 Renewable Energy Directive

The Renewable Energy Directive sets the overall targets for renewable energy use within the EU and the rules to fulfill these objectives. Currently, the directive requires that 32% of all energy use in the EU is from renewable sources by 2030, including fuels for transportation services [32].

Under the directive, the EC recently proposed new rules that define what constitutes renewable hydrogen in the EU, and how CI values will be determined using LCA modelling. The new rules focus on hydrogen and hydrogen-based fuels as renewable fuels of non-biological origin, which implies pathways relying on electrolysis powered by renewable sources.

3.4.2 Fuel Quality Directive

The Fuel Quality Directive covers a wide range of specifications to reduce emissions of air pollutants from vehicles and to promote a single fuel market that allows vehicles to operate equally, everywhere within the EU [33]. It also establishes a mandate and sets sustainability criteria for biofuels in road transportation in order to prevent the exploitation of land that is important for supporting biodiversity and fixed carbon, such as natural forests. Additionally, the directive establishes limits on the lifecycle CI of transportation fuels, currently set at 6% below a 2010 baseline of approximately 94 gCO_2e/MJ.

3.5 United Kingdom

The UK Low Carbon Hydrogen Standard was implemented in 2022 [34]. It is not a regulated requirement for hydrogen producers in the UK, but it serves to determine eligibility requirements under two separate government-funded, competitive grant programs:

- The Net Zero Hydrogen Fund, which supports the commercial deployment of new, low-carbon hydrogen production projects that launch within the 2020s; and
- The Hydrogen Production Business Model, which is a revenue support instrument for producers to bridge hydrogen facility operating cost gaps and thereby incentivize investment in low-carbon production.

Additionally, the UK Low Carbon Hydrogen Standard is now being considered for use in ongoing reporting and to facilitate certification schemes. It requires applicants to meet a GHG emissions intensity of no more than 20 gCO_2e/MJ up to the point of production. A hydrogen emissions calculator (HEC) is provided to applicants for reporting, but other models that follow the same methodology can also be used. Furthermore, submissions must include a risk mitigation plan to address the potential for fugitive hydrogen emissions.

Hydrogen is also indirectly incentivized under the UK Renewable Transport Fuel Obligation, which mandates large fuel suppliers to demonstrate that, in each year, a certain percentage of their fuel comes from renewable and sustainable sources [35]. Suppliers can earn credits toward compliance through the provision of advanced fuel types, including hydrogen from renewable sources (i.e., renewable power or biomass).

3.6 Australia and New Zealand

Australia is at an advanced stage of developing hydrogen systems according to its National Hydrogen Strategy, which is driven by a vision of Australia becoming a major user and exporter of hydrogen, levering its abundant natural resources [36]. Trials of hydrogen export have been demonstrated, with Japan as the recipient [37].

New Zealand is also exploring its potential to participate in the development of hydrogen systems as an international partner in projects and also as a host for clean hydrogen initiatives, thereby building domestic capacity and knowledge [38].

However, at the time of writing, neither country has developed hydrogen pathway rules or restrictions relating to CI or feedstock sources.

3.7 China, India, and Japan

The jurisdictional scan did not identify any policies in China, India, or Japan pertaining to hydrogen production pathways. However, China has been pursuing hydrogen systems from an economic development perspective, particularly relating to the export of technology. The China Hydrogen Alliance, an industry group, has defined three classes of hydrogen: low-carbon, clean, and renewable. Low-carbon and clean hydrogen have thresholds up to 120.9 and 40.8 gCO_2e/MJ, respectively, and renewable hydrogen has the same threshold as clean but from renewable sources [39].

"In 2022, the G7 announced the Hydrogen Action Pact, a collaborative initiative to accelerate the development of systems of hydrogen (and hydrogen derivatives) production and use."

Japan has long supported the development of hydrogen systems as a centrepiece of its industrial strategy and climate action [40].

In 2023, India announced a financial investment plan valued at more than US$2B to promote hydrogen made from renewable power, in order to support the nation's target of achieving net zero GHG emissions by 2070. The plan aims to achieve 50 megatonnes of hydrogen production by 2030, powered by 60 to 100 gigawatts of newly-built electrolysis capacity [41].

3.8 The Middle East and Africa

The jurisdictional scan did not identify any rules or laws that promote specific hydrogen production pathways among nations in the Middle East and Africa. However, ambitious plans for hydrogen have been announced by governments and companies within the United Arab Emirates (UAE) [42], Oman [43], Israel [44], Morocco [45], and South Africa [46]. The UAE and Oman have established capacities and knowledge in the handling of natural gas, which can be used to accelerate hydrogen projects. In particular, Morocco is considering hydrogen as a way to mobilize its solar energy resources for export to Europe [47].

3.9 G7 Hydrogen Action Pact

In 2022, the G7 announced the Hydrogen Action Pact, a collaborative initiative to accelerate the development of systems of hydrogen (and hydrogen derivatives) production and use [48]. The pact focuses on hydrogen from low-carbon and renewable sources. Recommendations for actions to meet the pact's objectives were presented in a report from the International Renewable Energy Agency (IRENA), which also includes a taxonomy of the terms each member nation uses to refer to the hydrogen pathways envisioned under the pact, as shown in Table 1.

Table 1: IRENA Hydrogen Action Pact: Terminologies by country

G7 Hydrogen Action Pact countries	Terminology used in low-carbon or renewable hydrogen objectives
Canada	Low carbon
European Union	Clean, sustainable, renewable
France	Decarbonised, renewable
Germany	Colour coding
Italy	Colour coding
Japan	CO_2-free
United Kingdom	Low carbon
United States	Clean

There are nearly as many ways to classify hydrogen as there are signatories to the pact. This presents the potential for confusion, as discussed in Section 1, but it also creates an opportunity for the emergence of a singular, international classification system.

4 Review of LCA Methods and Models for the CI of Hydrogen Pathways

In Section 3, policies that directly or indirectly promote the production and use of hydrogen around the world were identified. Some of the policy instruments discussed were regulations requiring quantification of the CI of hydrogen pathways to be calculated using prescribed LCA models.

In this section, LCA methods and models commonly used for estimating fuel pathway CI values, including for hydrogen, are examined in order to understand how LCA methods and models can be used to support the effective classification of hydrogen by its supply chain attributes. LCA models are used to measure compliance with regulation, sometimes to two decimal places of precision. But does a classification system designed to help producers and consumers engage in the exchange of hydrogen benefit from this level of accuracy? Moreover, do output CI values from different LCA models vary significantly for the same hydrogen pathway assessed? These questions guided the research presented in this section, and the findings informed the recommendations presented in Section 7 that relate to the use of LCA in a classification system.

4.1 LCA Model Architectures: Attributional vs. Consequential

The design of an LCA model usually reflects a specific need. The need for a simple and expedient way to compare different fuel pathways might yield a model that considers only a few key variables of concern and is sufficient for a certification program. Alternatively, an LCA model may be designed to more precisely mimic a real system in all of its complexity in order to better answer research questions that will inform policy decisions. The spectrum of LCA model architecture tends to include attributional models at one end and consequential models at the other [49]:

- **Attributional** LCA (ALCA) models are concerned with the central production of the supply chain only. In attributional modeling, GHG emissions factors are applied according to a status quo knowledge base, which means the emissions factor does not change as a consequence of changes to the supply chain, such as a manifold increase in production. ALCA models are generally easier for novice users but lack comprehensiveness and are non-predictive of effects to the broader system in which the supply chain exists.

  An example of an attributional emissions factor would be assigning the average CI for electricity supplied from a transmission grid to an electrolysis plant for hydrogen production. In this example, the CI value assigned to grid power would not change regardless of how much electricity is used or when.

- **Consequential** LCA (CLCA) models are concerned with the effects of the supply chain on the surrounding system. In consequential modelling, GHG emissions factors represent a marginal effect, which can vary as a consequence of supply chain throughput levels. CLCA models require more experience to operate and rely on more detailed information that can be difficult to source or estimate. However, they better simulate the reality of supply chain dynamics.

  An example of a consequential emissions factor would be considering the actual CI for grid-supplied electricity at the instant of use and as a consequence of how much is used. This would reflect whether the marginal demand for power drives the CI value upward, perhaps because fossil fuel-fired peaking power plants must ramp up to meet demand. The further-reaching effects of mobilizing a greater supply of energy resources to meet the increasing demand for power might also be part of a consequential analysis.

Many LCA models represent a practical philosophy that lies somewhere on the spectrum between these two extremes, as a mix of attributional and consequential design choices. The mixed approach often strives for a balance of simplicity and accuracy, bounded by the availability of data.

In the context of hydrogen supply chain pathways, an ALCA model would estimate what share of the global environmental implications belong to the hydrogen product, based on averages of available data. Then allocation would be performed by partitioning environmental burdens of the supply chain across each of its identified links. This approach describes the environmentally relevant physical flows to and from the hydrogen supply chain. ALCA model inputs and outputs are thus attributed to the functional unit of hydrogen production (e.g., kg, MJ) by linking or partitioning the unit processes of the system according to a normative rule [50].

In contrast, a CLCA model for a hydrogen supply chain pathway may provide the global environmental consequences affected by its production and use. Marginal data would be used in many parts of the supply chain, which would vary according to broader system conditions. A CLCA model would aim to describe how environmentally relevant flows would change in response to possible changes in demand for a functional unit of hydrogen [50].

The distinction between these two types of LCA modelling first arose in response to production processes with more than one functional unit (or product) of value or concern. Table 2 displays the relationships between attributional and consequential LCA models, and shows that as a model becomes more precise in determining the CI of hydrogen in a narrowly defined supply chain, it may become less complete in assessing the possible changes to emissions across the broader system of which it is a part [51]. It further indicates that using both types of models may be advisable to fully appreciate the implications of different hydrogen supply chains.

Table 2: Attributes of LCA modelling frameworks [51]

Modelling Framework	Precision	Completeness
ALCA	High	Low
CLCA	Medium	Medium
Integrated Model	Low	High

When determining where an LCA model belongs according to Table 2, certain distinguishing factors can be used. For CLCA models, the goal of the assessment must be to support a decision made over the product system. A decision-induced change supported by a CLCA model would affect the status quo of the product system and the net benefit can be modelled. With ALCA models, a decision cannot be supported across the whole product system, and therefore cannot affect the status quo, nor can the net benefit of the induced change be modelled [52].

4.1.1 ISO Standards for LCA

The International Organization for Standardization (ISO) has produced several climate action-related standards [53], including the following, which address use of LCA methods and calculation of GHG emissions:

- ISO 14040, *Environmental management – Life cycle assessment – Principles and framework* [54] outlines the four phases of an LCA study, including goal and scope definition, inventory analysis, impact assessment, and interpretation. The framing of an LCA following ISO 14040 can apply to both attributional and consequential models. Note that some LCA models reviewed in this study were established before ISO 14040 was developed.
- ISO 14044, *Environmental management – Lifecycle assessment – Requirements and guidelines* [55], outlines the details for conducting an LCA for practitioners. Of the LCA models discussed in this study, only Canada's Fuel LCA Model, which was recently developed, adheres to ISO 14040 and ISO 14044.
- ISO 14064 series relates to GHG emissions assessment and reporting:
    - ISO 14064-1, *Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions* [56];
    - ISO 14064-2, *Greenhouse gases — Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements* [57]; and
    - ISO 14064-3, *Greenhouse gases — Part 3: Specification with guidance for the verification and validation of greenhouse gas statements* [58]. This standard is used to validate and verify the GHG statements provided by following ISO 14064-1 and 14064-2. It is also used for ISO 14067.

- ISO 14067, *Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification* [59], addresses only climate change as an impact category defined in ISO 14040 and follows ISO 14044. This standard does not include assessment of any social or economic consequences outside of climate change, which is consistent with the capacities of attributional LCA models. ISO 14067 enables users to create GHG statements for products or services, much like ISO 14064-1 and 14064-2. Additionally, ISO 14064-3 can be used for verification and validation of ISO 14067.

