DEVELOPMENT APPROVAL OF HYDROGEN REFUELLING STATIONS

A BLUEPRINT FOR PROJECT DEVELOPERS AND LOCAL AUTHORITIES

FINAL REPORT- MAY 2016

H2U
THE HYDROGEN UTILITY

SUPPORTED BY:

CNCA
CARBON NEUTRAL CITIES ALLIANCE

CITY OF SYDNEY

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The Hydrogen Utility™ (H2U) is a specialist developer of hydrogen-energy infrastructures for sustainable mobility and renewable energy storage.

H2U operates with a unique business model, combining ESCO-style performance-contracting mechanisms with a portfolio of energy services focused on integration of renewable energy resources, and deployment of fleet-based sustainable mobility solutions.

H2U is a spin-off of Talent with Energy Pty Ltd (TWE), a strategy and project development consultancy focused on commercialization of sustainable emerging energy technologies.

H2U is based in Australia and operates throughout the Asia-Pacific region.

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CONTENT

ABBREVIATIONS and ACRONYMS

AWE	Alkaline Water Electrolysis
BEV	battery electric vehicles
CGH2	compressed gaseous hydrogen
CNCA	Carbon Neutral Cities Alliance
EIGA	European Industrial Gases Association
EPA	Environmental Protection Authority
EPC	Engineering, Procurement, and Construction
FA	Funding Authority
FC-RE	fuel cell range extender
FCEV	fuel cell electric vehicles
H35	35 MPa compressed gaseous hydrogen refuelling
H70	70 MPa compressed gaseous hydrogen refuelling
HRS	hydrogen refuelling station
IEC	International Electrotechnical Commission
ISO	International Standardisation Organisation
LH2	liquid hydrogen
MA	Market Authority
NEDO	New Energy and Industrial Technology Development Organisation (Japan)
NOW	Nationale Organisation Wasserstoff – und Brennstoffzellentechnologie (Germany)
OEM	Original Equipment Manufacturer
P&ID	process and instrumentation diagram
PA	Planning Authority
SAE	Society of Automotive Engineers
SMR	Steam Methane Reforming
TA	Technical Authority
ZEV	Zero-Emission Vehicle

Executive Summary

Why is hydrogen important?

Widespread adoption of Zero-Emissions Vehicles (ZEVs) is a key element in the strategy to meet health-based air quality requirements and climate- driven greenhouse gas emissions targets, as well as to reduce the dependence of the economy on foreign oil production.

ZEVs, which include plug-in battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs), share two fundamental attributes: they are powered by electric drivetrains with zero tailpipe emissions.

BEVs store electricity on-board in batteries, which in turn are used to supply power directly to an electric drive that transfers power to the wheels and to the vehicle auxiliaries (air conditioning and electronics).

FCEVs generate electricity on board using hydrogen and fuel cells. The hydrogen stored in high pressure tanks is released to the fuel cell, a highly-efficient energy conversion device capable of converting the chemical energy in the fuel directly into electricity that is in turn transferred directly to an electric drive to the wheels and to the vehicle auxiliaries (air conditioning and electronics).

The apparent simplicity of powertrain arrangements for BEVs over FCEVs is offset by the substantial weight and low energy density of the batteries (theoretical limit 0.12 kWh/kg for Li-Ion), and recharging times (typically in excess of 4h for commercial chargers), therefore limiting their application to passenger vehicle applications – particularly with limited range (<150 km) and power requirements.

Conversely, FCEVs thanks to the high energy density of hydrogen (33 kWh/kg) and high efficiency of the fuel cells (in excess of 50%), and the rapidity of the refuelling process (typically less than 3 minutes for a full charge), can accommodate enough fuel for driving ranges in excess of 700 km, and power capacity to meet the most demanding driving duty cycles, from large SUVs to Buses and Trucks.

The two ZEV platforms rather than being in competition are thus complementary, and their adoption combined can thus provide an alternate solution to diesel- and petrol-powered vehicles across the entire spectrum of road vehicle applications. Moreover ZEV, platforms share many elements (the drive, power controls and the battery[1] themselves), which is why many automakers are developing the two in parallel along newly established joint assembly lines.

Both BEVs and FCEVs – by virtue of the higher storage/conversion efficiency of batteries and fuel cells (when compared to internal combustion engines), and the superior performances for electric drivetrains – can deliver significant life-cycle GHG emission benefits on the basis of existing fuel and electricity mix.

It should be noted however, in the renewed context of urgency for significant greenhouse gas mitigation arising from the recent COP21 in Paris, it is imperative to combine advanced powertrain options with renewable energy resources, so as to maximise the benefits associated with the Transport sector.

With this purpose in mind, in this Blueprint we consider exclusively renewable hydrogen pathways, including water electrolysis and steam reforming of 100% biogas.

[1] Although FCEV integrate a battery system, it should be observed how these are significantly smaller thatn those used in BEVs, effectively they are integrated to recover braking energy, and thus improve overall powertrain efficiency, much like in hybrid electric vehicle such as the Prius.

Fuel cell electric vehicles and refuelling infrastructure commercialization

2015 has been a watershed year for the commercialization of fuel cell electric vehicles (FCEVs). Following nearly 20 years of global research and development efforts by the majority of automotive OEMs (Original Equipment Manufacturers), Hyundai and Toyota have delivered the first mass-produced FCEVs to customers in North America, Japan and Europe. Several other manufacturers have announced their commercialization plans over the 2016-18 period, including Honda (2016), Mercedes and Nissan (2017), Audi and Volkswagen (2018).

Hydrogen Refuelling Stations are the lifeline of FCEVs. Their adoption requires development of suitable networks to enable sufficient infrastructure coverage and to enable driving between locations.

Several jurisdictions have sought to address the infrastructure challenge through allocation of large infrastructure development grants (California and Japan) and/or the establishment of public-private partnership models to co-ordinate the efforts of automakers and infrastructure developers in providing early deployment (such as the H2 Mobility initiative in Germany). This latter model is proving very popular in Europe with similar public-private partnerships under development in Denmark, France and the United Kingdom.

As a result of these activities, the key markets of California, Germany and Japan are on track to meet their deployment targets - each exceeding 100 operational stations by 2020, enough to provide coverage across metropolitan areas and key intercity corridors.

More importantly, the automakers' efforts to develop, test and now commercialize FCEV technologies, and these large infrastructure deployment programs, combined have resulted in the availability of a harmonised and comprehensive body of international standards covering all aspects of hydrogen refuelling station design, development, and commissioning.

Increasingly, this has facilitated the development of a standardized offering for commercial-scale hydrogen refuelling station designs. Key producers such as Linde Gas from Germany have now initiated serial production of hydrogen refuelling station modules at the ATZ facility in Vienna, Austria, and H2 Logic, a subsidiary of NEL of Norway, have announced similar plans.

Why this Blueprint?

With commercial solutions now available for both vehicles and refuelling infrastructure, other jurisdictions can take advantage of the level of maturity now reached by these technologies and initiate commercial deployment without the need for establishing heavily subsidised infrastructure roll-out programs

Several jurisdictions, including entire Countries, or specific Regions currently not served by any infrastructure can now leverage this comparative advantage and advance deployment of FCEVs within their transport fleets.

While commercial technologies are now available, one key challenge to deployment in these countries or regions remains the lack of appropriate development, licensing and permitting guidelines for these type of facilities at the local level. Municipalities are typically the Authorities tasked with the evaluation and issuing of development approvals, and the comprehensive set of international technical standards that is now available, needs to be incorporated within the context of relevant local rules and regulations for development approvals.

The Carbon Neutral Cities Alliance, as a global network of Cities with leading greenhouse gas mitigation programs, is committed to support transformational decarbonisation activities.

The purpose of this Blueprint is to provide Project Developers and Planning Authorities alike with a comprehensive knowledge base on hydrogen refuelling stations – including details of technologies, standards and regulations – and to provide a detailed process for preparation, review and approval of hydrogen refuelling station development applications, designed in accordance with internationally-adopted best practices, yet flexible enough to adapt to local planning scheme requirements.

Structure of this report

The *Blueprint* presented in the main body of this report, is organized as a standalone document describing the key activities involved in the process of developing hydrogen refuelling stations, the roles and responsibilities of key stakeholders involved, and a detailed stage-gate process describing all the key activities to be undertaken at each stage of the licensing and permitting process – from pre-application to issue of a final occupancy permit and operational licence, and opening of the facility for public use – with detailed activity checklists for both HRS Developers, and Planning Authorities.

Complementing the *Blueprint*, and providing Project Developers with a comprehensive knowledge base on technologies, standards and regulations, the following set of *Technical Appendixes* are provided:

- A ***Primer*** on fuel cell vehicles and hydrogen refuelling stations,
- An ***Annotated Review*** of International Standards, Codes and Regulations,
- An overview of existing ***Guideline Tools*** for project developers in Germany and California, and
- Selected ***Case Studies*** for hydrogen refuelling stations in Europe, Japan and the United States.

Acknowledgments

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H2U THE HYDROGEN UTILITY

Overview

Objectives

The *'Blueprint for Development Approval of Hydrogen Refuelling Stations'* (hereinafter *the Blueprint*) is a '*best practice'* guideline tool designed to support Project Developers, and Planning Authorities through the process of requesting, reviewing and obtaining the necessary approvals for the construction, commissioning and operation of public Hydrogen Refuelling Stations (HRS).

Designed for broad applicability in different geographies and jurisdictions, the *Blueprint* breaks down the approval process as a comprehensive *stage-gate* workflow – covering the scope of development approval activities from conceptual design to public opening of a proposed hydrogen refuelling station – organised in the following six stages:

- **Stage 1. Preliminary activities**
- **Stage 2. Pre-application outreach**
- **Stage 3. Planning application**
- **Stage 4. Planning review**
- **Stage 5. Construction**
- **Stage 6. Commissioning**

Scope

The *Blueprint* is focused on hydrogen refuelling stations that are, at least in part, used for public hydrogen refuelling operations, e.g. stations that can accept public refuelling customers.

The scope of Hydrogen Refuelling Station operations covered within the Blueprint are classified according to the following parameters:

- **TYPE:** Public/Fleet/Hybrid[2];
- **SITE:** Hosted[3]/Standalone
- **H2 DISPENSING[4]:** Integrated[5]/Separate;
- **H2 SUPPLY:** Delivered[6]/On-site[7].

Structure

In this section we introduce first the overall development process for a generic hydrogen refuelling station, with an overview of key actors involved with details of their roles and responsibilities.

Within this process the *Blueprint* is introduced as the *critical path* associated with obtaining the necessary approvals for construction, commissioning and operation of public Hydrogen Refuelling Stations.

For each Stage in the Blueprint, we provide a comprehensive overview of objectives, key activities, milestones and go/no-go gateways along with detailed checklists for HRS Developers, and Planning Authorities, as applicable.

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[2] Hybrid operation, supporting fleet and public refuelling.
[3] On existing forecourt station, or within existing fleet operations.
[4] The Blueprint considers only compressed gaseous hydrogen (CGH2) dispensing, in accordance with SAE J2601 fuelling standards.
[5] Within existing dispensing area.
[6] Including: CGH2-T, Compressed Gaseous Hydrogen via Tube-trailer Trucks; CGH2-P, Compressed Gaseous Hydrogen via Pipeline; LH2-T: Liquid Hydrogen Delivery via Tanker Trucks.
[7] Including: AWE, Alkaline Water Electrolysis; PEM, Proton Exchange Membrane electrolysis; SMR, Steam Methane Reforming.