ISO standards for LCA and for determining carbon footprint can be readily applied to hydrogen production in terms of CI but also in relation to other supply chain characteristics. Some LCA models referenced in certain jurisdictional regulations (reviewed in Section 4.2) pre-date the development of the ISO standards identified above and can therefore differ regionally in their application. ISO provides for a globally consistent framework, to which new systems of assessment and classification could be developed, thus facilitating international trade in hydrogen.

4.2 Review of LCA Models Used by Jurisdiction

4.2.1 GREET/CA-GREET (US and California)

The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model is an elaborate MS-Excel spreadsheet developed by the Argonne National Laboratory [60] that is freely available to the public. The GREET LCA model focuses on transportation pathways and includes both a fuel cycle and a vehicle cycle component. The spreadsheet calculates emissions of GHG and criteria air contaminants based on a range of user-defined inputs. However, it does not report results for discrete fuel production pathway components, returning only aggregate values for upstream of use (i.e., well-to-tank) and downstream (i.e., tank-to-wheel) emissions.

The GREET model has more than 100 predefined fuel pathways, including petroleum distillates, natural gases, biofuels, electricity, and hydrogen. Combinations of vehicles and fuels can be modelled for the period from 1990 to 2020 in five-year increments to account for changes in powertrain configuration and performance. The model outputs thus reflect changes in vehicle efficiency according to vintage and fleet averages.

GREET is considered an industry-standard model for assessing the lifecycle emissions of different fuel production pathways, and is referenced in regulation under the US Renewable Fuel Standard program, which is a liquid fuel standard so it does not affect hydrogen.

GREET (version 1.8b) was modified specifically for the California Air Resources Board to administer and facilitate California's LCFS [11]. The new model is called CA-GREET (currently at version 3.0). The CI values produced by the model for various fuel pathways are adjusted by an energy economy ratio to represent the efficiency with which the fuel energy is converted and utilized within the vehicle system [61]. This reflects the LCFS focus on transportation energy use.

The CA-GREET is also freely available as an MS-Excel spreadsheet, in which users can define their own inputs. However, there is a user interface that enables easy switching between different US regions, each with a distinct set of inputs reflecting regional feedstock supplies that link into the California fuels market. The model also includes certain waste-based and biogenic fuel pathways. Criteria air emissions are aligned with the California Air Resources Board standards for California's Low-Emission and Zero-Emission Vehicle programs [62], [63].

GREET is most often used as an attributional model, but elements of consequential analysis can be conducted by the user. This utility has been incorporated to address questions of displacement, when a valued by-product of the main supply chain product (e.g., oxygen is a by-product of water electrolysis to produce hydrogen) displaces other energy and emissions that would otherwise have occurred to produce the by-product. A user may choose to model these effects because the results of the analysis for a special circumstance may indicate additional benefits, system-wide. GREET is thus considered an attributional LCA model with some capacity for consequential analyses.

"The GHGenius model is attenuated with Canada-specific inputs and parameters and, in contrast to CA-GREET, its scope is not limited to transportation fuel pathways."

Importantly, CA-GREET defines several hydrogen pathways and allows for the examination of intermediate calculations as the inputs are varied. It is also widely used by industry as the central tool for administering the LCFS, including assessing compliance among regulated parties and the generation of credits [64], which are a market driver for hydrogen as a fuel in California.

4.2.2 GHGenius (Canada)

GHGenius is a lifecycle energy and emissions assessment model developed in MS-Excel in 1999, originally used as a tool for public policy analysis by Natural Resources Canada, long before regulating the CI of fuels was considered [65]. It is now referenced under BC's Renewable and Low Carbon Fuel Requirements Regulation as the model for calculating compliance and credit generation. The GHGenius model is limited to Canada-specific inputs and parameters and, in contrast to CA-GREET, its scope is not limited to transportation fuel pathways. Generally, GHGenius outputs are considered to diverge the most from the GREET models in the US in pathways based on agricultural feedstocks, perhaps due to differences in parameters for land use and allocations for use of co-products.

Since its release, GHGenius has become more comprehensive in scope and level of detail. Extensive input information is required to model energy usage for fuel production and feedstocks. Additional factors for non-GHG emissions from these sources, as well as for vehicle types, are also required. This is to encompass wider system boundaries that better reflect emissions from equipment manufacturing. GHGenius also incorporates special analytical tools for the user to undertake more complex scenario simulations. For example, there are two sensitivity solvers that allow users to manipulate any input parameter to determine the implications on numerous output values. A Monte Carlo simulation tool is also available to users for probabilistic outcome analyses when input variables are random.

As with GREET, the elements of consequential analysis within GHGenius and the extensiveness of conditional modelling make it more predictive than a straight attributional model. It is therefore considered an attributional model with capacity for some consequential modelling.

In terms of hydrogen, GHGenius is pre-set with several dozen hydrogen pathways for GHG emissions and CI calculations.

4.2.3 Fuel Life Cycle Assessment Model (Canada)

To support the implementation of the Clean Fuel Regulations, ECCC commissioned the Fuel LCA Model, which was released as a publicly available tool in 2020 [17]. The model was developed in compliance with ISO 14040 and ISO 14044, which respectively address the principles and guidelines for modelling methods [66].

Per the ISO guidelines, Canada's Fuel LCA Model is built around a clearly stated goal, which is to calculate the lifecycle CI of energy and fuels produced in Canada. It also aligns to the four phases of LCA, as defined in ISO 14040 and listed below.

- Goal and scope definition phase
- Inventory analysis
- Impact assessment
- Interpretation

The Fuel LCA Model provides transparent and traceable calculations for different fuel pathways across the four phases of LCA methodology. The results of one phase can affect previous and subsequent phases, meaning that this model can employ an iterative process to more accurately simulate changes within a supply chain.

Canada's Fuel LCA Model was developed using openLCA [67], which is free open source software for sustainability and LCA. The software uses the database published by ECCC which allows the user to model processes to represent feedstock production and transport, fuel production, fuel distribution, fuel combustion, and fuel CI for all fuel pathways defined, drawing on factors in its database to generate quantitative results. The interaction between the data library and fuel pathways is presented visually in one of the figures in the Fuel LCA Model user manual [68].

The Fuel LCA Model operates at three levels. Each element at the fuel pathway level, representing a key link in a fuel supply chain, can be composed of a collection of discrete unit processes that are defined at the lifecycle stage level. At the third level, each unit process can apply factors to intermediate flows of the product under assessment (measured in kg, MJ, etc.) so that elementary flows (e.g., GHG emissions) can be calculated. The elementary flows for each unit process roll-up in the lifecycle stage level and then sum over the sequence of fuel pathway level elements. Thus, the intensity of emissions for the pathway is determined as a function of the flows measured at each unit process.

The hydrogen pathway in the Fuel LCA Model can be configured by the user and includes defaults relating to feedstock options, electricity supply, and carbon capture and storage (CCS). The inclusion of CCS is a unique feature of this model, as it is not present in GREET or GHGenius. Notably, the Fuel LCA Model's cycle stage and unit process levels include provisions for hydrogen as an input to other fuel production processes. This feature is illustrated in Table 3, which presents an example of the use of hydrogen in bioethanol production.

Table 3: Production system of bioethanol produced from corn (adapted from [68])

No.	Process Steps	Input	Output
1	Feedstock Production	275,000 tonnes of corn (14% moisture content)	not specified
2	Feedstock Transport	150 km by truck	not specified
3	Fuel Production	350 TJ of natural gas 1350 tonnes of **hydrogen**	Process Emissions ▪ 0.05g CH_4/MJ of fuel ▪ 0.01g N_2O/MJ of fuel 38,000 tonnes of animal feed 100 million litres of ethanol
4	Fuel Distribution	450 km by train	not specified
5	Fuel Combustion	In an internal combustion engine vehicle	not specified

This example reveals an important aspect of the Fuel LCA Model because hydrogen is used in the refining of many fossil fuels and renewable fuels to hydrotreat or hydrocrack intermediate products. Using lower CI hydrogen as an input feedstock to fuel production reduces the overall CI of that fuel product. Thus, low CI hydrogen as an output of this model could be fed back into other fuel pathways, which establishes the capacity for some market-mediated consequential effects to be assessed.

Canada's Fuel LCA Model is thus considered an attributional model with significant capacity for consequential modelling.

4.2.4 GHG Emissions Calculation Tool (GHG Protocol, International)

Established in 1997, the GHG Protocol is a joint initiative of the World Resources Institute and the World Business Council for Sustainable Development [69]. It developed the GHG accounting and reporting standards that are the most widely adopted and used by private companies worldwide. To support its mandate and its community of practice, GHG Protocol provides a suite of services and tools that are freely available to assist organizations in assessing the GHG emissions directly from their operations and indirectly through their supply chains. One of these tools was an LCA model called the GHG Scope 3 Evaluator [70], which was discontinued during the research for this report but is included to illustrate the differences in tools that are widely used. GHG Protocol now provides new tools for more specific applications, including calculators for cross-sector, country specific, sector specific GHG emissions, and for countries and cities [71].

Consistent with GHG accounting and reporting standards, the tool generated estimates of an organization's emissions within three domains: Scope 1 emissions are those generated directly from an organization's operations, and are within its direct control; Scope 2 emissions are related to energy procured by an organization to support its operations, and often include electricity or heat delivered; and Scope 3 emissions relate to processes that occur upstream in the value chain or are outside the direct control of an organization, such as transportation, business travel, and employee commuting.

The GHG Emissions Calculation Tool was based in MS-Excel and currently uses default emission factors that vary by country. Separate sets of emission factors were available for the UK and the US. Location-based Scope 2 emission factors were also available for the US, Canada, and Australia, while market-based mix emission factors are available for other countries. Further to the calculation tool, GHG Protocol offers a corporate value chain standard that uses a separate evaluator tool for fifteen Scope 3 categories, ranging from purchased goods and services to disposal of products, as a more detailed modelling alternative to a single Scope 3 transportation category. Note that this evaluator tool will be discontinued on August 30, 2023.

Because direct and indirect emission types are scoped by the tool, it could serve as an LCA model to a certain extent, but that is not its expressed purpose. Rather, the GHG Emissions Calculation Tool generated GHG estimates for accounting and reporting purposes instead of CI values for regulatory compliance and policy analysis. The model is oriented toward simplicity of use and consistency of results. These characteristics are important to appreciate. According to GHG Protocol, in 2016, 92% of Fortune 500 companies used their guidance and tools, either directly or indirectly [72].

From an LCA design perspective, the GHG Emissions Calculation Tool was attributional. It was primarily intended for businesses, not researchers, to report on status but not to conduct predictive analyses. It has the option for users to input custom emission factors, enabling the consideration of hydrogen pathways, but CIs are not explicitly generated. In fact, the spreadsheet did not define any default hydrogen pathways, and would require user-customized factors to approximate hydrogen scenarios.

4.2.5 UK Hydrogen Emissions Calculator and New Zealand Hydrogen Modelling Tool

Two LCA models have been made publicly available in the UK and in New Zealand, respectively, and they are briefly discussed in this section.

The UK Department for Business, Energy, and Industrial Strategy commissioned E4Tech, a consultancy with expertise in LCA methods and application, to develop the hydrogen emissions calculator (HEC). The HEC is an attributional model with some elements of consequential analysis, such as land use change effects. Three versions are available that align to three defined project types: (1) electrolytic projects, streamlined for typical electrolysis pathway projects; (2) fossil gas reforming with carbon capture and storage, streamlined for methane reforming pathway projects; and (3) a full version, which will accommodate any project defined by the user [73]. The HEC uses boundary conditions that align with the well-to-gate definition in other LCA models. GHG emissions upstream of production are included, but downstream effects are out of scope.

The Government of New Zealand has developed a new modelling tool specific to hydrogen scenarios to encourage interested stakeholders and members of the general public to explore the potential outcomes of new hydrogen market scenarios at the national level. The model was made available following the release of New Zealand's vision for hydrogen in 2019, and is informing the public consultations that are underway to develop a national hydrogen roadmap. The model was produced by Castalia and has an online dashboard based in MS-Excel. From the dashboard, users can vary input assumptions using slider bars to examine the long-term impacts on energy use and GHG emissions in the country, based on future levels of hydrogen production and use [74].

The version of the hydrogen modelling tool currently available to the public is for informational use only and provides limited insight into the functional aspects of the underlying model. Due to this, the scope of this modelling tool does not include LCA associated with the CI of hydrogen. Instead, the scope is limited to the effects of hydrogen as a vehicle fuel and heating fuel, and the tonnes of CO_2 avoided through its use is the key metric of the model. The strengths of the model are simplicity and ease of use. The design most likely reflects an attributional philosophy, as its purpose is public education through scenario-play in the context of meeting the country's decarbonization goals.

4.3 Observations and Implications for Classifying Hydrogen

Of the LCA models reviewed in this report, all were constructed using attributional model architecture, which reflects a need for simplicity on the part of the user. It also indicates a value placed on consistency of outputs, which is helpful for reporting, especially for regulatory compliance purposes. However, the LCA models that are referenced in CI regulations or are used to inform policy analysis often have capacity for some level of consequential LCA, which reflects an additional need for a more complete picture of the impacts of the modelled pathway to the broader system in which it operates. Furthermore, all of the reviewed models generate a narrow set of outputs, either lifecycle GHG emissions or CI, which are different expressions of the same relation. While this is expected, it reinforces that no LCA models generate a quantitative evaluation of all the dimensions of sustainable development characteristics for a fuel supply chain, even though climate action is presently the characteristic of overriding concern.

Section 4.1 presented Table 1, which compared LCA model architectures according to precision and completeness. Similarly, Table 4 includes three of the models reviewed in Section 4.2 with an evaluation of each design's tendency toward attributional and consequential LCA characteristics.

Table 4: LCA models compared by key characteristics

LCA Model	Precision	Completeness
GREET	Medium/High	Low
Canada Fuel LCA	Medium	Medium
GHGenius	Medium	Low

For the purpose of business reporting and commerce, the GHG Emissions Calculation Tool is widely used and represents attributional methods. GREET, GHGenius, and Canada's Fuel LCA Model are each referenced in the regulations of different jurisdictions in the US and

Canada, and represent a mix of attributional and consequential methods. As discussed, hydrogen production pathways can be assessed for CI using the more complex, hybrid LCA models. However, the GHG Emissions Calculation Tool is much more widely used by the international business community, demonstrating that ease of use and expedience are important factors.

When considering the development of a hydrogen classification system, if GHG emissions or CI is all that matters in the hydrogen marketplace, then methods and models exist for suppliers and consumers to negotiate hydrogen based on CI values alone. However, given the emergence of other classification schemes, this is evidently not the case, and other supply chain attributes matter. In order to express these additional attributes in a classification system, a simple yet robust communication of CI is advisable, which favours the use of attributional LCA approaches.

In Section 5, best practices in consumer information systems will be considered by examining successful systems for simple and effective communication on complex matters relating to products and their systems of supply.

5 Adapting Best Practices in Consumer Information Systems to Hydrogen Supply Chain Attributes

The previous sections of this report explored policy drivers that favour hydrogen supply chains that tap into renewable and low-carbon feedstocks, including energy inputs. LCA models referenced in CI regulations were also reviewed. From these scans, it appears that regulations tend to rely on quantitative methods to determine lifecycle CI as a precise and consistent metric for compliance. By contrast, the targets in aspirational plans and directives of some jurisdictions are defined using renewable terminologies. However, low-carbon and renewable are not the same, as demonstrated by the review of LCA models. This distinction is an apparent driver of interest in special labels and certifications for hydrogen that qualifies as green, some of which are explored later in this section.

Evaluating the sustainability of supply chains, as well as the output findings of such an effort, is a complex undertaking. Multiple indicators can be quantitatively or qualitatively assessed, but the importance assigned to each is often subjective based on the concerns of the end user. For example, a can of tuna may bear one of many different markers that imply the principles behind its sourcing. Each designation emerges from a different set of evaluations intended to help individual consumers make informed decisions on the issues of greatest concern to them.

It may seem logical to assume that consumers would demand and appreciate detailed sustainability assessments to inform their procurement choices, and act upon this information in predictable ways that align to their values. However, sustainability classifications, certifications, and labels are often identified as a point of frustration among consumers. At the time of writing, the Ecolabel Index is tracking 456 ecolabels in use across 25 industry sectors, each of which can be associated with multiple standardization schemes. Increasingly, this proliferation has been criticized by business, academia, and non-governmental organizations as a source of confusion [75]. The sustainability labelling landscape is criticized for trying to convey “too much, too complex, too similar, and too ambiguous information” [75].

In Section 5.1, a collection of diverse systems for communicating complex information to consumers are presented and reviewed. Learnings and guidance are then drawn from these systems regarding characteristics that could be applied in the development of a classification system for hydrogen in the context of sustainable development criteria. Specifically, this report evaluated how different systems strike the right balance between thoroughness and simplicity in order to facilitate exchange between suppliers and consumers while cultivating trust among a broader set of indirect stakeholders and observers. The durability of certain consumer information systems provides a strong indicator that such balance and trust has been achieved and maintained.

5.1 Review of Selected Consumer Information Systems

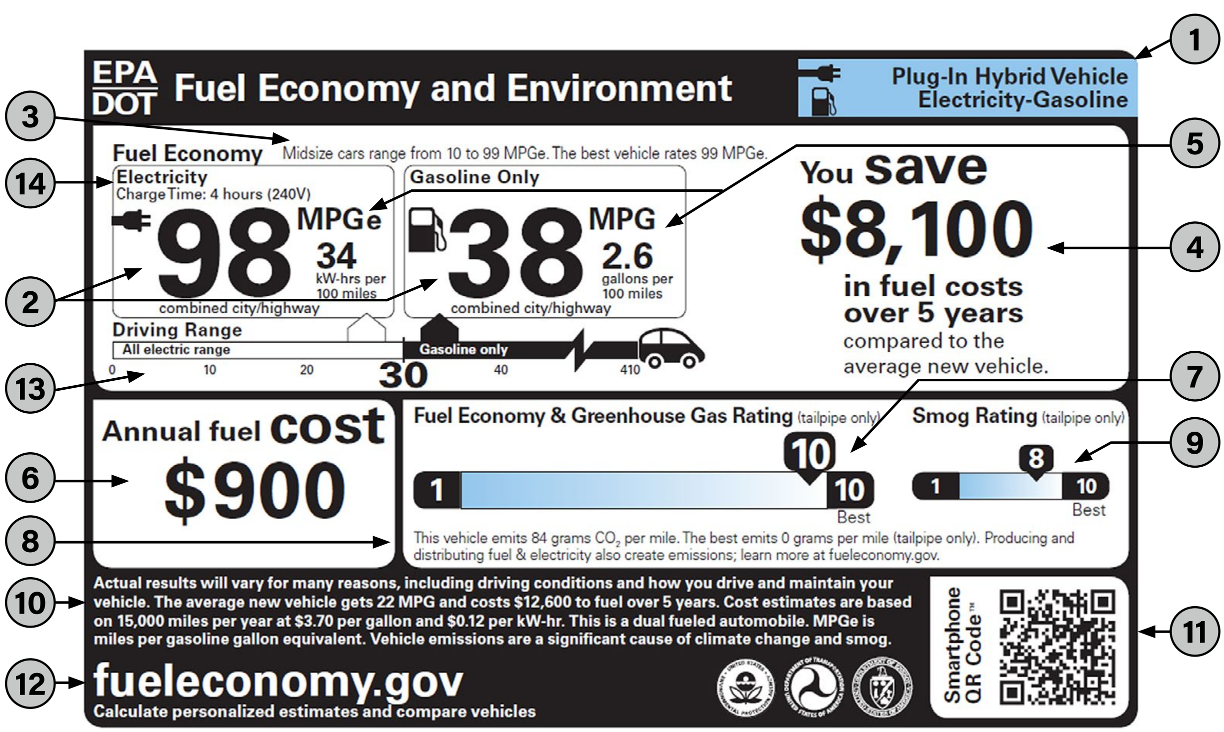
In each of the subsections herein, a selected consumer information tool is described, followed by a brief analysis of its design and potential effect. This discussion is presented in the context of strengths that could be adapted to a sustainable development-focused hydrogen classification system, and weaknesses to avoid.

5.1.1 US Environmental Protection Agency: Fuel Economy Labelling on Light-Duty Vehicles

The Energy Policy and Conservation Act of 1975 was passed by the US Congress in response to the 1973 oil crisis [76]. It established a suite of measures to ensure security of energy supply, including the strategic petroleum reserve, energy efficiency standards for consumer products, including light-duty vehicles, and a mandate that all new automobiles bear a label showing their fuel economy rating and estimated annual fuel cost beginning with the 1977 model year [76]. Since then, the design of the label has undergone several revisions and it is now administered by the US Environmental Protection Agency (EPA) and incorporates both energy use information and emissions performance [77].

There are three variations on the current label, each mapping to one of the three dominant powertrain options in the market: (1) combustion engine-powered vehicles (including hybrids); (2) vehicles with some plug-in recharging capacity and a combustion engine (i.e., plug-in hybrids); and (3) vehicles with no combustion engine that are fully electric (plug-in EVs). A sample label for a plug-in hybrid vehicle is provided in Figure 4.

Figure 4: Label for plug-in hybrid vehicles. Reprinted with permission from [78].



As shown, the label communicates 14 items of information to prospective customers.

1. **Fuel and Powertrain Type:** This item on the label tells the reader that this vehicle runs on gasoline and can be plugged in, providing greater range in all-electric mode.

2. **Fuel Economy Rate:** This item shows the number of miles drivable on a gallon of fuel (i.e., MPG) is represented for both engine-based operation and for all-electric operation. Because no gallons of gasoline are consumed during all-electric drive, an effective equivalence of energy consumption is provided (MPGe). Both the MPG and MPGe values represent a blend of city driving (frequent starts and stops) and highway driving (higher, consistent speed operation).

   Fuel economy values are derived from a set of standardized test protocols administered by the EPA. These tests have been developed to generate vehicle emission performance data that are used under a number of policies and programs, including for automaker compliance with federal emissions regulations for both criteria air contaminants and GHG emissions. Note that fuel economy ratings are not consistently accurate predictors of what any one driver may experience, because fuel consumption varies with driving conditions, but the values are considered suitable for comparing between models.

3. **Best in Class Comparison:** This item identifies the highest fuel economy rating for a vehicle in this size class, and advises whether a vehicle in another size class might offer better fuel economy.

4. **Fuel Expense Savings Compared to Average:** Based on fuel economy values, this item provides an estimate of the difference in the cost of fuelling this vehicle for five years compared to the average vehicle, based on a defined annual mileage and unit cost of gasoline and electricity.

5. **Fuel Consumption Rate:** Instead of showing only fuel economy (a measure of distance travelled per fuel consumed, MPG), this item also shows fuel consumption (a measure of fuel consumed per distance travelled, MPG) because it facilitates an easier comparison between models of different efficiency ratings.

6. **Estimated Annual Fuel Cost:** This item is based on the same calculations used in item 5.

7. **Fuel Economy and Greenhouse Gas Rating:** This item provides a ranking of this model on a scale of 1 (worst) to 10 (best) regarding how well its fuel economy and its GHG emissions compare to all other models available for sale from the same model year. The absolute values for fuel economy and GHG emissions (measured as gCO_2/mile) mapping to 1 through 10 thus change from year to year.