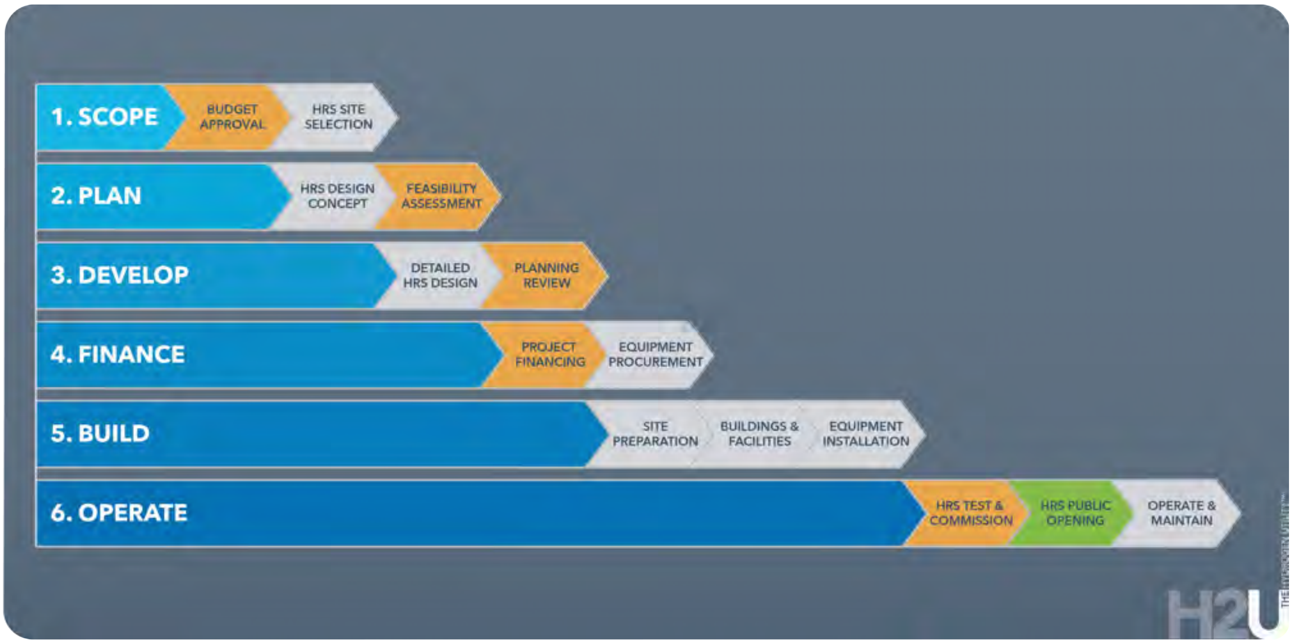
The Blueprint

HRS DEVELOPMENT PROCESS

The development process for a hydrogen refuelling station (HRS), illustrated in the diagram below, includes the following key phases:

1. **SCOPE,** including Budget and Management Approval, HRS Site Selection;
2. **PLAN,** including HRS Design Concept, Feasibility Assessment and Business Case Review;
3. **DEVELOP,** including Detailed HRS Design, Planning Review;
4. **FINANCE,** including Project Financing, Equipment Procurement;
5. **BUILD,** including Site Preparation, Buildings & Facilities, Equipment Installation; and
6. **OPERATE,** including Testing & Commissioning, Public Opening, Operation & Maintenance.

FIGURE 1. TYPICAL DEVELOPMENT PROCESS FOR HYDROGEN REFUELLING STATIONS



The diagram highlights in yellow the following key go/no-go gateways in the development process:

- **Budget Approval,** HRS Developer project development team establishes a preliminary business case for the proposed HRS facility, applies to management for review and approval of a preliminary budget request to undertake activities listed under 1. Scope, and 2. Plan.
- **Feasibility Assessment and Business Case Review,** HRS Developer, Site and Development Partners conduct a Feasibility Assessment and Business Case Review to approve next steps in project development, and to negotiate partner roles, responsibilities, including funding.
- **Planning Review,** Planning Authority, with support from relevant Technical Authorities, – conducts a review of the Planning Application for the proposed HRS facility, and issues an *Approval-to-Build Permit* detailing construction timeframe, and other key technical requirements.
- **Project Financing,** HRS Developer and Project Partners engage with Funding Authorities and Financing Institutions, to secure project finance to undertake detailed implementation activities listed under Scope 5. Build and Scope 6. Operate.
- **HRS Testing & Commissioning,** Planning Authority conducts a final inspection to verify completion of construction and installation, and reviews results of a series of commissioning tests conducted to approve and issue the HRS *Final Occupancy Permit* and *Operational Licence*.

SCOPE OF THE BLUEPRINT

The ultimate objective of the development process is to enable the HRS Developer establish a facility which can satisfy the key performance, safety and operational requirements to be authorised to be open to the public.

A thorough understanding of the Development Approval process, including the roles and responsibilities of the various actors and stakeholders, and of the relevant regulatory, safety and planning requirements, is thus the key to successful project development.

The objectives of the *Blueprint*, is to provide a flexible guideline tool that enables:

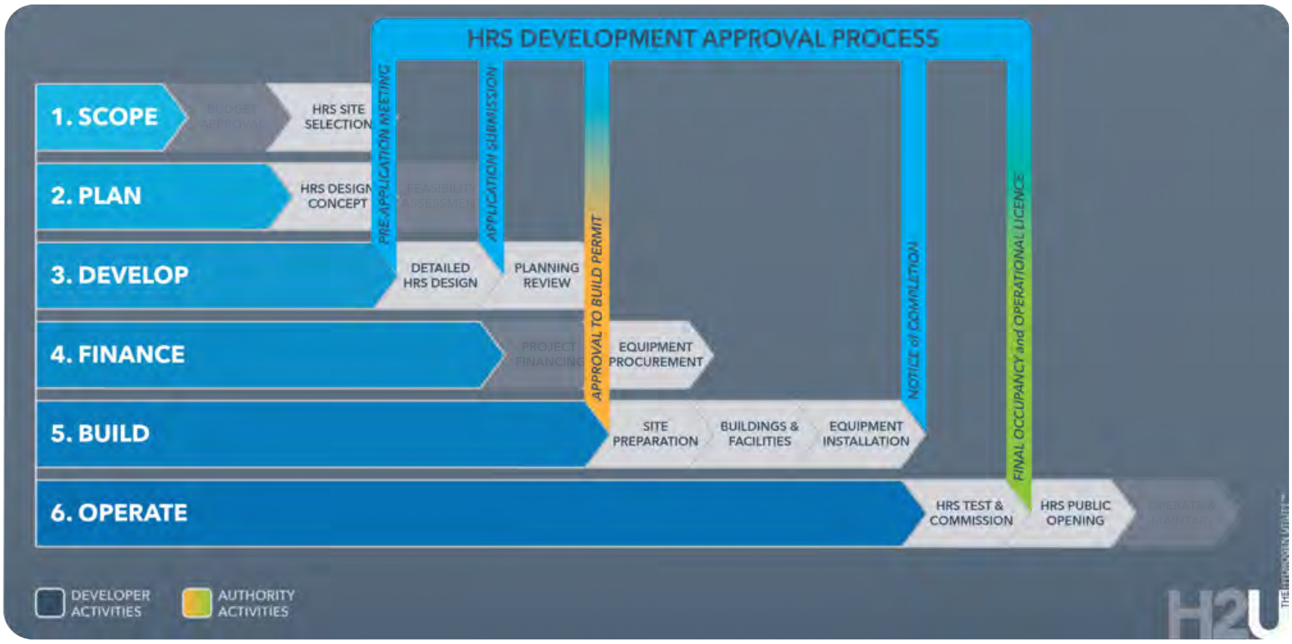
- **HRS Developers,** prepare, organize, and submit a comprehensive Development Application package for the proposed HRS facility, aligned with international best practice, for review and approval by the relevant Planning Authority.
- **Planning Authority,** review and approve the proposed HRS facility, and issue the HRS Developer with the necessary permits and licences to undertake development, commissioning and operation of the proposed HRS facility.

The *Planning Review* gateway discussed earlier is thus just one, albeit critical, step in this Development Approval process, which extends to and influences a range of HRS Development activities throughout the, from HRS Site Selection to HRS Public Opening.

These activities constitute the ***critical path*** highlighted in the diagram below. The key milestones in this process are:

- **Pre-Application Meeting**, between HRS Developer and Planning Authority;
- **Submission of Development Application**, to Planning Authority;
- **Approval to Build Permit,** issued to HRS Developer following review of Planning Application;
- **Notice of Completion**, issued to Planning Authority on completion of Construction activities;
- **Final Occupancy and Operational Permit,** issued following HRS Testing & Commissioning.

FIGURE 2. DEVELOPMENT APPROVAL ACTIVITIES



STAKEHOLDER ROLES and RESPONSIBILITIES

In order to bring a hydrogen refuelling station to fruition, the onus is on HRS Developers to manage and facilitate the effective co-ordination of a number of different stakeholders. These can be grouped broadly in two main categories, Project Partners, and Relevant Authorities.

PROJECT PARTNERS

The partners involved in the development of a Hydrogen Refuelling Station are:

- **HRS Developer,** with ultimate responsibility for the outcome of the project development initiative, the HRS Developer secures access to the site, co-ordinates technical input in the design phase from Technical Consultants and Equipment Providers, liaises with the Planning Authority for the purpose of obtaining the necessary development approvals, engages the EPC Contractor, oversees testing and commissioning activities, and hands over the facility to the HRS Operator.
- **Site Partner,** agrees to host the site on the basis of a Commercial Agreement with the HRS Developer detailing the areas allocated to the proposed Hydrogen Refuelling Station, access arrangements (including right-of-way and opening hours), the duration and cost of the lease.
- **Equipment Supplier(s),** responsible for the provision of HRS equipment manufactured in compliance with relevant standards, codes and regulations in regard to design, safety and performance.
- **Technical Consultants,** including design, engineering, and planning consultants supporting the HRS Developer with specialist technical input throughout the design and development process.
- **Local Utilities**, including review of connection arrangements for proposed HRS site to electricity, gas and water networks (as required).
- **EPC Contractor,** engaged by the HRS Developer to co-ordinate the scope of Engineering, Procurement, and Construction (EPC) activities during project implementation, typically with other sub-contractors.
- **FCEV OEMs,** Original Equipment Manufacturers of Fuel Cell Vehicles, responsible for assisting HRS Developers and Operators conduct Fuelling Protocol Tests.
- **HRS Operator,** the entity responsible for ongoing commercial operation of the HRS facility[8].

RELEVANT AUTHORITIES

A number of authorities are involved in the process of licensing and permitting a refuelling station.

- **Funding Authorities (FA)**, in many jurisdictions the majority of HRS installed have been through projects with an element of public funding. FAs play an active role in determining specific performance requirements, financial and environmental outcomes of HRS projects, and require grantees to commit to knowledge sharing activities to foster industry development;
- **Planning Authority (PA)**, typically the Local Government Planning Department having jurisdiction over review and approval of planning licences;
- **Market Authority (MA)**, typically the regulatory agency, or agencies, overseeing compliance of retail activities with the relevant Trade Practices' Legislation; and
- **Technical Authorities (TA)**, authorities having jurisdiction over compliance over specific technical aspects, including Fire Protection and Safety, Environmental Protection, and Technical Standards.

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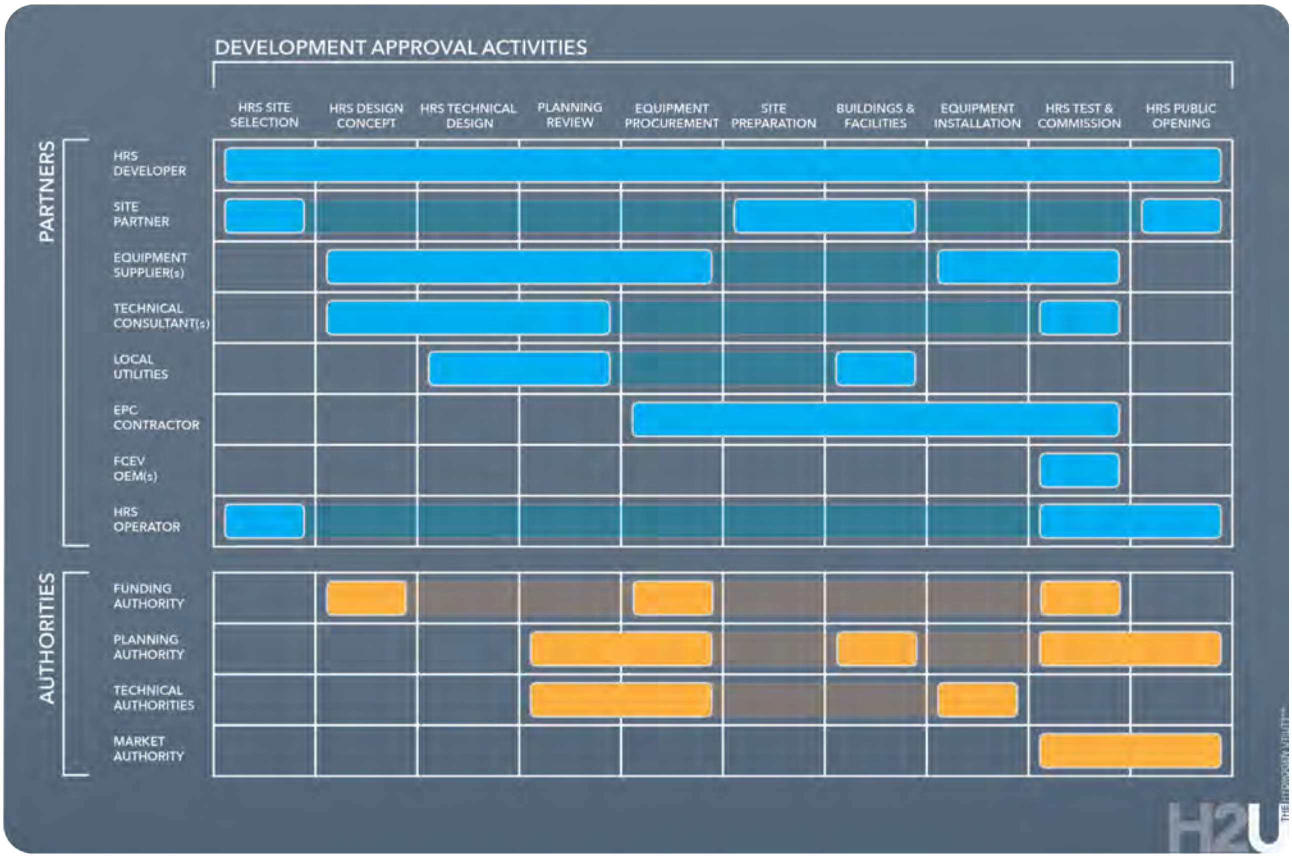
[8] Depending on the business model, the functions of HRS Developer and Operator could be either separate or integrated within the same entity.

With reference to the *critical path* described earlier, the diagram below shows how responsibility over the each activity, is allocated between Project Partners and Relevant Authorities.

FIGURE 3. BREAKDOWN OF PARTNER RESPONSIBILITIES THROUGHOUT THE STATION INSTALLATION PROCESS[9]



STAGE-GATE PROCESS

The table in the following page organizes the critical path of Development Approval activities as a comprehensive *stage-gate* workflow – covering the scope of development approval activities from conceptual design to public opening of a proposed hydrogen refuelling station – organised in the following six stages:

- **Stage 1. Preliminary activities**
- **Stage 2. Pre-application outreach**
- **Stage 3. Planning application**
- **Stage 4. Planning review**
- **Stage 5. Construction**
- **Stage 6. Commissioning**

In the remainder of this section we provide a detailed overview of the key steps involved in this *stage-gate* process with a set of stage-by-stage checklists (the *Blueprint*).

[9] Modified from materials originally presented in (Element Energy, 2015)

TABLE 1. DEVELOPMENT APPROVAL BLUEPRINT – STAGE GATE PROCESS

STAGE 1 – PRELIMINARY ACTIVITIES	
1A	CONFIRM/SECURE SITE ACCESS
1B	IDENTIFY RELEVANT AUTHORITIES
1C	STRATEGIC COMPLIANCE REVIEW
STAGE 2 – PRE-APPLICATION OUTREACH	
2A	PRE-APPLICATION MEETING WITH PLANNING AUTHORITY
STAGE 3 – DEVELOPMENT APPLICATION	
3A	PRE-SUBMISSION REVIEW
3B	APPLICATION SUBMISSION
STAGE 4 – PLANNING REVIEW	
4A	REVIEW OF PLANNING APPLICATION
4B	APPROVAL TO BUILD (go/no go gateway)
STAGE 5 – CONSTRUCTION	
5A	PROCUREMENT and CONSTRUCTION
5B	INSPECTIONS
5C	NOTICE OF COMPLETION
STAGE 6 – COMMISSIONING	
6A	FIRST-FILL COMMISSIONING
6B	OPERATOR TESTING
6C	FUELLING PROTOCOL CONFIRMATION
6D	COMMERCIAL TESTING
6E	FINAL OCCUPANCY PERMIT and OPERATIONAL LICENCE (go/no go gateway)
6F	STATION OPENS TO THE PUBLIC

Stage 1. PRELIMINARY ACTIVITIES

Prior to approaching the relevant Planning Authority (PA), project developers of hydrogen refuelling station projects (hereinafter *HRS* Developers) should undertake three key preliminary activities:

1. Securing site access;
2. Identify relevant authorities; and
3. Conduct a strategic compliance review.

1A. CONFIRM/SECURE SITE ACCESS

Prior to undertaking any detailed project development activities, the relationship between HRS Developers and Site Partner (the Host) should be formalized, and subsequently confirmed through two key steps:

- **Exclusivity Rights to Negotiate Agreement (ErnA)**, providing the HRS Developer with exclusivity over access to the site for a defined time period enabling Feasibility Assessment and joint Business Case Review for the proposed HRS facility, and to carry out negotiations with the Site Partner in regard to site rent, right-of-way, development constraints, etc.
- **Project or Site Development Agreement (PDA)**, defining the terms and conditions under which the Site Partner is granting the HRS Developer access to the site for the purpose of developing and operating a hydrogen refuelling station.

Seamless communication between HRS Developer and Site Partner is absolutely vital in securing the station site. Site Partners must be fully committed to the proposed station arrangement and remain part of the process to quickly enable any necessary changes along the way.

1B. IDENTIFY RELEVANT AUTHORITIES

The HRS Developer should identify all the relevant authorities involved in the review and approval of development applications for hydrogen refuelling stations, including

- **Planning Licence Authority (PA)**, typically the local government planning department having jurisdiction over review and approval of planning licences;
- **Market Authority (MA)**, typically the regulatory agency, or agencies, overseeing compliance of retail activities with the relevant Trade Practices' Legislation; and
- **Technical Authorities (TA)**, authorities having jurisdiction over compliance with relevant fire protection and safety regulation and environmental protection legislation.

1C. STRATEGIC COMPLIANCE REVIEW

The HRS Developer, with assistance from its nominated Technical Consultants, Equipment Supplier(s) and Engineering, Procurement and Construction (EPC) contractors, should conduct a strategic review of the proposed site in regard to its ability to accommodate the proposed HRS facility.

This strategic review should in particular focus on assessing the likelihood of compliance with relevant Planning, Safety, and Environmental Protection Regulations, and on identifying any requirements for special licensing provisions that may be required due to specific site zoning or heritage constraints.

A detailed checklist of preliminary activities is provided in the following page.

STAGE 1. PRELIMINARY ACTIVITIES PROJECT DEVELOPER CHECKLIST	
SECURE SITE ACCESS Is the site owner committed to the project?	☐ **YES**
	☐ **NO** Get formal commitment from property owner.
RELEVANT AUTHORITIES Identify relevant licensing (planning, operation) and technical (fire protection and safety, quality/compliance testing) authorities	☐ **PLANNING AUTHORITY (PA)** Identify Authority with jurisdiction over review and approval of Planning and Operational Licences.
	☐ **MARKET AUTHORITY (MA)** Identify relevant Authority for verification of accuracy of measurements and pricing.
	☐ **TECHNICAL AUTHORITIES (TAs)** Identify relevant Authorities for verification of: • Fire protection and safety compliance; • Product quality/performance compliance; and • Environmental protection compliance.
SITE ZONING Is the proposed site appropriately zoned for hydrogen refuelling?	☐ **YES**
	☐ **NO** 1. Verify with Planning Authority (PA) the possibility of a variance or rezoning; or 2. Find a new site.
LOCAL PLANNING SCHEME Is the ability to add hydrogen infrastructure to the property likely to be impacted by other special provisions in the local planning scheme?	☐ **YES**
	☐ **NO** 1. Verify with Planning Authority (PA) the possibility of a variance or rezoning; or 2. Find a new site.
SITE LAYOUT and SAFETY DISTANCES Can the refuelling station equipment fit on site and accommodate set-back distances prescribed under relevant safety legislation?	☐ **YES** with/without mitigation measures
	☐ **NO** 1. Identify appropriate mitigation measures and submit for review to relevant Fire Protection and Safety Authority; or 2. (If review negative) find a new site.
ENVIRONMENTAL PROTECTION LEGISLATION Are operations for the proposed site likely to remain within the thresholds applicable under relevant environmental quality legislation and/or existing operational licences (brownfield sites)?	☐ **YES** Seek a ***Pre-Application Meeting*** with PLA
	☐ **NO** 1. Submit relevant project documentation, and/or examples of similar projects to Environmental Protection Authority to obtain an advanced ruling on compliance; or 2. (If ruling negative), revise design as needed.

Stage 2. PRE-APPLICATION OUTREACH

2A. PRE-APPLICATION MEETING

The main objective of engagement with the Planning Authority, and other key stakeholders, ahead of formal submission of a Development Application, is to ensure that the HRS Developer and the Planning Authority have reached a shared understanding of the key steps involved in the licensing and permitting pathway.

These meetings help the HRS Developer ensure their Development Application provides all the information the Planning Authority needs to approve the proposed HRS facility, saving time and resources throughout the Development Approval process.

HRS developers and Planning Authorities can leverage a variety of resources to help with community outreach and education, including (but not limited to) FCEV OEMs, Industry Associations, Funding Authorities, Fire Departments and Environmental Protection Authorities.

Pre-application meetings are highly recommended and provide an excellent opportunity to bring the Planning Authority and other stakeholders up to speed with the broad effort to deploy hydrogen-powered FCEVs. These early meetings provide also an opportunity to identify potential issues that may delay the permitting process or lead to the denial of an application, such as:

- Problems with the proposed site, such as parking, circulation, right-of-way, or clearances;
- Specific requirements the project must meet to achieve approval;
- Issues with similar projects in the jurisdiction;
- Neighbourhood concerns; and
- Environmental issues.

The pre-application meeting can take place any time before the Development Application package is submitted, but earlier in the process is typically better, even if a very rough general arrangement document or aerial photo of the site are the only design documents available.

During the pre-application meeting, the HRS Developer should layout the overall plan, describe the proposed development workplan, learn which permits or approvals will be required to complete the project, and gain a clear understanding of the level of detail each relevant Department would like to see in the Development Application package.

The checklist in the following page lays out key areas to be addressed at this Pre-Application Meeting from the perspective of both HRS Developer and Planning Authority.