8. **GHG Emissions Information:** This item includes further explanation about the GHG emissions characteristics of this vehicle. Upstream GHG emissions are disregarded in the ranking scale.

9. **Smog Emissions Rating:** Levels of criteria air contaminants emitted from vehicles that contribute to smog formation and poor air quality are regulated in the US (as well as in Canada), but each model varies somewhat from the average. Smog-forming emissions do not always scale with fuel consumption, since different models can have more robust emissions control systems than others, and no emissions are produced during all-electric drive. This item provides a rank for this model on a scale of 1 to 10 that recognizes vehicle models for having unique, clean-running performance.

10. **Disclaimer:** This item qualifies values as estimates because real-world driving conditions and fuel prices vary. Claims of misleading fuel economy information have been litigated in the past, and this acknowledgement is to prevent frivolous legal action.

11. **QR Code®:** This item provides a mobile link to additional information about this model, as well as guidance on best practices and good driving habits that help keep fuel expenses to a minimum.

"Consumers can accept the label as a comparative information tool and not as an absolute certification of performance."

12. **Fueleconomy.gov:** This item directs drivers to a website where they can access additional information and personalized tools relating to fuel economy estimation and monitoring.
13. **Range Limits Between Fuel Refills/Recharging:** This item provides an approximation of the operating range on a full tank and/or full charge.
14. **Charging Time:** This item indicates how long it takes to fully recharge the battery pack from fully drained using a level 2 charging service (240-volt service).

The application of this label is required by federal regulation [79] and it conveys a lot of quantitative data that is based on standardized, laboratory testing protocols. Some of the data is direct, as in measured fuel economy and fuelling costs, and some is simplified and abstracted for comparison purposes, via the 1 to 10 ranking scale. The information considered most important to the prospective vehicle buyer is made large and clear, so it's easy to use, while supplementary information is provided in smaller text and using graphical elements.

This consumer information tool packs a lot of information about a fairly narrow range of metrics, namely the fuel efficiency, GHG emissions, and relative performance on smog-forming emissions during operation of the vehicle. It may be that any one user of the label will be interested in only one or two pieces of the provided information, but different users may focus on different aspects of the information.

Disclosure of information appears to be a driving principle in the design of this label. Comparative ranking is offered, which encourages buyers to consider a more energy efficient, cleaner alternative, but the effect is diminutive compared to the central, bold presentation of energy use metrics and costs. First and foremost, this label focuses on disclosing operating costs, with supplementary emissions information. As a consumer information system arising from the economic shocks of the oil crises of the 1970s, this focus is understandable. Canada's variation on the US fuel economy program, EnerGuide for vehicles, promotes a similar information label that is not required by law [80], which suggests that consumers value the disclosure of information that the label provides.

Despite the comprehensive information provided in the EPA label, it declares its own uncertainties via the included disclaimer. Thus, consumers can accept the label as a comparative information tool and not as an absolute certification of performance. In other words, it helps the consumer to progress toward more fuel efficient, lower-emission vehicle models, rather than asserting a particular model as meeting a superior standard. By informing consumer decisions in this way, automakers receive signals of the value that the market places on their investments in fuel-saving, emissions-reducing technologies and designs.

5.1.2 US Green Building Council: Leadership in Energy and Environmental Design (LEED)

The LEED certification program was developed by the US Green Building Council to help owners and developers create buildings and built environments that are consistent with the principles of sustainable development [81]. The program broadly promotes and guides industry in the construction of high-performing, resilient buildings that reduce carbon emissions, save water, conserve energy, and reduce waste. Since its inception in 1993, the program has expanded and undergone periodic revisions, and now encompasses conditions for indoor health, comfort, and productivity. As of 2021, there were more than 80,000 LEED-certified buildings around the world [82].

LEED includes a rating system with scores that are applied in seven main categories of evaluation: (1) integrative process, (2) location and transportation, (3) sustainable sites, (4) water efficiency, (5) energy and atmosphere, (6) materials and resources, and (7) indoor environment quality; plus two bonus categories: (1) innovation in design, and (2) regional priority. In each category of evaluation there can be prerequisite conditions for which no points are awarded, as well as credit conditions for which additional points can be awarded. For example, under the sustainable sites category, pollution prevention measures are required for construction activities, while site development that protects or restores natural habitat is an option for which credit points can be given to the developer [83].

The points acquired in each category are summed for a given project, with the total mapping to one of the following four certification ranks [82]:

- **Certified:** Corresponds to a score of 40–49 points. This rank accounts for approximately 15% of all buildings that have received a LEED certification.
- **Silver:** Corresponds to a score of 50–59 points. About 30% of LEED-certified buildings have this rank.
- **Gold:** Corresponds to a score of 60–79 points. This rank is most common, representing roughly half of LEED-certified projects.
- **Platinum:** Corresponds to a score of 80 points or more. This is the top rank, and approximately 10% of projects achieve this ranking.

The certification process, including verification, for developments and building projects is performed by LEED professionals who have acquired credentials through examinations administered by the Green Business Certification Institute, which also grants the LEED certifications. There is a fee to register a project for consideration. The direct costs of acquiring LEED certification has been estimated to add less than 2% to the overall costs of a project [84].

The four LEED certification levels represent a highly simplified presentation of the outputs of a complex, multi-dimensional assessment process that cuts across numerous domains of sustainable development. Because few buildings are identical, the certification is not a metric of equivalence. Rather, it indicates the level of best practice applied by the developer, and the commitment of the project to the ideals of environmental responsibility and resource use efficiency.

As with any merit badge, a separate authority determines whether minimum thresholds have been met and best efforts have been applied. Some level of subjective judgement is inherent in the process, but it is limited by rigorous evaluation criteria. The program is also constantly being revised and adapted to evolving circumstances. The beneficiaries of the LEED certification program are the occupants and users of the built environment, few of whom are expected to understand the technical achievements represented by the certification. Nonetheless, the adoption of the program worldwide indicates the success in the simplicity of a merit-based expression of the certification.

5.1.3 Nutrition Facts Table and Canada's Food Guide

Since 2007, labelling of the standardized Nutrition Facts table has been required by regulation on most prepackaged food products in Canada [85]. Canada follows the Food and Drug Regulations on how information will be presented on a label [86]. The table is considered foundational to the promotion of a healthy population and similar consumer information systems exist in many developed nations. The purpose is to provide nutrition information based on standardized testing of food products, so consumers can make decisions about how the product fits into their personal health and diet goals.

The table standardizes the presentation of information that nutritionists and Health Canada consider most important for fulfilling a healthy diet [85]. Serving size is defined first, followed by calories. The share of calories is broken down by fats, carbohydrates, and proteins (i.e., macronutrients). The share of fat that is saturated is also included, due to its association with cardiovascular disease, as are the levels of fibre and sugar in the carbohydrate total. Salt and other mineral contents are also listed. A sample Nutrition Facts table is provided in Figure 5.

Figure 5: Sample nutrition facts table for a pre-packaged food

Nutrition Facts
Valeur nutritive
Per 1 cup (250 mL)
pour 1 tasse (250 mL)

Calories 110	**% Daily Value*** **% valeur quotidienne***
Fat / Lipides 0 g	0 %
Saturated / saturés 0 g + Trans / trans 0 g	0 %
Carbohydrate / Glucides 26 g	
Fibre / Fibres 0 g	0 %
Sugars / Sucres 22 g	22 %
Protein / Protéines 2 g	
Cholesterol / Cholestérol 0 mg	
Sodium 0 mg	0 %
Potassium 450 mg	10 %
Calcium 30 mg	2 %
Iron / Fer 0 mg	0 %

*5% or less is **a little**, 15% or more is **a lot**
*5% ou moins c'est **peu**, 15% ou plus c'est **beaucoup**

It is important to note that the metrics on the label can vary. For example, a serving size may be volumetric, gravimetric, or number of pieces. To relate the masses of macronutrients to the calories as a share of daily intake recommendations, there is an additional column showing the percentage share. Salt and other nutrients are also presented as a share of total recommended daily intake. At the very bottom of the label, there is a reminder that more than 15% in any category is considered a significant share of the daily recommended level. This is to provide simplifying context to the calorie and mass levels shown.

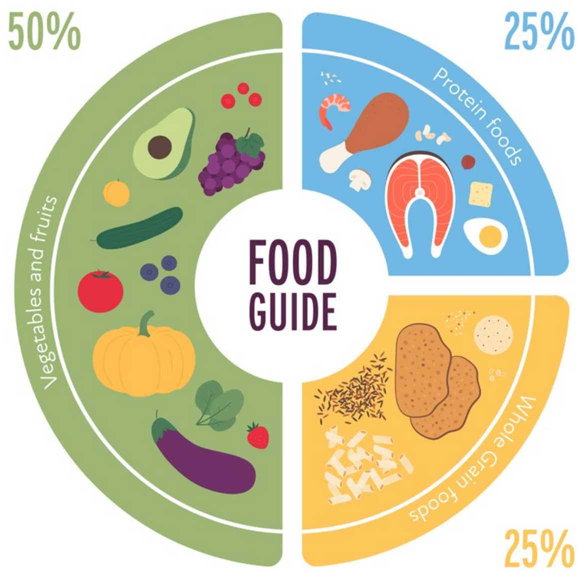
Similar to the fuel economy label described in Section 5.1.1, the Nutrition Facts table presents a lot of information. In contrast to the fuel economy label's focus on one aspect of the vehicle (i.e., energy and emissions), many different types of information are included here, and a degree of knowledge and understanding about personal nutrition is needed to interpret the information. Thus, the driving principle of the Nutrition Facts table appears to be disclosure of information.

The complexity of regulated nutrition labelling and the time required to read and interpret the provided information may undermine its effectiveness in guiding people to make healthy eating choices. Because of this, supplementary certifications have been developed to simplify consumer decision-making. For example, until 2014, the Heart and Stroke Foundation's Health Check program offered a marker on qualifying products [87]. The marker was a simple logo composed of a check mark that packaged food producers could add to their packaging. Similarly, Loblaws has a line of packaged food products bearing the PC Blue Menu colouring and brand [88]. Supplementary certification schemes such as these are intended to help consumers make healthier choices at a glance, on the basis of trust in the marker.

To address the inherent complexity of the Nutrition Facts table, along with recognizing that unpackaged foods do not require labelling, the Government of Canada also maintains Canada's Food Guide, which provides a visual guide to maintaining a healthy diet based on a balance of nutritional inputs [89]. An example is provided in Figure 6.

In a departure from traditional food guides that visually rank foods, often as part of a pyramid with proteins at the top, the newest version of Canada's Food Guide uses a plate to represent the healthy distribution of food types. From this image, consumers learn that one half of any meal should be vegetables and fruit for nutrients and fibre, one quarter should be complex carbohydrates (i.e., whole grains), and one quarter should be lean, protein-rich foods. The only healthy hydration needed is water. The guide has quantitative information, yet it communicates the essentials of healthy eating in terms of what constitutes food and in what proportions food types should be consumed.

Figure 6: A healthy diet based on a balance of nutritional inputs



The strength of Canada's Food Guide is in its simplicity. If your plate looks like the plate in the image, then you are eating healthily. In addition to the plate snapshot, the guide includes a broader set of information tools that are available through the website, including recipes and tips for healthy lifestyles. The guide is also notable for what is not included, such as food products that contain no proven, additional nutritional value.

Together, the Nutrition Facts table and Canada's Food Guide are a pair of tools that represent a comprehensive consumer information system that communicates quantitative data as well as contextual and qualitative guidance. The two formats are very different, but work toward a common purpose and are mutually reinforcing.

5.1.4 Ocean Wise and the Marine Stewardship Council: Sustainable Seafood Programs

Ocean Wise and the Marine Stewardship Council (MSC) are two different organizations that advocate for the sustainable development of marine resources and the preservation and conservation of marine environments [90] [91]. Each organization has a program intended to inform sustainable seafood choices among consumers. The details of the respective program designs are not explored here, but they are summarized to demonstrate different approaches to communicating assessment results.

Ocean Wise uses a criterion scoring method with binary outputs (i.e., pass or fail) [92], while MSC scores seafood across a range of indicators under three principles to generate an average score [93]. Based on the outcome of the Ocean Wise scoring system, seafood is either recommended as *Ocean Wise or Not Recommended*. Qualifying seafood can bear the Ocean Wise label to inform customers of the product's certification. MSC generates three judgements based on its scoring system: *Fail, Conditional Pass, or Unconditional Pass.* Seafood from fisheries that MSC evaluates as harvesting sustainably can bear a blue MSC label intended to inform customers [93].

Both of these systems involve complex, expert analysis of multiple variables to yield recommendations to the consumer about whether to enjoy the seafood and support their recommended fisheries, or to reconsider the choice.

5.1.5 Minimum Efficiency Reporting Value and the 80 PLUS® Certification Program

The Minimum Efficiency Reporting Value (MERV) rating is a measurement scale developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers that indicates the performance of air filters in building heating, ventilation, and air conditioning systems. Air filters are characterized by a MERV number that can range from 1 to 16, corresponding to the range of particle sizes (measured in microns) that can pass through, as well as the resistance to airflow [94]. Table 5 summarizes the different MERV applications.

There is no standardized label under MERV, so the MERV rating number can appear on air filter packages however the manufacturer wishes to display it.

The 80 PLUS® specification is a voluntary certification program developed by companies in the electronics industry and launched in 2004 [95]. Most often applied to transformer power supplies for personal computers,

Table 5: Applications of filters by MERV rating (adapted from [94])

MERV	Minimum particle size	Typical application
1–4	>10.0 μm	Residential window air conditioner units, minimal filtration
5–8	10.0–3.0 μm	Better residential buildings, commercial buildings, industrial workspaces
9–12	3.0–1.0 μm	Superior residential buildings, better commercial buildings, hospital laboratories
13–16	1.0–0.3 μm	Superior commercial buildings, hospital inpatient care, and general surgery

it certifies that a test product is at least 80% energy efficient at 20, 50, and 100% of its rated load, and has a power factor of 0.9 or greater at 100% load [96]. 80 PLUS® is sometimes considered an ecolabel program because it promotes electricity consuming components that are more efficient and use less energy.

Over time, designations for higher levels of energy efficiency have been added, creating a tiered system of recognition. Table 6 summarizes the labels assigned to certified 80 PLUS® products, which now has six distinct levels. These labels appear on the package of the component, so they are easily visible to the consumer.

Both the MERV rating and the 80 PLUS® certification programs are examples of clear and unambiguous consumer information systems. A simple, one-dimensional element of information about the product is communicated to the consumer, based on a standardized test procedure. No values are ascribed to the certification. MERV numbers and 80 PLUS® ratings do not speak to the overall quality of the product. No tier is necessarily better than another in these systems; rather, the certifications simply guide a consumer toward the product that is the best fit for their purpose.

5.1.6 Motion Picture Classification Corporation of Canada: Canadian Home Video Ratings System

The Canadian Home Video Ratings System (CHVRS) was developed by the Canadian Motion Picture Distributors Association to establish a uniform system for use in each province, as this is not considered federal jurisdiction. It is a voluntary consumer information system led by the industry. Six film classification boards across the country determine the rating for a film, and then a weighted average is applied to determine how the film will be classified. Quebec has a separate classification system administered by its Ministry of Culture and Communications.

The classification symbols appear on video packaging and digital media in accordance with the CHVRS, and are described as follows [97]:

- **G on a green circle:** Suitable for viewing by all ages.
- **PG on a blue circle:** Parental guidance advised. Themes or content may not be suitable for children.

Table 6: 80 PLUS® certification levels for typical 115V power supply (adapted from [96])

Power supply load	80 Plus	80 Plus Bronze	80 Plus Silver	80 Plus Gold	80 Plus Platinum	80 Plus Titanium
20%	80%	82%	85%	87%	90%	92%
50%	80%	85%	88%	90%	92%	94%
100%	80%	82%	85%	87%	89%	90%

- **14A on a yellow circle:** Suitable for people 14 years of age or older. Those under 14 should view with an adult. No rental or purchase by those under 14. Parents cautioned. May contain violence, coarse language, and/or sexually suggestive scenes.
- **18A on an orange circle:** Suitable for people 18 years of age or older. Persons under 18 should view with an adult. No rental or purchase by those under 18. Parents strongly cautioned. Will likely contain explicit violence, frequent coarse language, sexual activity, and/or horror.
- **R on a red circle:** Restricted to 18 years and over. No rental or purchase by those under 18. Content not suitable for minors. Video contains frequent use of sexual activity, brutal/graphic violence, intense horror, and/or other disturbing content.
- **E on a white circle:** Exempt. Contains material not subject to classification, such as documentaries, nature, travel, music, arts and culture, sports, and educational and instructional information.

This consumer information system often relies on the subjective assessment of numerous reviewers, whose inputs determine the final rating. This approach yields a decision that is expected to align with the preponderance of viewers' opinions. Thus, the label serves to set expectations for the audience and the CHVRS makes no comment on the quality of the product.

Interestingly, the G rating is green and the PG rating is blue, which correspond to the informal colour-coding system used for hydrogen, where green maps to a renewable pathway and blue to a natural gas plus CCUS pathway. This seems to establish a tiered system, in which the product considered most benign and broadly acceptable is green. Blue follows, reflecting an increase in reservation about the product, and so on.

5.1.7 Discussion

The consumer information systems discussed in sections 5.1.1 through 5.1.6, some of which involve product classification and certification, have either grown rapidly in response to market demand or have withstood the test of time to date. Specific learnings can be drawn from these success stories, including:

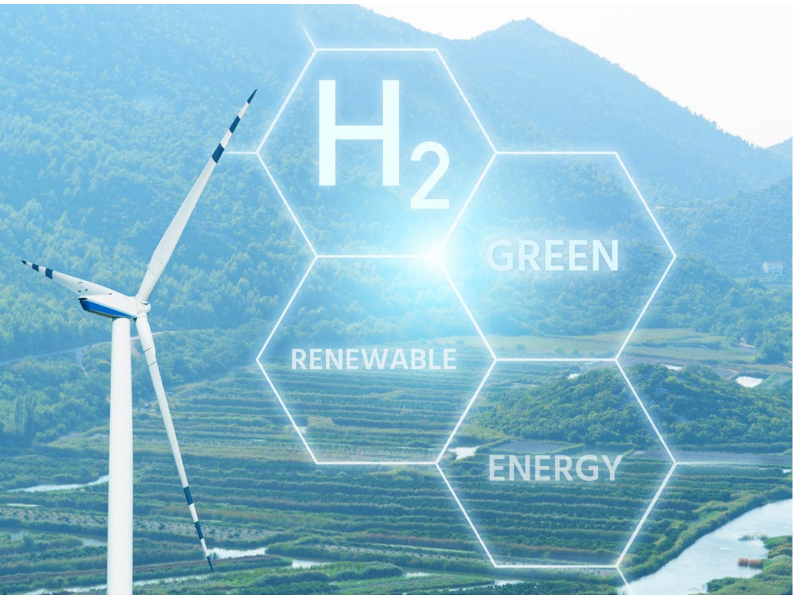
1. Credibility and trust seem to emerge from a consistent application of testing protocols and transparent procedures. Subjective evaluations are acceptable, provided the principle of objective analysis is relied upon to inform judgement, to the extent reasonable.
2. Consumers value disclosure of information, even if it only partly informs their procurement decisions. It is sometimes useful to complement the disclosure of detailed information with a simplified visual in which some details may be lost, but the meaning is amplified.
3. Simplicity and expediency are characteristics of consumer information systems that are embraced by the market when available. A simplified representation must still be grounded in comprehensive assessment, but the more quickly and intuitively the market can act on the information, the better, provided that the pursuit of simplicity does not introduce confusion.

5.2 Emerging Hydrogen Certification Systems

In response to government policy requiring hydrogen to satisfy sustainable development criteria, and the general market interest in hydrogen that is sourced from renewable or low-carbon feedstocks, several hydrogen certification programs have already been launched. Some of the dominant programs are described here and considered in the context of the consumer information system best practices explored in the preceding section.

5.2.1 CertifHy™ Guarantee of Origin Certification

CertifHy™ [98] is a program funded in part by the European Commission and administered by the CertifHy™ Consortium, which is led by Hinicio, a consultancy specializing in hydrogen market development [99]. The program issues guarantees of origin (GO) for hydrogen that qualifies as either green or low carbon. These GO certificates have value in certain markets, such as in the EU, and are transferrable to the certified hydrogen consumer.



"In response to government policy requiring hydrogen to satisfy sustainable development criteria, and the general market interest in hydrogen that is sourced from renewable or low-carbon feedstocks, several hydrogen certification programs have already been launched."

Hydrogen suppliers seeking certification submit their product to a central registry for consideration by an auditor. A hydrogen product that is confirmed to have a CI level that is at least 60% below the benchmark level (i.e., hydrogen from natural gas via steam methane reforming) qualifies as CertifHy™ Low Carbon Hydrogen. This includes hydrogen from non-renewable energy sources (i.e., nuclear, fossil with CCUS). If it is further demonstrated that the origin of the hydrogen is renewable (e.g., biogenic, hydroelectric, wind, or solar), then it qualifies as CertifHy™ Green Hydrogen.

The GO is issued as an electronic document that includes information for the final users of the hydrogen, who can refer to the certificate as evidence of having complied with policy or fulfilled a directive, depending on the jurisdiction. A CertifHy™ GO includes:

- Energy source from which the hydrogen was produced [100];
- Information on the facility that produced the hydrogen (e.g., location, start date of operation, operator, etc.);
- Time of production of the hydrogen;
- CI of the hydrogen, measured in CO_2e/MJ; and
- Date that the GO was issued.

Once the hydrogen has been consumed, GO cancellation statements are issued from the central registry, thus ensuring that the volume of certified hydrogen can only be used once.

The steam methane reforming source of hydrogen that serves as the benchmark is considered by CertifHy™ to have a CI of 91 gCO_2e/MJ, referring to the well-to-gate portion of its lifecycle [101]. However, this value may be revised periodically.

The CertifHy™ program is most active in Europe, where the scaling-up of hydrogen production and hydrogen imports is currently an energy security objective. GO certificates have already been issued to a number of producing facilities in Europe, and the architecture of the program can be transferred to other jurisdictions as needed.

5.2.2 TÜV SÜD Standard CMS 70: GreenHydrogen and GreenHydrogen+

TÜV SÜD is an international company headquartered in Germany that provides a wide range of technical testing services, including certification, and has expertise and capacity in the areas of sustainable development and hydrogen systems. In 2021, TÜV SÜD published a new standard on the production of green hydrogen, CMS 70 [102]. Hydrogen supplies satisfying the standard can be issued a GO certificate, similar to the CertifHy™ program, and there are two designations that can be earned under the CMS 70 standard: GreenHydrogen and GreenHydrogen+.

According to CMS 70, GreenHydrogen is defined according to a set of conditions, including the following [102]:

- The system boundary in which the hydrogen is defined, including its GHG emissions, includes the production plant and ancillary units, such as water treatment, on-site energy inputs, and hydrogen purification up to the point of transfer to a separate system of distribution. Upstream of the system boundary, energy and feedstock production are considered exogenous to the system boundary. At the point of transfer to downstream systems, the hydrogen must have purity of at least 99.9%vol and up to an overpressure level of at least 3 MPa. Within the system boundary, ISO 14040 and 14044 LCA principles and guidance are followed.
- The scope of certification must be documented with certain details, including:
  - Production process;
  - Generation sites with total output and average total annual work done;
  - Purpose of production;
  - Energy sources used;
  - Owner of the plant;
  - Mode of transport and transport routes; and
  - Service providers that perform functions relevant to certification.
- The use of the hydrogen must reduce GHG emissions by at least 70% from a reference value. This reference value may change depending on the situation, but it is currently set to state-of-the-art steam methane reforming hydrogen production, estimated at 94 gCO_2e/MJ. This corresponds to a CI upper limit of 28.2 gCO_2e/MJ.
- The hydrogen must be proven to be synthesized from renewable feedstock, which can include renewable electricity for electrolysis or biogas/methane.