Stage 2. PRE-APPLICATION OUTREACH

HRS DEVELOPER CHECKLIST

- [ ] **ORGANIZATIONAL KNOWLEDGE on HYDROGEN REFUELLING STATIONS**
  - Has the Planning Authority reviewed hydrogen refuelling station projects in the past?
  - Would it be useful to host a dissemination workshop for key Authority representatives?
- [ ] **SITE ZONING, ARCHITECTURAL, and HERITAGE CONSIDERATIONS**
  - Are there zoning and/or heritage restrictions applicable to the area of the proposed site?
  - Are there operating hours constraints applicable to the area of the proposed site?
- [ ] **APPLICATION PROCESS**
  - How should the Planning Application be structured to facilitate review by each Department?
  - Are there any steps that can be taken to reduce the Review and Approval timeline?
  - Should community consultation be undertaken prior to, or after submitting an application?
- [ ] **APPLICATION SUBMISSION**
  - Should an intake meeting be scheduled prior to, or after submitting an application?
- [ ] **PLANNING REVIEW PROCESS**
  - Will the application be subject to a public hearing (e.g. by City Council or Committee)?
  - Can Council/Committee Members be approached prior to the meeting?

Stage 2. PRE-APPLICATION MEETING

PLANNING AUTHORITY CHECKLIST

- [ ] **HYDROGEN REFUELLING STATION CONCEPT**
  - How will the station be supplied with hydrogen?
  - Is a conceptual layout and process flow diagram available?
- [ ] **HYDROGEN REFUELLING STATION DESIGN**
  - What Codes and Standards have been adopted for the selected HRS design?
  - What safety measures are in place for the proposed HRS?
- [ ] **HYDROGEN REFUELLING STATION OPERATION**
  - What type of fuel cell vehicles (e.g. cars, trucks, buses) will refuel at the site?
  - How do you expect traffic to flow through the site?
  - Will the station open to the general public?
  - What are the expected public opening hours?
  - Will refuelling at the station be assisted or user-operated?
- [ ] **STATUS OF DEVELOPMENT ACTIVITIES**
  - Have you secured access to the proposed site?
  - Have you engaged the local utility?

Stage 3. PLANNING APPLICATION

3A. PRE-SUBMISSION REVIEW

Prior to submitting the Development Application the HRS Developer and its Technical Partners – preferably with the assistance of independent technical consultants and planning approval experts - should perform a thorough review to verify accuracy and completeness of the Development Application package. The key areas to review are:

- Development Application Package;
- Codes and Standards;
- Zoning and Planning Scheme;
- Site Layout and Safety Distances;
- Safety Plan; and
- Environmental Protection Legislation.

Where special planning or licensing provisions are required, it is advisable that the relevant Technical Authorities are contacted ahead of submission to obtain an expert opinion or an advanced ruling on the specifics of the key amendments sought.

A detailed HRS Developer checklist for this review is provided in the following page.

3B. SUBMISSION

Once the pre-submission review has been completed, including any review conducted by relevant Technical Authorities, the Development Application package can be submitted to the Planning Authority.

Stage 3. DEVELOPMENT APPLICATION HRS DEVELOPER CHECKLIST	
APPLICATION PACKAGE Is the structure of the Development Application package appropriately tailored to satisfy the documentation needs of each Department?	☐ **YES**
	☐ **NO** Revise ahead of submission
CODES and STANDARDS Does the Development Application clearly reference the Codes and Standards that systems and components have been designed to?	☐ **YES**
	☐ **NO** Revise ahead of submission
ZONING and HERITAGE PROVISIONS Does the proposed HRS comply with relevant zoning and heritage provisions in the Local Planning Scheme?	☐ **YES**
	☐ **NO** Document request for zone variance or rezoning.
SITE LAYOUT Does the proposed site layout comply with minimum set-back distances prescribed under relevant safety legislation?	☐ **YES**
	☐ **NO** 1. Seek approval from Fire Department for suitable mitigation measures to be adopted for the proposed site. 2. Document mitigation measures, and provide evidence of Fire Department approval.
SAFETY Has the Safety Plan for the proposed HRS been clearly articulated in the Development Application?	☐ **YES**
	☐ **NO** Revise ahead of submission.
ENVIRONMENTAL PROTECTION LEGISLATION Are operations for the proposed site likely to remain within the thresholds applicable under relevant environmental quality legislation?	☐ **YES** Submit ***Planning Application*** to PA
	☐ **NO** 1. Seek approval from Environment Protection Authority for suitable environmental protection measures to be adopted for the proposed site. 2. Document environmental protection measures, and provide evidence of Environmental Protection Authority approval.

Stage 4. PLANNING REVIEW

4A. REVIEW OF PLANNING APPLICATION

Planning review is a required part of the permitting process that ensures that a proposed station fits within a community's zoning codes as per the local planning scheme, and overall aesthetics.

The checklist in the following page, mirroring the one for the HRS Developer, details the key verification activities to be undertaken by the Planning Authority during the Planning Review Stage.

Based on general Development Approval experience, and particularly for early HRS developments with little to no experience available, it is very likely that the Planning Review will be carried out as an iterative process, where the Planning Authority will require extra information from the HRS Developer as it works its way through the Development Application package and the relevant Departments familiarize with the specific requirements of hydrogen installations.

4B. APPROVAL TO BUILD PERMIT (go/no-go gateway)

Upon successful completion of this Review, the Planning Authority will issue the HRS Developer with an ***Approval to Build Permit*** detailing the following:

- design, and operational performances agreed for the proposed HRS site;
- the term of validity of the permit (during which construction should be completed); and
- any specific arrangements that may be required to address potential encroachment of construction activities over local government, or third-party right-of-way during the construction process.

The Planning Authority is not obliged to issue a permit, and under certain circumstances (particularly when the application is subject to Public Hearing), the HRS Developer should be aware that the PA ruling might be final and not allow for the submission to be further modified to achieve compliance.

Stage 4. PLANNING REVIEW
PLANNING AUTHORITY CHECKLIST

APPLICATION PACKAGE Is the ***Planning Application*** package submitted by the HRS Developer complete, with relevant sections tailored for referral to each Department?	☐ **YES** ☐ **NO** Return to HRS Developer with recommendations for changes and any additional documentation required ahead of re-submission.
CODES and STANDARDS Has the HRS Developer clearly referenced the body of Codes and Standards that systems and components for the proposed HRS have been designed to?	☐ **YES** ☐ **NO** Return to HRS Developer with recommendations for clarifications to be provided ahead of re-submission, and/or for an independent review by the National Standardisation Body.
ZONING and PLANNING SCHEME Does the application address relevant zoning and local planning scheme constraints?	☐ **YES** ☐ **NO** 1. Review request for zone variance or rezoning 2. (If not suitable) Return to Applicant with recommendations for changes required ahead of re-submission
SITE LAYOUT Does the site layout comply with the minimum set-back distances prescribed under relevant safety legislation?	☐ **YES** ☐ **NO** 1. Review mitigation measures adopted, and evidence of fire department approval; 2. (If not available) Return to Applicant with recommendations for changes and required ahead of re-submission.
SAFETY Has the station's safety plan been clearly articulated?	☐ **YES** ☐ **NO** Return to Applicant with recommendations for changes required ahead of re-submission.
ENVIRONMENTAL PROTECTION LEGISLATION Are operations for the proposed site likely to remain within minimum thresholds applicable under relevant environmental quality legislation?	☐ **YES** Issue ***Approval to Build Permit*** *to* HRS Developer ☐ **NO** 1. Review environmental protection measures adopted, and evidence of positive ruling on compliance from Environmental Protection Authority; 2. (If not available) Return to HRS Developer with recommendations for changes and any required ahead of re-submission.

Stage 5. CONSTRUCTION

5A. PROCUREMENT and CONSTRUCTION

The Construction stage can begin after the *Approval to Build* has been issued by the Planning License Authority (PLA). The project developer will finalise agreements with major equipment suppliers, and the Engineering, Procurement. and Commissioning (EPC) contractor to finalise the project schedule and commence construction and installation works

5B. INSPECTIONS

Throughout the construction process the station is subject to inspections by the PLA to ensure that project developers build their projects in compliance with the specifications agreed upon in previous phases of the process.

The frequency and requirements for inspection processes can vary from jurisdiction to jurisdiction. It is vital for HRS Developers to fully understand the process involved before commencing construction.

Many jurisdictions will require multiple inspections, others a single inspection upon project completion. Either way, inspections should be worked into the project plan and scheduled as soon as possible to avoid long lead times.

Project developers should proactively seek to arrange multiple ‘work in progress’ inspections as they help avoid potentially costly misunderstandings between Project Developers and the PLA.

5C. NOTICE OF COMPLETION

On completion, the HRS Developer will file a notice of completion to the Planning Authority and begin HRS Testing and Commissioning activities.

Stage 5. HRS CONSTRUCTION
HRS DEVELOPER CHECKLIST

PROCUREMENT and CONSTRUCTION	☐ **EQUIPMENT SUPPLIER(S)** Finalise ***Equipment Supply Agreements*** for all major HRS equipment, agree on delivery terms and timeframes with Equipment Suppliers.
	☐ **EPC CONTRACTOR** Finalise ***Engineering, Procurement and Construction (EPC) Agreement***, agree on project development schedule with EPC Contractor.
PROJECT IMPLEMENTATION PLAN	☐ **DEVELOPMENT WORK PLAN** Establish detailed schedule of project development activities, highlighting key milestones, critical path, and contingency measures, communicate to all relevant stakeholders.
	☐ **INSPECTION SCHEDULE** Agree on a schedule of inspections with PA, including ***Work-in-Progress*** and ***Final inspection***.
PROJECT MANAGEMENT Are procurement activities and construction works progressing as per the project work plan?	☐ **YES** 1. Review progress at regular intervals 2. Issue a ***Notice of Completion*** to PA
	☐ **NO** 1. Activate contingency measures, and communicate changes to stakeholders; 2. Liaise with PA to revise schedule of inspections, as required.

Stage 5. HRS CONSTRUCTION
PLANNING AUTHORITY CHECKLIST

WORK-IN-PROGRESS INSPECTIONS Are procurement activities and construction works progressing as per the project work plan?	☐ **YES**
	☐ **NO** Seek clarifications, and request HRS developer for revised of work plan and inspection schedule.
NOTICE OF COMPLETION Has the developer issued a notice of completion within the term of the *Approval to Build* permit?	☐ **YES** Schedule ***Final Inspection*** with HRS Developer.
	☐ **NO** Issue a *Permit Expiry Notice* and communicate with project developer on steps to be undertaken to obtain a *Permit Extension*

Stage 6. COMMISSIONING

The commissioning stage begins once a station has been fully constructed and a ***Notice of Completion*** has been submitted to the Planning Authority.

The process drives towards two key milestones: a station becoming

1) *'Operational'*, e.g.
    a. The station has successfully completed a hydrogen quality test;
    b. The station can fuel a vehicle;
    c. The station is publicly accessible; and
    d. The PA has issued a ***Final Occupancy Permit*** and ***Operational Licence***;
2) And then *'Open for Public Use'*, meaning it can accept FCEV vehicles for refuelling.

6A. FIRST-FILL COMMISSIONING

The Station Operator and HRS Equipment Supplier(s), will fill the system with hydrogen and administer a series of tests to ensure the station performs as expected.

6B. OPERATOR TESTING

The station developer is responsible for constructing the station to the plans and specifications approved by the PA in *the Approval to Build Permit*. Once construction and verification has been completed, the developer will liaise with the PA to schedule a final inspection.

6C. FUELLING PROTOCOL CONFIRMATION

Station developers will work closely with Original Equipment Manufacturers (OEMs) to ensure new stations can safely fill FCEVs and meet the necessary performance requirements, including fuel quality and ability to conduct filling according to the protocols specified in the SAE J2601 standard.

The requirement to carry out fuelling protocol testing with OEMs is transitory and is expected to hold into the foreseeable future (Eckerle & Jones, 2015). Once the market matures these activities can be carried out by a third-party verification body. The process is expected to be iterative and will include direct automaker involvement

6D. COMMERCIAL TESTING

Prior to issuance of an *Operational Permit*, the HRS must be certified by the relevant Market Authority (MA) to ensure that a kg of hydrogen sold is a kg of hydrogen received, that the point of sale system functions appropriately, and that the hydrogen dispensed meets the purity requirements for use in FCEV.

6E. FINAL OCCUPANCY PERMIT and OPERATIONAL LICENCE (go/no-go gateway)

Once Testing and Commissioning activities have been completed, the HRS Developer and the Planning Authority will schedule a ***Final Meeting*** to review all the relevant documentation, issued the HRS Operator with a ***Final Occupancy Permit*** and ***Operational Licence*** for the now operational HRS site.

6F. OPENING THE STATION FOR PUBLIC USE (final milestone)

A station will be open to FCEV drivers when each of the following steps have been completed:

1. The PA has issued the '***Final Occupancy Permit*** and ***Operational Licence'*** to the HRS developer;
2. Fuelling protocol has been confirmed by the automakers and/or a recognized third party system;
3. The dispenser has been certified to sell hydrogen by the kilogram; and
4. The station developer declares the station is ready to serve the public.

TABLE 2. HRS DEVELOPMENT APPROVAL - STAGE 6 CHECKLIST

Stage 6. HRS COMMISSIONING HRS DEVELOPER CHECKLIST	
OPERATOR COMMISSIONING Is the station equipment performing as expected following a ***First-fill Commissioning Test***? Is the hydrogen dispensed compliant with minimum quality requirements?	☐ **YES** Schedule ***Final Inspection*** with PA Schedule ***Fuelling Protocol Test*** with OEM(s)
	☐ **NO** Liaise with Equipment Supplier(s) and EPC Contractor to investigate issues and adopt contingency measures, as required.
FUELLING PROTOCOL CONFIRMATION Can the station safely fill FCEVs and meet the necessary performance requirements according to protocols specified in the SAE J2601 standard?	☐ **YES** Schedule ***Commercial Testing*** with MA.
	☐ **NO** Liaise with Equipment Supplier(s) and EPC Contractor to investigate issues and adopt contingency measures, as required.
COMMERCIAL TESTING Has the Market Authority (MA) successfully verified dispensing operations for accuracy of refill measurements and pricing?	☐ **YES** Schedule ***Final Meeting*** with PA
	☐ **NO** Liaise with Equipment Supplier(s) and EPC Contractor to investigate issues and adopt contingency measures, as required.
FINAL REVIEW MEETING Has the PA successfully verified the outcome of all commissioning activities and issued ***Final Occupancy Permit*** and ***Operational Licence***?	☐ **YES** Schedule ***HRS Public Opening***
	☐ **NO** Liaise with Equipment Supplier(s) and EPC Contractor to investigate issues and adopt contingency measures, as required
Stage 6. HRS COMMISSIONING PLANNING AUTHORITY CHECKLIST	
FINAL INSPECTION Has construction of the station been completed according to the specifications in the ***Approval to Build Permit***?	☐ **YES** issue ***Final Occupancy Permit*** to HRS Developer
	☐ **NO** Issue ***Failure to Comply Notice*** to HRS Developer listing all outstanding requirements
FINAL REVIEW MEETING Has the HRS Developer successfully completed testing and commissioning activities? Including: • ***First-fill Commissioning***, • ***Fuelling Protocol Confirmation***, and • ***Commercial Testing***	☐ **YES** issue ***Operational Licence*** to HRS Operator
	☐ **NO** Issue ***Failure to Comply Notice*** to HRS Developer listing all outstanding requirements

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APPENDIX A. FUEL CELL VEHICLES AND HYDROGEN REFUELLING STATIONS

A PRIMER ON TECHNOLOGY, EQUIPMENT AND OPERATIONS

THE HYDROGEN UTILITY

Fuel Cell Vehicles

Fuel cell electric vehicles have entered the marketplace

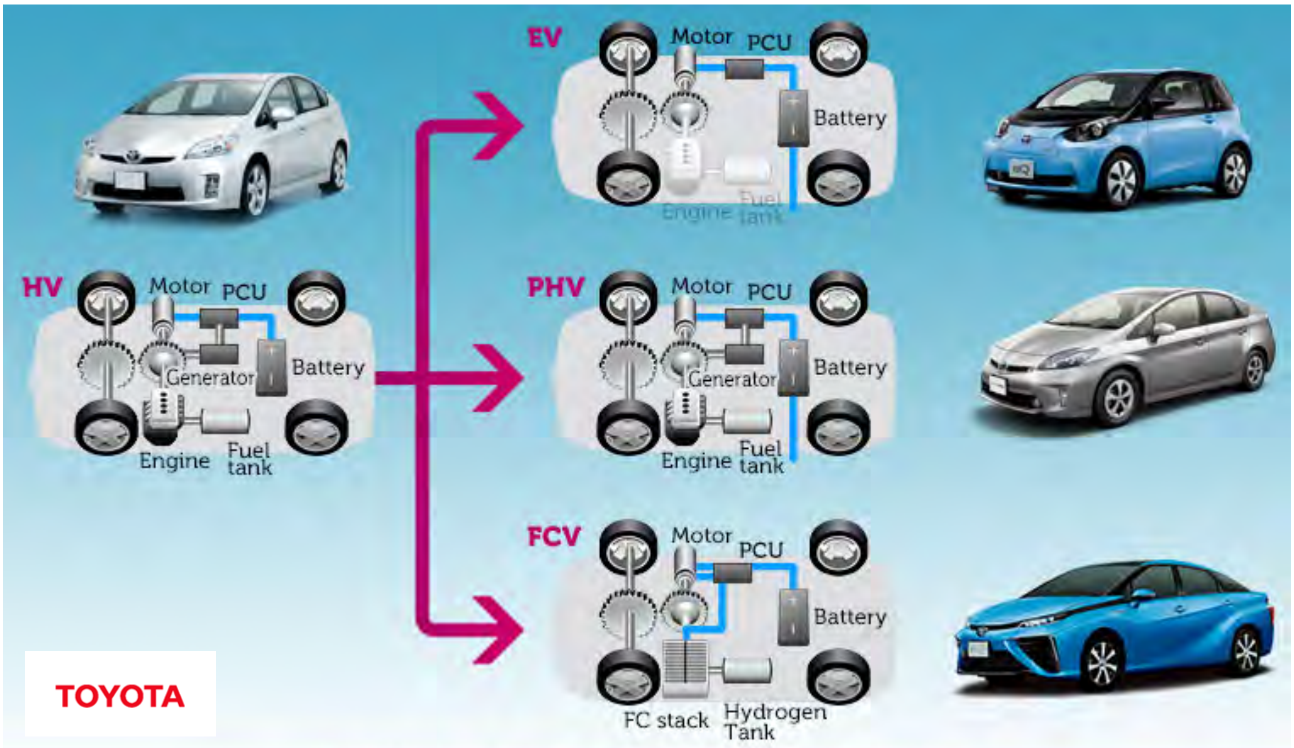
2015 has been a watershed year for the commercialization of fuel cell electric vehicles (FCEVs). Following nearly 20 years of global research and development efforts by the majority of automotive OEMs, Hyundai and Toyota have delivered the first mass-produced FCEVs to customers in North America, Japan and Europe.

Several other manufacturers have announced their commercialization plans over the 2016-18 period, including Honda (2016), Mercedes and Nissan (2017), Audi and Volkswagen (2018).

Fuel-cell and battery electric vehicles

Fuel cell electric (FCEVs) and battery-electric vehicles (BEVs) are complementary technologies that, combined have the potential to substitute conventional petrol, gas and diesel vehicles across the wide range of vehicle types and applications.

FIGURE 4. ELECTRIC VEHICLE POWERTRAIN CONFIGURATIONS

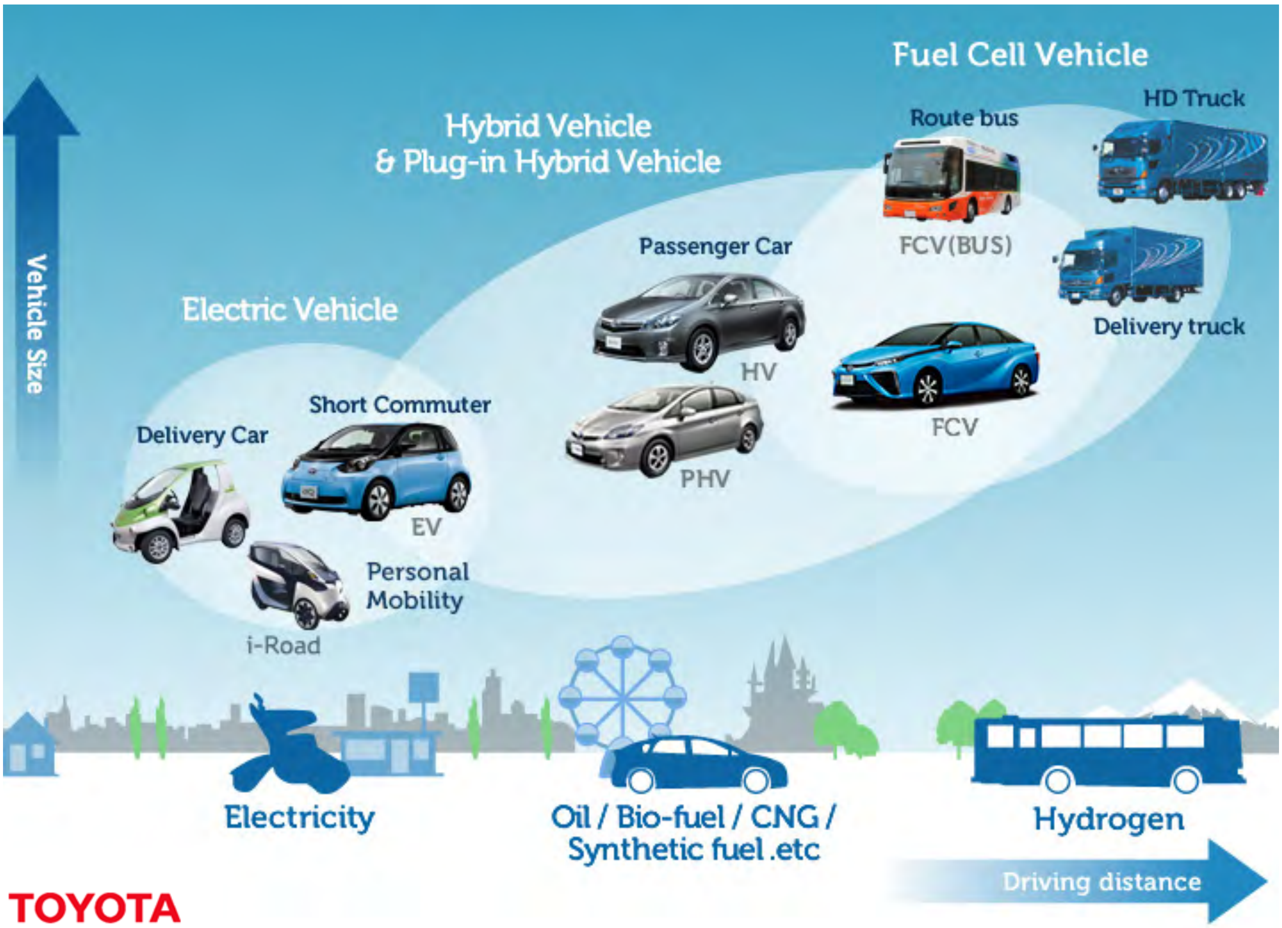


While both vehicle platforms share the same, all-electric vehicle drivetrain, the differences in powertrain designs between the two platforms determine their fit to different vehicle tasks and applications.

- **Battery electric vehicles (BEVs),** are powered exclusively by a battery pack, releasing direct current (DC) power directly to the vehicle's electric motor and auxiliaries, the battery in turn requires an external power source for recharging.
- **Fuel cell electric vehicles (FCEVs),** integrate two power sources, arranged in a hybrid configuration. The primary power source is a fuel cell, converting hydrogen into DC power for the vehicle's electric motor and auxiliaries. A small battery pack acts as a secondary power source, providing the vehicle's electric motor with additional power during start-up and acceleration transients.