GreenHydrogen+ is considered to be produced when the requirements for GreenHydrogen have been met but under an expanded system boundary that includes the transport of the hydrogen to its end user. Furthermore, at the time the hydrogen production facility is commissioned, there must not be any grid supply bottlenecks that constrain or divert renewable electricity from other important uses. The GreenHydrogen+ certification is thus more stringent, although there are no changes to the numeric thresholds for CI.

The GreenHydrogen and GreenHydrogen+ GO certifications are similar to those of CertifyHy™, but CMS 70 tightens the scope by excluding fossil fuel-based sources even if they are low in CI.

5.2.3 The GH2 Green Hydrogen Standard

In 2022, the Green Hydrogen Organisation (GH2) launched a GO certification program as part of its Green Hydrogen Standard [103]. The program shares some design features with CertifHy™ and GreenHydrogen/GreenHydrogen+, but the process of submitting a project to the GH2 Registry involves public consultation, although GH2 is not an accredited standards development organization. The Green Hydrogen Standard sets the CI maximum at 1 $kgCO_2e/kg\text{-}H_2$. The standard also requires that hydrogen be produced only from water electrolysis using renewable power, including hydroelectric, wind, solar (thermal and photovoltaic), geothermal, tidal, and other ocean energy pathways.

Additionally, under the Green Hydrogen Standard, hydrogen qualifying for certification must fulfill a set of environmental, social, and corporate governance performance requirements, some of which refer to the International Finance Corporation's Environmental and Social Performance Standards [104]. These requirements mean that the Green Hydrogen Standard addresses a broader range of sustainable development criteria than other policies and programs, and include [103]:

- Stakeholder engagement and government approval, to ensure the project is compliant with regional laws and is not in conflict with any property, land use, or water rights.
- Social impact assessment to demonstrate that the hydrogen project is developed in consultation with the local community, that its long-term impacts and performance are understood, and that it supports local business and the value chain generates local benefits. Issues considered include:
  - Effects on communities and livelihoods, such as public health, human rights, and local sustainable development goals;
  - Resettlements are avoided;
  - Indigenous peoples affected by the project provide free, prior, and informed consent;

  - Labour and working conditions, including fair wages and union representation; and
  - Modern slavery, child, and forced labour are absent or their eradication is advanced through the project, and there are measurable improvements in skilled labour and knowledge transfer.
- Environmental impact assessment to ensure no avoidable, negative impacts to local environmental and public health, including:
  - Water use and quality are assessed through a public evaluation to ensure no negative effects on water availability or rights occur from the project;
  - Biodiversity impacts are identified and addressed; and
  - Noise and air quality impacts are identified and mitigations are undertaken.
- Project health and safety.
- Governance of the project upholds the principles of anti-corruption and transparency of benefits, subsidies, and contracting.

The Green Hydrogen Standard's requirements for certification reflect an international perspective on hydrogen project development, particularly in countries or communities with developing economies, where local laws may fail to meet global best practices for environmental, social, and corporate governance. In this respect, the standard can be seen as an instrument for advancing principles of economic progress and social justice by levering commercial hydrogen production, local use, and export opportunities.

5.2.4 Discussion

Of the three emerging hydrogen certification programs discussed in sections 5.2.1 through 5.2.3, CertifHy™ and GreenHydrogen/GreenHydrogen+ both focus on feedstock type, in order to elevate the value of hydrogen made from renewable energy sources. This is appropriate because the purpose of the certifications is to fulfill a jurisdiction's GHG emissions reduction goals, first and foremost, by facilitating and expediting trade in hydrogen that accelerates decarbonization. Other thresholds of sustainable development are not addressed, perhaps because further restrictions may contradict a companion purpose, which is to rapidly increase hydrogen supply in the EU, including through international import, to meet energy security objectives.

According to Henry Mintzberg, strategy is "a pattern in a stream of decisions" [105]. When evaluating certifications and their associated classification systems for patterns, it is as important to consider what is included in the scope as what is absent.

In the context of best practices for consumer information systems, these two certifications exhibit the quality of disclosure, given the scope of information documented in the certificates. The certifications are also relatively simple, as the definitions for low-carbon and renewable feedstocks are clearly and succinctly described and conform to current, common hydrogen production pathways. This may change, however, with the emergence of new technologies that complicate the pathway definitions.

The Green Hydrogen Standard, in contrast, promotes a broader vision of hydrogen development that advances numerous sustainable development goals. It appears to strive for a gold standard that some hydrogen project proponents may have difficulty achieving. Certification under this standard could be viewed as a rare and exclusive designation, consistent with the highest ideals of hydrogen production. While there may be added project costs to comply with the standard, the certified hydrogen may sell at a higher price in the market, if consumers value the principles reflected in the standard.

6 Themes Emerging from Interviews with Sector Experts and Stakeholders

The primary research conducted for Phase 2 of this report consisted of interviews with subject matter experts and representatives of different elements of the hydrogen value chain. This section summarizes the themes and perspectives on the subject of hydrogen classification systems that emerged from the interviews. Some of the findings from this primary research informed the content in previous sections of the report, so this section includes additional views and ideas expressed during the interviews.

CI and source feedstock are the attributes of hydrogen supply chains that a classification system must address first and foremost.

While many sustainable development characteristics of the hydrogen supply chain are important, the attributes interviewees noted as having the most immediate relevance were lifecycle CI (namely from well-to-gate) and identification of the source feedstock. Interest in these two distinct attributes is driven by government policy, including compliance with directives, regulations and incentive programs, and general market demand.

Social aspects of the supply chain and sustainable water use followed in overall importance. The social dimension was mainly expressed as good employment opportunities, especially if the hydrogen is used in the regions where it is made (i.e., local hydrogen commercial ecosystems). Interviewees suggested that these characteristics should be considered in any new classification system, but they are not currently constraints on market growth, so there is time to consider how best to integrate them alongside CI and source identification.

Many interviewees pointed out that climate action is the main driver of new hydrogen markets. Other benefits of hydrogen use, such as improvements to local air quality, were often perceived as less important but not trivial, especially in regional contexts. For example, in water-stressed regions, water use may become a key factor in any development, not just hydrogen projects. It was also noted that in openLCA, it is possible to build datasets and assess social impacts by calculating social indicators related to a hydrogen process unit.

A new classification system should refer to LCA methods and models that adhere to a common standard for consistency, comparability, and replicability of outputs.

Many LCA models are designed to compare fuel pathways of different types, but none were specifically designed to address hydrogen supply chains. Hence, hydrogen is sometimes assessed according to boundary conditions more relevant to other fuel pathways and pursuant to other objectives. To better facilitate hydrogen-to-hydrogen comparisons and distinguish between supplies and suppliers, interviewees noted that the market would benefit from an LCA methodology designed for this purpose.

In 2022, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) released a working paper that proposes a consistent methodology for calculating the GHG emissions associated with hydrogen production [106]. IPHE is a government-to-government organization, which may facilitate the proposed methodology being adopted into an international standards development process. To that end, there is an expectation that the IPHE methodology will be considered by ISO's Technical Committee on hydrogen technologies (ISO/TC 197) for development into a formal ISO standard. This is a process that could take several years, but it could yield a globally-recognized standard for determining and disclosing the CI (or GHG emissions intensity) of a specific supply of hydrogen.

Different standards compete for adoption in the international marketplace. Until a standard is incorporated by reference in regulations, market actors will need to determine which best practices to follow. An analogy is the use of Generally Accepted Accounting Principles, in that several different methods may align with the principles, within which there may be some variation of outputs. The aim is to strike a balance between ease of use, consistency, and completeness.

Interviewees widely noted that the environmental attributes of a hydrogen supply chain are part of what is being transacted in the exchange of hydrogen, and that commercial decisions will be based on these attributes. Thus, aligning a classification system to an LCA method that is transparent, auditable, and simple is advised. Moreover, certification of hydrogen will be a crucial instrument of cross-border trade in hydrogen, so a classification system that refers to such certification is more likely to be adopted globally.

Attributional LCA models are preferred for simplicity and consistency of results.

While consequential LCA models are appropriate for simulating complex systems, they can be very sensitive to boundary effects. For example, consider two equivalent hydrogen producing facilities. Both make hydrogen but sell their co-product oxygen to different customers, who use it to displace other sources of oxygen that they would otherwise have to procure. Depending on the nature of those third-party oxygen sources, which are well outside the scope of control of the hydrogen producers, a consequential LCA assessment may yield very different CI values for each of their hydrogen products. In contrast, attributional LCA methods would likely assign an equivalent CI value to each operation as the fate of the oxygen is disregarded or considered to be the same. The output may be inaccurate in an absolute sense, but it is accurate as a comparator of the two operations. More to the point, it can motivate improvements at both facilities that are within the direct control of the owners.

Thus, attributional LCA modelling better enables policy measures and programming. In addition, the outputs are less likely to change over time as new information is generated, which helps to sustain trust among direct stakeholders and the public.

Development of a new classification system should consider its use in hydrogen derivatives.

Bilateral trade in bulk hydrogen derivatives has already begun. Shipments of ammonia from the Middle East to Europe and liquefied hydrogen from Australia to Japan have occurred, in which the CI of hydrogen was a feature of the contracts and the prescribed methods of calculation [107], [108]. In order of market demand, derivatives of low-carbon and green hydrogen include ammonia, methanol, and steel. Thus, consideration of the sustainable development concerns most relevant in those sectors may inform which attributes are identified in a new hydrogen classification system.

Currently, bulk purchases of hydrogen are directly negotiated between parties, meaning that the absence of a formal classification system is not a barrier to exchange. However, as volumes grow and pipeline transport emerges as the norm, in which many different sources of hydrogen are aggregated, blended, and distributed, classification and certification programs will become critical, both for direct uses of hydrogen and indirect uses of its derivatives (e.g., green steel, green ammonia).

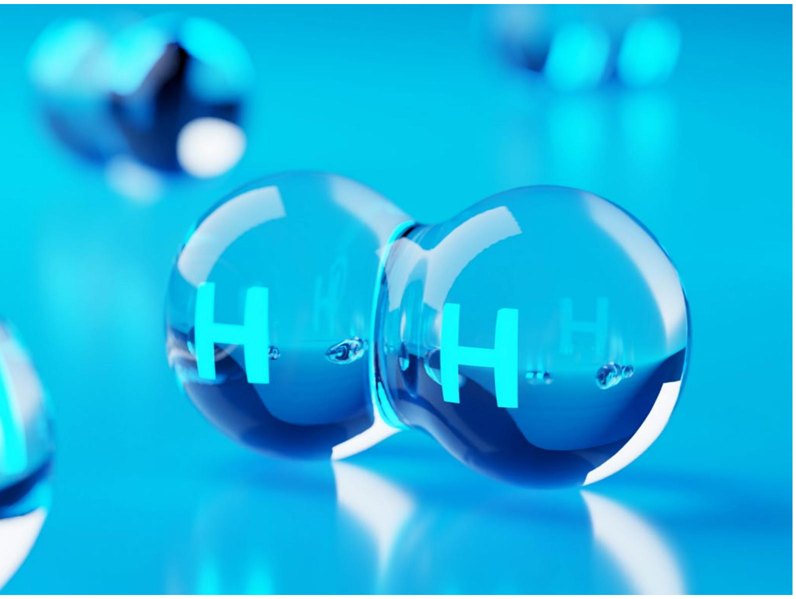
An alternative to the informal colour-coding system for classifying hydrogen is desired.