The diagram below captures the optimal application domains for BEVs (low-power, limited range applications) and FCEVs (high-power, extended range applications) according to Toyota.

FIGURE 5. DOMAIN OF APPLICATION FOR ELECTRIC VEHICLE POWERTRAINS



While BEVs are particularly well-suited to personal vehicle use, their potential in commercial and service vehicle applications is limited by two factors: autonomy or *range* – limited by the significant trade-off between battery capacity and vehicle weight – and, more importantly, significant recharge times – up to 12 hours depending on battery size and charge point configuration – during which the vehicles lie idle, with significant impact on productivity.

The higher power density, long range and fast refuelling times (<3 minutes) associated with FCEVs make this platform as the ideal electric drivetrain solution for a wide range of commercial and service vehicle applications including utility vehicles, vans, light trucks and buses.

Both vehicle platforms provide zero tailpipe emissions, and can provide zero life-cycle GHG emissions when renewable electricity is used to recharge the BEV battery pack, or renewable hydrogen is used to refill the FCEV hydrogen tank.

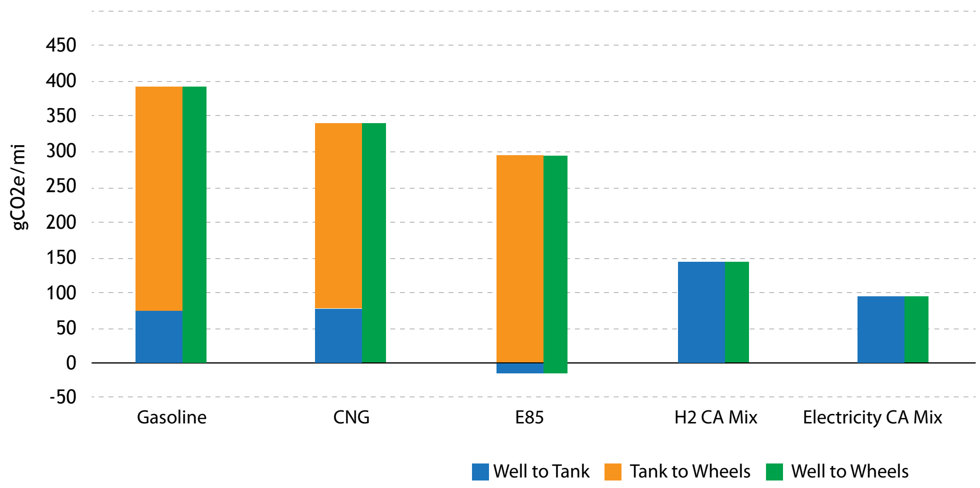
Life-cycle GHG emission benefits

Zero-emission vehicles, such as battery-electric and fuel cell vehicles have no tailpipe emissions (except water vapour for FCEVs), and can bring a significant contribution to urban air quality in terms of reduced air pollutant loadings from transport activities.

When considering life-cycle greenhouse gas emissions, the emissions from fuel cell and battery electric vehicles and battery electric vehicles are heavily dependent on the methods used to produce the electricity or hydrogen, respectively.

The diagram below presents a comparison of life-cycle GHG emissions from alternative power trains in California, based on the existing electricity and hydrogen generation mix.

FIGURE 6. GREENHOUSE GAS EMISSIONS ASSOCIATED WITH CALIFORNIA MIX OF FUELS IN GRAMS PER MILE[10]



Both BEVs and FCEVs – by virtue of the higher storage/conversion efficiency of batteries and fuel cells (when compared to internal combustion engines), and the superior performances for electric drivetrains – can deliver significant life-cycle GHG emission benefits on the basis of existing fuel and electricity mix.

It should be noted however, in the renewed context of urgency for significant greenhouse gas mitigation arising from the recent COP21 in Paris, how it becomes imperative to combine advanced powertrain options with renewable energy resources, so as to maximise the benefits associated with the Transport sector.

With this purpose in mind, in this Blueprint we consider exclusively renewable hydrogen pathways, including water electrolysis and steam reforming of 100% biogas.

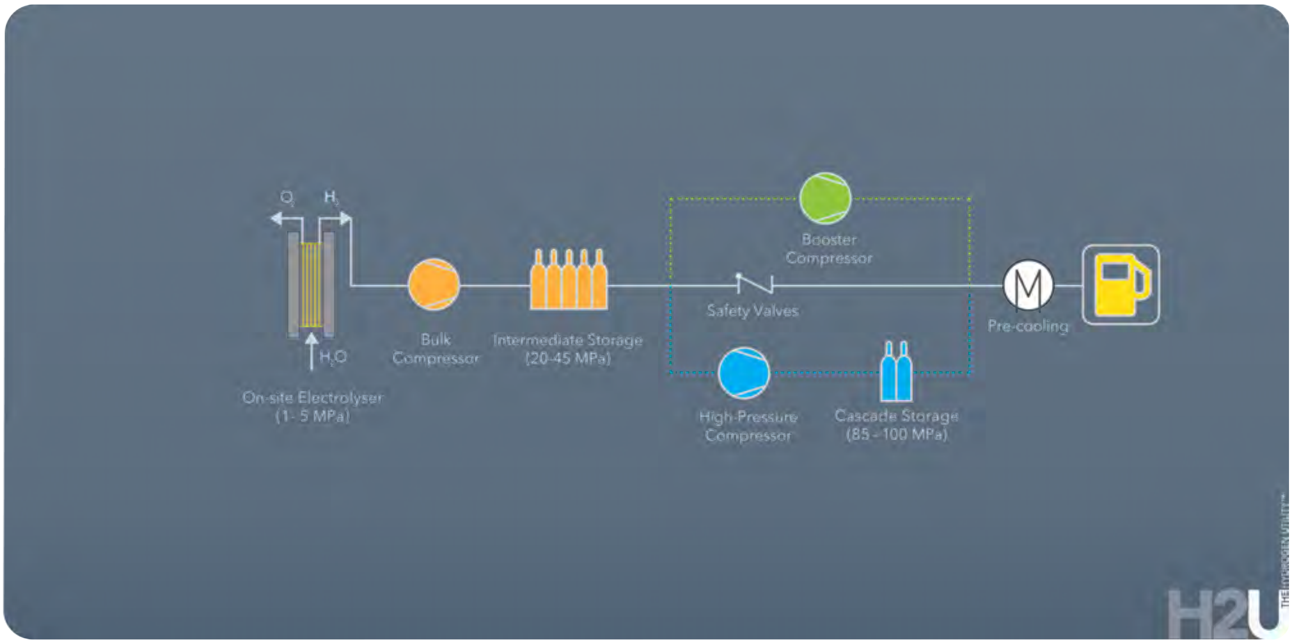
[10] Reproduced from (Eckerle & Jones, 2015)

Refuelling infrastructure concepts

1. Hydrogen refuelling station with on-site production

In this scheme the refuelling station integrates an on-site distributed hydrogen generator based on either alkaline water electrolysis (AWE) or Proton-exchange membrane (PEM) electrolysis.

FIGURE 7. HYDROGEN REFUELLING STATION WITH ON-SITE PRODUCTION[11]



According to the schematic presented above the forecourt station includes the following delivery components:

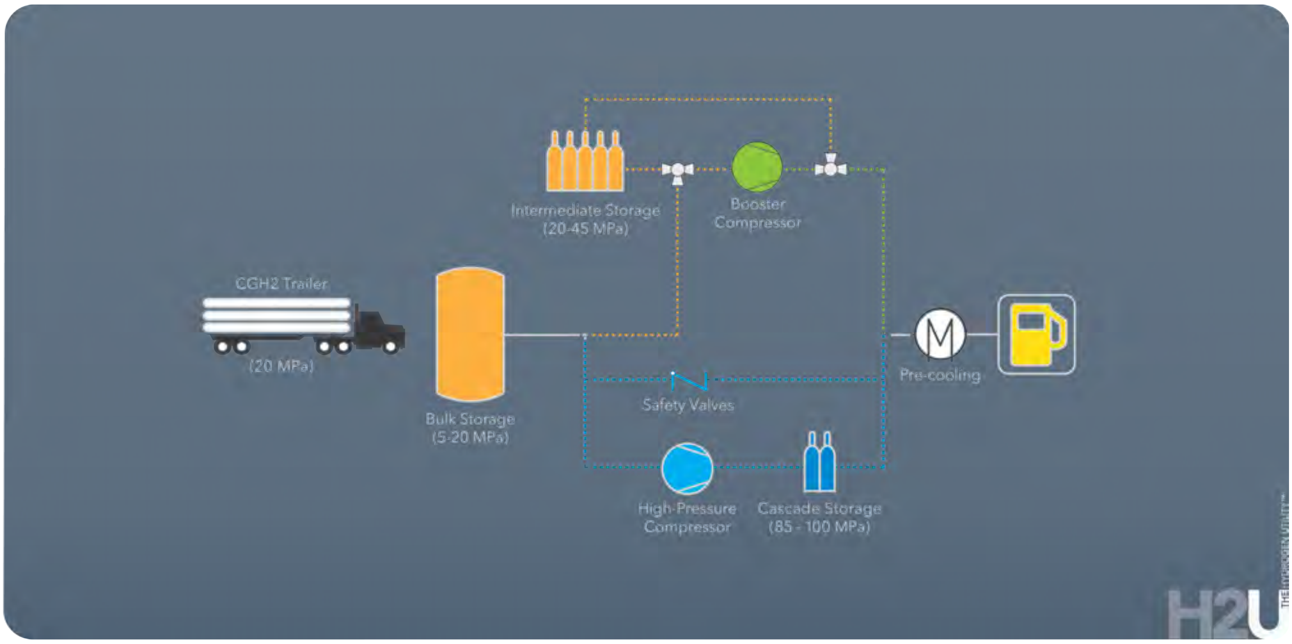
- on-site hydrogen generator,
- primary (storage) compressor,
- primary CGH2 storage,
- secondary (forecourt) compressors, and
- secondary CGH2 'cascade' storage, and
- CGH2 dispensers.

[11] Adapted from (ISE, 2013)

2. Hydrogen refuelling station with gaseous hydrogen delivery via truck

In this scheme compressed gaseous hydrogen is transported in bundles of long steel cylinders mounted on a truck trailer bed. Once filled, the trailer is attached to a truck and driven to the refuelling station where the trailer is detached from the tractor and left on-site serve as the primary on-site storage. The empty trailers are attached to the tractor and returns them to the terminal for refilling.

FIGURE 8. HYDROGEN REFUELLING STATION WITH COMPRESSED GASEOUS HYDROGEN DELIVERY VIA TRUCK TRAILER[12]



The tube-trailer acts as the primary storage for the station. Hydrogen is then compressed to the dispensing pressure and stored into a high-pressure 'cascade' secondary storage system ready for fast-fill dispensing to a vehicle.

The refuelling station includes the following components:

1. primary storage (tube-trailer 'dropped off' at refuelling station site),
2. forecourt compressors,
3. secondary 'cascade' storage, and
4. hydrogen dispensers.

[12] Adapted from (ISE, 2013)

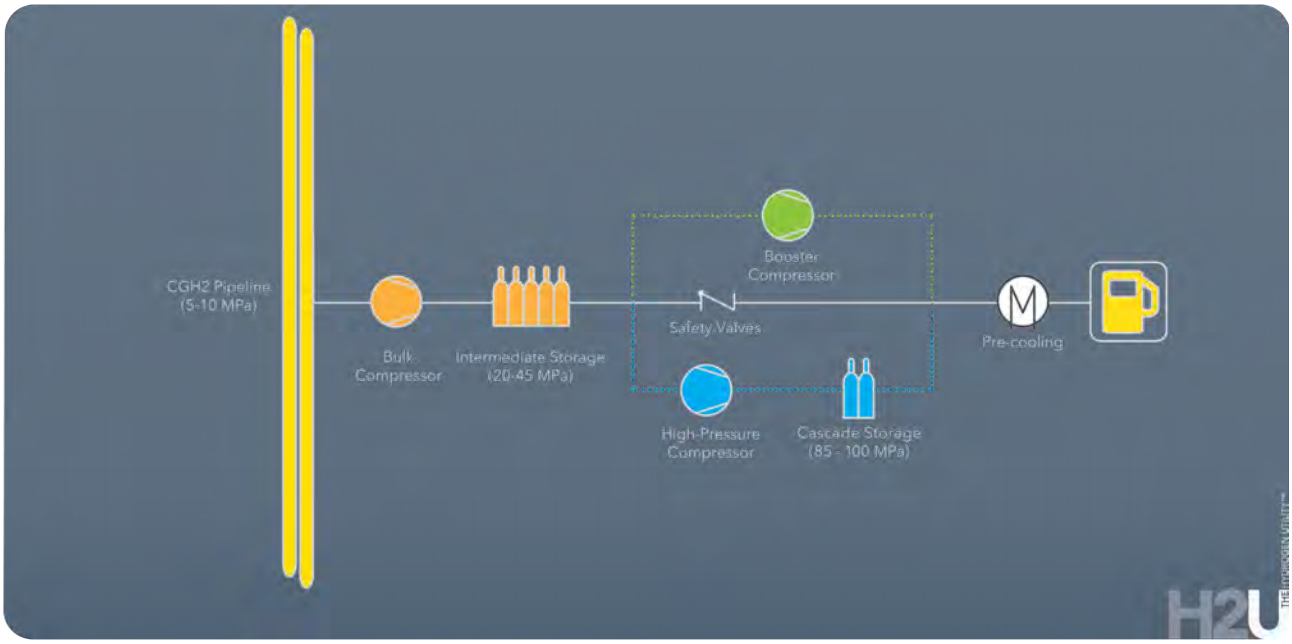
3. Hydrogen refuelling station with gaseous hydrogen delivery via pipeline

In this scheme hydrogen is transported from central generation plants to end-users through the following system of pipelines:

- transmission pipelines: from central plants to city gate,
- trunk pipelines: from city gate to service (or distribution) lines, and
- distribution pipelines: from service lines to end-use point.

The refuelling station is serviced by the distribution pipelines on a continuous basis (subject to pipeline availability) and does not require a primary storage system. Hydrogen is then compressed to the dispensing pressure and stored into a high-pressure 'cascade' secondary storage system ready for fast-fill dispensing to a vehicle.

FIGURE 9. HYDROGEN REFUELLING STATION WITH COMPRESSED GASEOUS HYDROGEN DELIVERY VIA PIPELINE[13]



According to the schematic presented in Figure C5, the forecourt station includes the following delivery components:

- forecourt compressors
- 'cascade' storage
- hydrogen dispensers

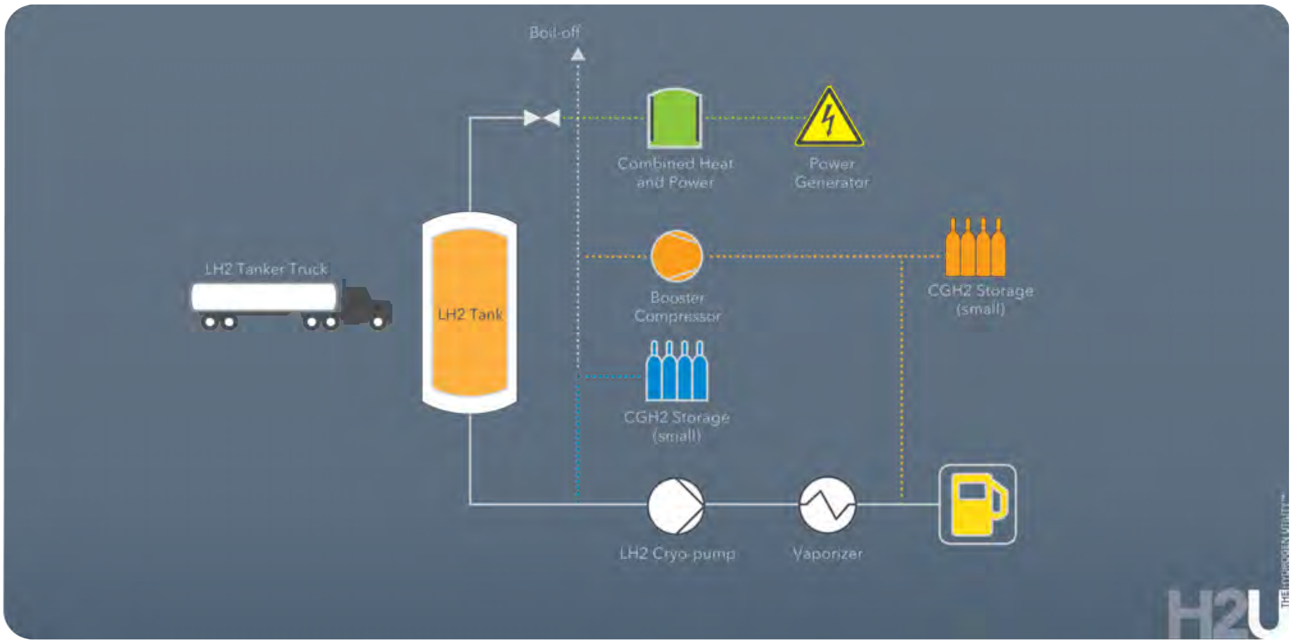
[13] Adapted from (ISE, 2013)

5. Hydrogen refuelling station with liquid hydrogen delivery

In this scheme hydrogen is liquefied and loaded onto liquid hydrogen (LH2) tanker trucks for transport to the forecourt refuelling station, according the schematic presented below.

LH2 tankers are filled at the LH2 terminal and driven off to refuelling stations where they unload part or all their load onto the primary LH2 forecourt storage. The number of deliveries per trip depends on the size of the LH2 storage system at the refuelling station

FIGURE 10. HYDROGEN REFUELLING STATION WITH LIQUID HYDROGEN DELIVERY VIA TANKER TRUCK[14]



At the forecourt LH2 station, liquid hydrogen delivered by a tanker truck is stored in the primary LH2 storage system, then pumped to the required dispensing pressure and vaporized. The compressed gaseous hydrogen is then stored on a secondary high-pressure 'cascade' storage system, ready for dispensing to on-board vehicle tanks.

The refuelling station includes the following components:

- primary LH2 storage,
- LH2 pumps and vaporizers,
- secondary CGH2 'cascade' storage, and
- hydrogen dispensers.

[14] Adapted from (ISE, 2013)

Hydrogen production technologies

Hydrogen generation via electrolysis

The electrolysis of water is an established method of hydrogen generation. The basic system – the electrolysis cell – consists of a pair of electrodes immersed in a conducting electrolyte dissolved in water. A direct current is passed through the cell from one electrode to the other; hydrogen is evolved at one electrode, oxygen is evolved at the other, and water is thus decomposed. In a continuously operating electrolysis cell, a pure water replacement is constantly supplied, and a steady stream of hydrogen and oxygen may be obtained from the two electrodes.

The absence of moving parts, its inherent operational simplicity and, thus, reliability make electrolysis the least labour-intensive of the hydrogen generation methods.

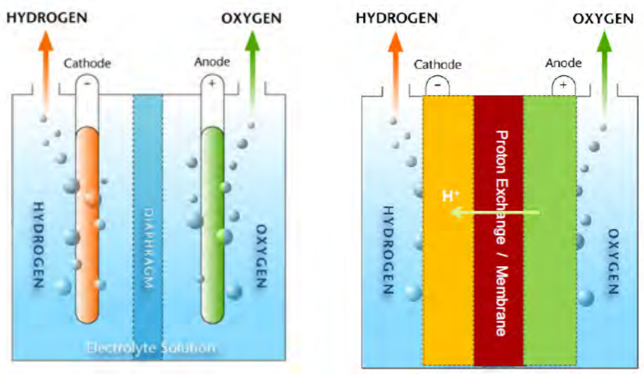
Electrolysis with its fast response and wide operating range is also very efficient for use in combination with intermittent renewable resources, such as wind and solar, its application in this area offers the opportunity top integrate the electricity and gas infrastructure through power to gas concepts.

When considering the generation of hydrogen as an energy carrier, various factors could contribute to tip the balance in favour of electrolytic hydrogen:

- the availability of cheaper electricity (e.g. generated during forced spillages in hydroelectric reservoirs or at off-peak times from wind-farms),
- a commitment to renewable hydrogen generation driven by environmental concerns and/or regulations,
- higher and/or more variable feedstock price levels for competing hydrogen generation technologies (natural gas price variability being a major concern of current large industrial hydrogen users such as refineries).

Large-scale electrolysers commercialized during the twentieth century are all based on conventional Alkaline Water Electrolysis (AWE). However Proton Exchange Membrane (PEM) electrolysis is emerging as the leading technology because of its higher performance and load flexibility.

FIGURE 11. TYPES OF ELECTROLYSIS PROCESSES: AWE (LEFT), AND PEM (RIGHT)



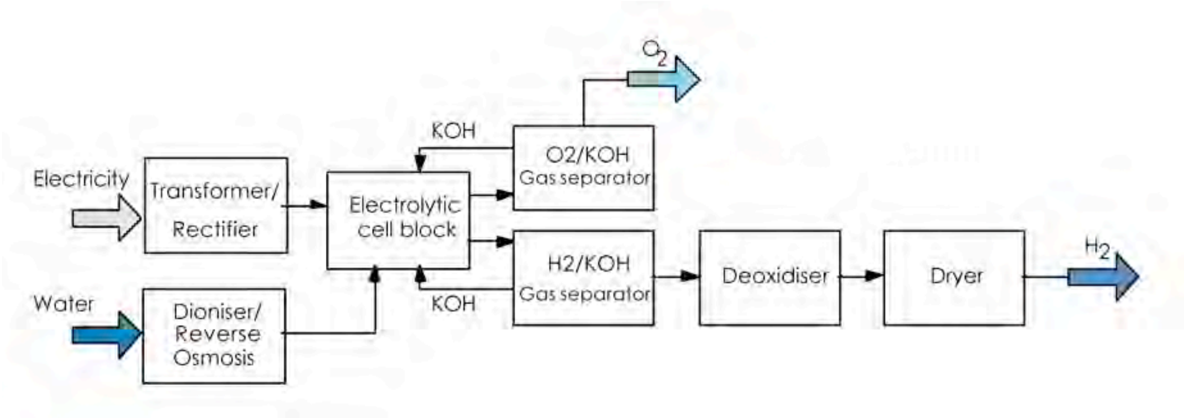
The basic principles and reactions for each of these electrolysis processes are discussed below.

Alkaline Water Electrolysers (AWE)

These electrolysers use an aqueous solution of potassium hydroxide as the electrolyte, circulated through the electrolytic cells. The (caustic) alkaline electrolyte enhances the ionic conductivity of pure water and is typically used with a concentration of 25-30 wt.%.

Alkaline electrolysis is a mature technology, with a significant operating record in industrial applications, and thus well suited to remote operation. Commercial electrolysers usually consist of a number of electrolytic cells arranged in a cell stack. The complete system contains the main components shown below.

FIGURE 12. PROCESS DIAGRAM SCHEMATIC OF ALKALINE WATER ELECTROLYSIS UNITS



Proton Exchange Membrane (PEM)

PEM electrolysers are based on the use of the polymeric Proton Exchange Membrane (PEM) – hence the name most commonly adopted nowadays – an acidic membrane of the same type used in the Proton Exchange Membrane Fuel Cells (PEMFC).

No liquid electrolyte is required for PEM electrolysers, which simplifies their design significantly. The electrolyte is an acidic polymer membrane. The main feature of these membranes is a high proton conductivity and a very low electronic conductivity.