The informal colour-coding system for distinguishing hydrogen products according to their supply chains is increasingly seen as reductive and inaccurate, a source of market confusion, potentially misleading, and, most importantly, it usually does not help suppliers or consumers. From a CI perspective, in some circumstances, blue hydrogen can be quantitatively cleaner than green hydrogen. Interviewees noted that the system has polarized the hydrogen movement, creating a false perception of good actors and bad actors within the sector and creating space for moralizing claims that do not support hydrogen adoption and trade. Interviewees indicated that the colour-coding system was originally developed to educate the public and communicate to the media, not to serve as a procurement specification.

Therefore, interviewees welcomed the prospect of formal classification system that identifies the market-relevant characteristics of a hydrogen product without bias or judgement.

A new hydrogen classification system should be intuitive and adaptable to changing market drivers.

Interviewees remarked that over the past 25 years, the number of fair trade coffee certifications and labels expanded dramatically to align with an increasingly diverse range of sustainability goals in coffee-growing regions, and then contracted to just few prevailing systems. At its peak, the audit burden on many bean growers of complying with the myriad certifications exceeded their capacities [109]. Interviewees used this reference as a cautionary tale. To avoid a paralyzing competition of hydrogen classification systems in the market, interviewees recommended the creation of a broadly applicable and readily understandable consumer information system. Furthermore, the system should be structured to convey new information as it becomes available and important. Such adaptability



> "There are currently no formal classification systems for hydrogen that inform and facilitate commercial exchange without bias or confusion."

will allow a hydrogen classification system to be durable and maintain trust over time. Without these elements, classification systems may be frequently retired and replaced, which does not serve the market well.

Interviewees also referred to the Principles for Credible and Effective Sustainability Standards Systems, published by the International Social and Environmental Accreditation and Labelling (ISEAL) Alliance [110], paraphrased here:

1. **Sustainability:** Sustainability objectives are clearly defined.
2. **Improvement:** Improved understanding leads to progress toward desired outcomes.
3. **Relevance:** Standards are appropriate for their purpose.
4. **Rigour:** Standards systems are designed to deliver quality outcomes.
5. **Engagement:** Stakeholders are empowered and participate in the development of standards.
6. **Impartiality:** Standards systems work to mitigate conflict and cultivate trust.
7. **Transparency:** Information about data and governance is freely available.
8. **Accessibility:** Standards systems are not overly burdensome to use.
9. **Truthfulness:** Standards systems are not misleading and facilitate informed choice.
10. **Efficiency:** Standards systems refer to and collaborate with other systems to improve consistency and viability.

7 Recommendations

The research presented in this report provides a scan of the international landscape of hydrogen classification systems, LCA CI tools, government policies and programs, and private sector-led initiatives to certify hydrogen according to its associated environmental and sustainability attributes.

Emerging from this research is a clear void: there are currently no formal classification systems for hydrogen that inform and facilitate commercial exchange without bias or confusion.

There are certifications that qualify only certain hydrogen supply chains for policy or program support, or to help communicate their intrinsic social and environmental value within markets, but these do not serve the purpose of a broad system of definition and identification. Such a system could complement and integrate with existing and emerging standards around the world, and contribute to market efficiency by establishing a common, singular definition of the hydrogen products that are being exchanged.

7.1 Taking Stock of the Landscape Scan Findings

In Section 3, the results of a jurisdictional scan were presented, which showed that low-carbon hydrogen production and use are increasingly being referenced as a way to comply with decarbonization policies in various jurisdictions around the world. In some instances, established low-carbon hydrogen supply chains are an explicit objective of government policy.

In Section 4, the LCA principles and methods that are currently applied to estimating the CI of hydrogen pathways were reviewed. Commonalities among the prevailing LCA models indicate a convergence on well-to-gate boundary selection and attributional methodologies. These approaches support consistency of outputs, which better meet the requirements of regulatory compliance and qualification for incentive and certification programs.

In Section 5, a diverse selection of consumer information systems was explored to better appreciate how their designs reflect their unique objectives as well as the limits of what can be communicated. Among these tools, several clear and common principles were at work, including consistent and transparent application of rules, disclosure of information, and simple, intuitive design. Current hydrogen certification programs were also reviewed in Section 5 to provide insight into their structure.

In Section 6, themes emerging from the interviews with representatives from the global hydrogen community of practice were consolidated and summarized.

The findings from each of these sections should be considered in the development of a new hydrogen classification system.

7.2 Guidance on Design Elements of a Hydrogen Classification System

The principles and design elements provided in sections 7.2.1 through 7.2.4 should be considered as guidance for the development of a new classification system for hydrogen. Specific recommendations are provided at the end of each section.

7.2.1 Statement of Purpose

The design of classification systems and consumer information systems must respond to an identified need, which should be clearly expressed in a statement of purpose. Beyond its traditional industrial uses, the growing interest in hydrogen is its capacity to decarbonize energy systems and manufacturing supply chains. In terms of sustainable development goals, climate action is the main driver, and CI is thus the dominant characteristic of concern.

However, there are other impacts and effects of hydrogen supply chains that are typically considered secondary, but in some cases can be equally important. In order of general importance, these are:

1. Nature of feedstock source: The source of energy and/or matter (e.g. renewable power, fossil fuel, biomass, nuclear, or waste recycling-based).
2. Nature of geographic supply chain: Does it create employment opportunities? Does the hydrogen supply support decent, local employment opportunities?
3. Water-intensiveness: Is the hydrogen driving unsustainable water use?

It should be noted that the importance of these and other issues are likely to vary across regions and over time. The country (or region) of origin may also grow in importance if international trade in hydrogen becomes commonplace.

Recommendation: The purpose of the hydrogen classification system should be to disclose basic information to hydrogen consumers about the essential sustainable development characteristics of the production pathway. The dominant characteristic of concern is CI, an indicator of which should be communicated first and foremost. The system should also communicate information about the hydrogen production method, pathway from source, nature of employment, and relative sustainability of resource (water) use.

7.2.2 Methods of Evaluation

Attributional LCA methods and models have already been adopted as the norm for assessing the CI of various fuel pathways under many jurisdictions' policies and programs. Moreover, for hydrogen production-focused policies, the boundaries of the LCA focus on production-related emissions and disregard the effects of fuel displacement at the point-of-use. This approach generally aligns with well-to-gate boundary selection and is appropriate when the end use of the hydrogen is not predetermined, as illustrated in Figure 7. Convergence on these principles provides an accepted reference on CI for a new hydrogen classification system, so no new methodology needs to be developed.

Recommendation: The source of data and LCA methodology used under a hydrogen classification system should reference a global standard. IPHE's proposed methodology for determining the GHG emissions associated with the production of hydrogen could serve as an immediate reference, as it is designed specifically for hydrogen and its purpose is to generate consistent, comparable CI figures.

7.2.3 Objectivity and Absence of Bias or Judgement

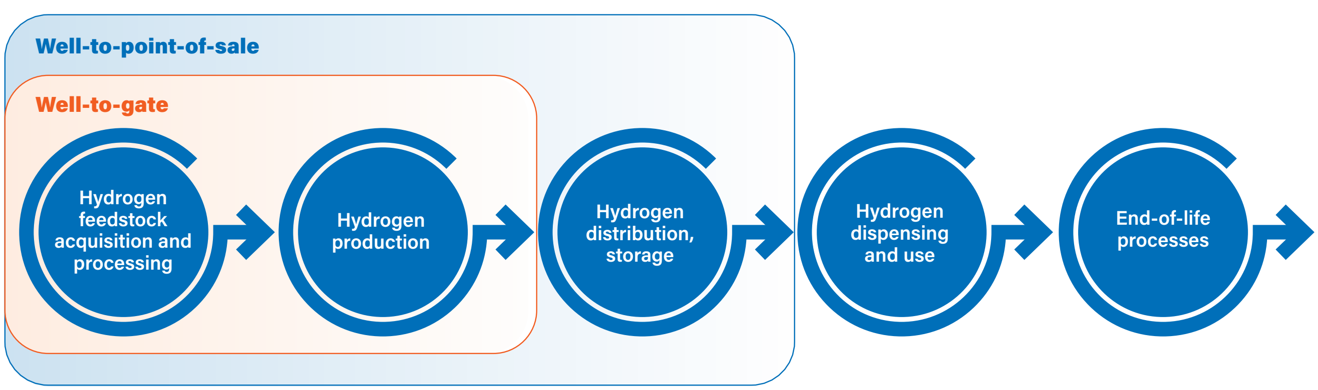
While the purpose of a prospective hydrogen classification system is to disclose basic information to hydrogen consumers about the essential sustainable development characteristics of the production pathway, it should refrain from making statements that are biased or exclusionary. Decisions as to whether certain hydrogen is inherently acceptable or unacceptable should be for a consumer to make. The objective disclosure of information (within a declared context) is a characteristic of successful consumer information systems. The perception of an absence of bias is enhanced by transparency about methods and sources of data and information.

Recommendation: Information communicated under a hydrogen classification system should be presented objectively. Context is useful and acceptable for expressing meaning, but values-based judgements should be avoided. Transparency about data sources and methods of evaluation should also be easily accessible to all parties.

7.2.4 Communicate Simply

While the evaluations conducted under a hydrogen classification system may be complex and detailed, communicating the information to the target audience should be done in a way that is simple, but without sacrificing credibility or legitimacy. Consumers of hydrogen are usually not the regulated party (producers are), and strong, simple messages can be more effective for fulfilling the purpose of the classification system than inundating consumers with data. However, if the consumer desires more detailed information, then it should be accessible to them per the previous recommendation.

Figure 7: Hydrogen production lifecycle elements and assessment boundaries



Recommendation: Strive for simplicity in the top-line communication about a hydrogen classification system. Where possible, use icons to express key messages instead of text. This will mitigate language barriers and support global adoption of the system. More detailed information about data sources and methods of assessment should be accessible, but should not be part of the top-line communication.

7.3 Sustainability Meta-Labelling: A Concept to Consider

Sustainability meta-labelling is an emerging field of practice and study in which a range of indicators or certifications relating to sustainable development are combined into a meta-label. This concept has evolved in response to the threat of consumer confusion caused by "too much, too complex, too similar, and too ambiguous information" [75] expressed in a landscape replete with labels. In theory, it is a way to aggregate and simplify information for consumers.

In a review by Torma and Thøgersen [75], the authors note that a meta-label can integrate form and sustainability content, which is often complex and multidimensional, using sub-labels that support visual simplification. The effect is to mitigate consumer confusion and amplify positive, informed decision-making through meta-labelling that offers "simpler, more salient, credible, comparable, comprehensive" [75] information.

A new hydrogen classification system could reflect the principle of aggregating information from several sources and, in a consistent manner, consolidate and meaningfully interpret the information for an audience simply and succinctly.

7.4 Illustrative Examples of Hydrogen Classification System Concepts

In this section, two sample concepts of hydrogen classification systems are presented that reflect the recommendations made in sections 7.2.1 through 7.2.4.

Figure 8: Sample hydrogen classification system using icons and alphanumerics

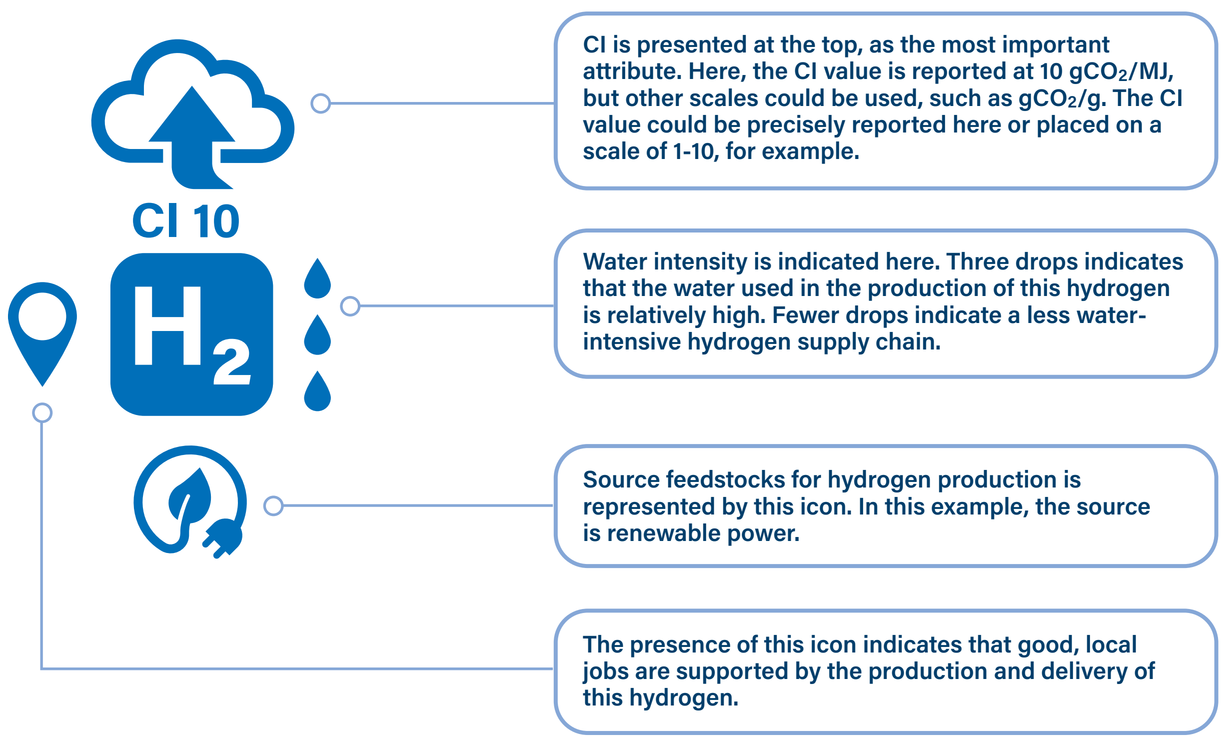
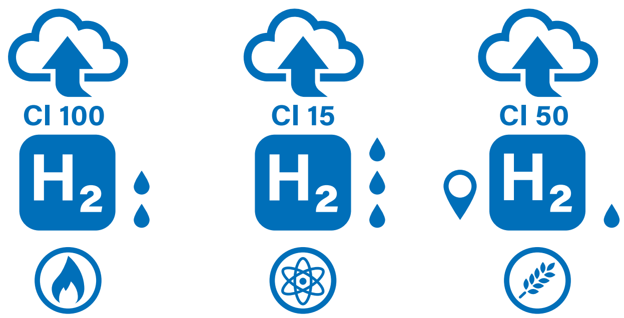


Figure 9: Three sample hydrogen classification systems using icons and alphanumerics



These are for illustrative purposes only, to demonstrate how the recommended design elements could be applied, and to provoke discussion and collaborative ideation.

Concept A: Using icons and alphanumerics to communicate a hydrogen classification system.

Concept A uses a combination of visual elements (icons) and numbers and letters to present key information about a hydrogen classification system, as demonstrated by the sample systems presented in Figure 8 and Figure 9.

From left to right, the sample classification systems presented in Figure 9 indicate:

a. Hydrogen from fossil fuel (e.g., natural gas), has high CI, is less water-intense, and is not locally sourced;

b. Hydrogen from nuclear power, has low CI, higher water-intensity, and is not locally sourced;

c. Hydrogen from biomass, has medium CI, low water-intensity, and is locally sourced.

Consistent with the recommendations in sections 7.2.1 through 7.2.4, Concept A provides information about the hydrogen supply chain on four attributes of importance to the market: CI, feedstock, local employment, and sustainability of water use. The CI value is assumed to be generated using a globally-recognized, standardized LCA method (using a well-to-gate boundary condition). The information is presented in a simplified format that is easy for a reader to comprehend so the key characteristics of the hydrogen supply can be understood and comparatively evaluated.

Concept B: Quantitative information presented in a data sheet format.

In contrast to Concept A, Concept B uses a data sheet format to present information in greater detail, as shown in Figure 10. While this may run contrary to the principle of simplicity, it accommodates the classification of hydrogen that represents a blend of various supply chains and sources. It begins by relaying information not directly related to sustainability criteria, such as purity levels, country of origin, and the specific LCA model used. CI is presented according to key aspects of its supply chain, in terms of the mass of CO_2 emitted per unit of energy and per unit of mass delivered. Next, feedstock types are ascribed a sustainability index value and multiplied by the share of the hydrogen sourced from that feedstock and summed to generate an overall score. A similar scoring is applied to the hydrogen supply according to the source energy type and, finally, the energy efficiency of the supply chain is broken down by key elements.

If the user wishes to apply a bias to the scores, a gold, silver, or bronze rating could be awarded, as shown at the bottom of the data sheet, although that would violate this report's recommendation for objectivity.

Figure 10: Sample hydrogen classification system using a data sheet

HYDROGEN PRODUCTION FACTS

General	
Country of Origin	eg., Canada
Modelling Tool	eg., GHGenius

Purity	
Percentage by weight	Weight here
Impurities, contains trace amounts of:	list contaminants
Compliance: complies with:	list standards

Carbon Content	Gram CO_2e per GJ	Gram CO_2e per KG
Extraction	aa	aa
Production	bb	bb
Distribution	cc	cc
TOTAL	**ddd**	**ddd**

Feedstock	%	Sustainability Risk Index	Score	Score
Water	ee	1	0	0
Renewable hydrocarbon	ff	1	0	0
Industrial process by-product	gg	2	ggg	ggg
Waste plastic	hh	3	hhh	hhh
Fossil fuel c/w CCU	ii	4	iii	iii
Fossil fuel c/w CCS	jj	5	jjj	jjj
Fossil fuel w/o CCUS	kk	6	kkk	kkk
TOTAL	**100**		**lll**	**lll**

Energy Source	%	Sustainability Risk Index	Score	Score
Renewable/Sustainable	mm	1	0	0
Nuclear	nn	2	nnn	nnn
Non-renewable/Non-sustainable	oo	3	ooo	ooo
TOTAL	**100**		**lll**	**lll**

Energy Efficiency	GJ per GJ	GJ per KG
Extraction	pp	pp
Production	qq	qq
Distribution	rr	rr
TOTAL	**sss**	**sss**
Score	**ttt**	**ttt**

Award		
	G	**G**
< ? = Gold ?–?? = Silver ??–??? = Bronze > ??? = Not Certified	**S**	**S**
	B	**B**

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Appendix A – Interview Guide

Classification of Carbon Intensity for Production of Hydrogen: Landscape Scan and Opportunities

The following questions were provided by the study team to interviewees in advance of their respective interview sessions. These questions were not intended to serve as a questionnaire, but to help frame the discussion with experts and stakeholders and provide guidance on the scope of issues to be addressed. The interviews were intended to be freely flowing conversations, and the questions presented herein were to help provoke dialogue with interviewees on issues in which they had special insights and opinions to share. The questions are grouped under three distinct themes.

Theme 1: Carbon-intensity of hydrogen supply chains and LCA models

a. Are there any formal or informal standards used in your industry to identify the carbon-intensity of hydrogen along its supply chain? Is the purpose of these standards regulatory compliance, to satisfy customer demand, or some other driver, such as internal targets for greenhouse gas emissions, external reporting to stakeholders, or offset and credit generation?

b. If the carbon-intensity of hydrogen is subject to scrutiny, then what models or methods are used? Is there conflict or debate over the efficacy of these tools, or do stakeholders share confidence in the outputs as accurate and meaningful?

c. Currently, are carbon-intensity estimates or requirements being referenced in procurement specifications defined by private or public sector buyers?

d. Is the current, informal colouring system for hydrogen (i.e., gray, blue, green, pink) a helpful tool among producers and consumers, or is it hindering commerce and market activity?

e. Within your industry or area of interest, how important is it to know the carbon-intensity of hydrogen? Does the development of new markets for hydrogen as a decarbonizing fuel or agent depend on an accepted means of assessing and reporting carbon-intensity, presently or in the future? Are other qualities of hydrogen and its use (e.g., free of carbon, source of feedstock) enough to drive its adoption?

f. Are current models and methods used to estimate carbon-intensity of hydrogen simple and straightforward to use, and do they produce clear and impactful results? Or, are the tools obtuse and contribute to market confusion?

g. In your opinion, what are the key qualities of a successful and meaningful carbon-intensity assessment tool or method in the context of fostering growth of new hydrogen markets, and investment in new hydrogen production? How do current standards and tools measure up?

h. Some lifecycle assessment models may generate more accurate and consistent estimates for the carbon-intensity of hydrogen products, yet these models may not be referenced in the regulations of certain jurisdictions. Does this create a potential conflict that the CSA should address? Is it necessary for the same models that are, or may be, referenced in regulation to be used in consumer information systems?

i. The study team observes that attributional models tend to be easier tools for users having no specialized training. GHG Protocol, for example, has a user-friendly interface that relies on quick, procedural inputs to generate carbon-intensity estimates. Whereas, consequential models, such as GREET to the Canada LCA model, require a detailed knowledge of the model construction so that an initiated user can customize scenarios using many input factors, thus generating more comprehensive estimates. Are there concerns over the administrative burden that consequential models may require, such as specialized training or certified personnel?

Theme 2: Beyond carbon-intensity, other important attributes of hydrogen supply chains

a. What impacts — either negative or beneficial — of hydrogen production are important to market stakeholders but are not directly addressed in carbon-intensity assessment models and methods (e.g., water use, types of feedstock used, jobs supported, regional economic activity, energy independence, energy prosperity)?

b. For the impacts identified, are there any standard methods or models used to estimate intensiveness? Are you aware of any examples where these estimates specified in any procurement specifications or negotiations?

c. How meaningful are quantitative assessments of hydrogen supply chain attributes, such as water use intensity? Do buyers have the required context or means to compare and evaluate such indicators? Would qualitative indicators be more effective for communicating some impacts?

d. How should other impacts and attributes of a hydrogen supply chain be weighted in importance against its carbon-intensity? Is the question of weighting irrelevant, so long as the information is available to consumers?

e. Should Country (or region)-of-Origin be part of a hydrogen consumer information system?

Theme 3: Consumer information systems

a. What are the essential pieces of information that a buyer of hydrogen needs to have when choosing between supply options or when writing a procurement specification?

b. Who are the audiences that a supplier or buyer needs to consider when making a decision about hydrogen production or consumption? When considering a hydrogen supply chain are the only attributes of concern just those of the suppliers and the buyers, or do the concerns of others, who may have an indirect stake in the negotiation, need to be addressed as well (e.g., local government, the public, shareholders)?

c. What benefit could a broadly accepted standard for communicating the qualities of hydrogen, based on its supply chain (or, alternatively, its provenance and lineage), have for the growth and evolution of new hydrogen markets? Can it be expected to facilitate exchange in hydrogen that advances sustainable development goals, or would it be largely irrelevant to the needs of the market.

d. What format would be most effective for a standard communication tool? Where should it appear, in a practical sense, to best connect with the intended audience?–

e. Considering the intended audiences for a hydrogen consumer information system and its utility, what level of detail do you think is appropriate? How simple (e.g., bronze, silver, gold) or complex (e.g., LEED® certification report) is needed to support the scale-up of commercial markets?

f. There are a great many potential feedstocks, processes, and supply chains for hydrogen delivered to market, with even more being developed. Considering the current, ad hoc colour-coding system, are we likely to run out of colours? Do you know of any examples of a similar problem in other sectors, where the system was unable to accommodate the evolution of the practice it was intended to define?

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In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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