PEM electrolysers can potentially be designed for operating pressures up to several hundred bars, and are suited for both stationary and mobile applications. The main drawback of this technology is the limited lifetime of the membranes. The major advantages of PEM over alkaline electrolysers are:

- the higher turndown ratio (operating ratio of part- to full-load),
- the increased safety and reliability due to the absence of caustic electrolytes,
- a more compact design due to higher densities (operating cells up to several amps per square centimetre with typical thickness of a few millimetres), and
- higher operating pressures (thanks to the membrane ability to sustain high differential pressure without damage, and prevent gas mixing efficiently).

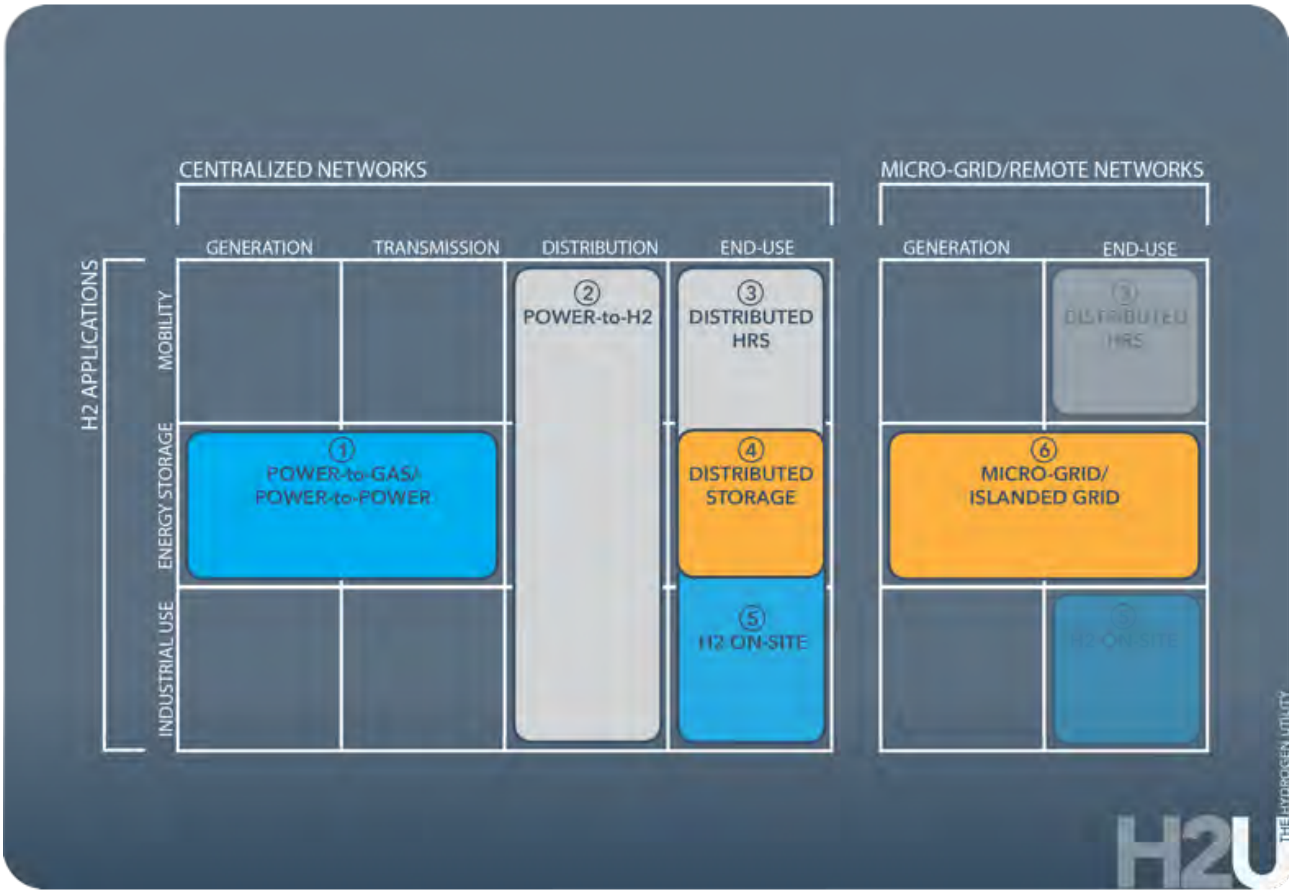
RENEWABLE ENERGY INTEGRATION CONCEPTS

Water electrolysis lends itself to a variety of renewable energy integration concepts. These can be mapped on two key dimensions:

- **Grid-level interface,** e.g. the level at which the project is connected to the grid[15]; and
- **Hydrogen applications,** including sustainable mobility, energy storage, and use as an industrial feedstock.

This approach is summarized by the matrix presented in the diagram below.

FIGURE 13. INTEGRATION CONCEPT FOR HYDROGEN IN RENEWABLE STORAGE APPLICATIONS



Against this landscape matrix, we can identify six broad families of applications:

1. Power-to-Gas/Power-to-Power
2. Power-to-Hydrogen
3. Distributed Hydrogen Refuelling Station (HRS)
4. Distributed Storage
5. On-site Hydrogen
6. Micro-grid

[15] Generation/transmission/distribution/end-use for centralized power networks, and generation/end-use for micro-grids and remote networks.

1 – Power-to-Gas/Power-to-Power

Multi-MW Electrolysis Plants for grid integration of large-scale renewables, integrated at the interface between large-scale renewable generation developments (solar or wind) and the transmission grid, or at major connection nodes along the transmission grid. This family includes two major applications.

- **Power-to-Gas,** with renewable hydrogen generated from excess wind/solar generation injected into the gas transmission grid – either directly as hydrogen or with an intermediate methanation step – compatibly with gas network operational requirements and regulatory constraints;
- **Power-to-Power**, utility-scale hydrogen storage with re-electrification with renewable hydrogen generated from excess wind/solar generation stored in salt caverns or depleted wells that is subsequently used in multi-MW fuel cell installation or hydrogen gas turbines to generate electricity for the grid in periods of low supply.

While deployments to date have focused entirely on power-to-gas schemes such as the E.On/Hydrogenics facility in Falkenhagen, Germany, it is expected that the importance and role of utility-scale, power-to-power schemes – one of very few foreseeable approaches for seasonal electricity storage – will increase in the future as thermal generators are progressively retired and the penetration of renewables into the grid continues to increase.

2 - Power-to-Hydrogen

MW-scale electrolysis plants, established at the interface between the transmission and distribution grids, and at strategic locations within distribution networks (e.g. at large industrial and commercial facilities).

Distribution-level electrolysis installations have the ability to contribute to the market for **ancillary grid services** that are crucial to support the transition of the energy system. Hydrogen is one of the technologies that can provide such services alongside other technologies such as battery based electricity storage or thermal load management.

These services include: Frequency reserves (containment, restoration, replacement), Demand response, and Congestion management.

The key challenges for grid-services technologies are:

a) the low level of utilization that the market for ancillary grid services can guarantee – typically lower than 500 hours per year – leading to high levelised costs, and
b) the limitations with regards to the amount of capacity that can be dispatched at any given time: For instance, the state of charge limits the amount of power that a battery can absorb/release at any given time, and similarly the ability to reduce/increase a thermal load is limited by operational requirements.

Unlike battery-storage or thermal technologies electrolysis is a *fully-dispatchable* technology, where the full operating range – 40-110% of rated capacity for alkaline technologies, and 10-150% of rated capacity for PEM technologies – can be called upon at any given time both to absorb excess power generated within the network, or to release a power load to match a projected decrease in available generation capacity.

Full dispatchability and fast response enable distribution-level electrolysis plants to act as **renewable energy aggregators,** able to effectively absorb the large reverse power flows associated with high levels of PV penetration, and thus contribute to avoiding or deferring upgrading costs for medium voltage or low voltage transformers along distribution subnetworks.

In addition to providing grid services and deferring network investments, distribution-level electrolysis can be used to establish **localized hydrogen supply chains.** The market for the product of electrolysis is not limited to re-electrification, as a far higher value can be captured by selling the hydrogen produced locally as a fuel for fuel cell vehicles or as a process feedstock for a variety of industrial users, hence guaranteeing high levels of plant utilization.

Projects such as EnergiePark Mainz, are demonstrating the viability of this concept, with a tube-trailer, and cylinder filling facility operated by Linde alongside the electrolysis plant to enable local hydrogen deliveries to mobility and industrial users.

Our analysis for this family of business cases will focus on integrated business models that can capture the hydrogen supply, renewable aggregation and ancillary grid services opportunities as they hold the promise of early viability while at the same time offer a highly replicable deployment option.

3 – Distributed Hydrogen Refuelling Station

Fleet-embedded hydrogen refuelling stations (HRS) with on-site hydrogen production.

Following the outcome of the seminal H2 Mobility studies for Europe and Germany, and in anticipation for the release of mass-produced fuel cell vehicles in 2015, developers of hydrogen refuelling station equipment have focused their effort on the standardization of refuelling station designs toward commercial-scale capacities starting at 500 kg_{H2}/day.

In distributed hydrogen refuelling station applications, with on-site production of hydrogen these stations require installed electrolyser capacities of 1-1.2 MW, comparable with unit capacities of electrolysers deployed for power-to-gas initiatives.

When combined with a renewable power supply[16], distributed HRS offer a clear case for an early deployment opportunity with high replication potential. They can capture all the benefits described earlier for power-to-hydrogen applications, with the added benefit of all the hydrogen being utilized on-site for refuelling the resident fleet, thus removing the need for costly hydrogen delivery terminal installations.

One example of such installation under operation in Europe is the Bolzano hydrogen refuelling station developed by H2 South Tyrol, featuring three 60 Nm^3/h alkaline electrolysers from Hydrogenics, for a combined capacity of 1 MW.

4. Distributed Energy Storage

Hybrid energy storage systems, integrating batteries and electrolysers and fuel cells.

As described earlier for Power-to-Hydrogen applications, electrolysis can compete with/complement other storage technologies – namely battery-based storage – to provide a range of ancillary grid services.

In distributed hybrid-energy storage applications, the two technologies are brought together to provide an integrated solution that can take advantage of high round-trip efficiencies of battery storage over short storage cycles, and the dependability associated with hydrogen for long-term storage and back-up power generation.

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16 For example a combination of on-site solar, with wind power or hydro-electricity sourced from the grid.

It is particularly interesting to evaluate the business case in the context of critical infrastructure, such as fixed telecommunication exchanges, where the hybrid energy storage solution, combined with solar installations could bring significant benefits over business as usual solutions requiring both battery UPS systems (for power quality and voltage control over DC distribution subnetworks), and diesel stand-by generation (for restoration of power supply during grid outages).

For these users, it will also be important to evaluate the opportunity to manage power supply from multiple sites in aggregate, through virtual power plant arrangements, and to deliver excess hydrogen to other uses within the organization, for example fuel cells used for back-up power supply for base transfer stations.

5. On-site hydrogen

On-site production of renewable hydrogen for industrial processes.

The availability of competitive, renewable energy supply and high delivery costs for industrial merchant hydrogen could create situations – much like is already standard practice in the glass manufacturing industry – for a variety of industrial processes to turn to on-site generation of feedstock hydrogen through electrolysis.

For this family of business cases we will focus on evaluating industrial applications such as the distributed production of renewable ammonia (as proposed by Proton Ventures in the Netherlands) and large applications such as the adoption of renewable hydrogen via electrolysis for refinery and steel making applications.

6. Micro-grid

Integration and Storage of Distributed and/or Islanded Resources

In micro-grid/islanded applications, with high-degrees of renewable penetration, electrolysis and fuel cells can enable the transition towards a 100% renewable system.

In these applications, the need for ancillary services and seasonal storage are established and typically met by diesel generation.

Premiums on fuel prices associated with delivery and storage operations, as well as the costs of maintaining diesel generators might contribute to boundary conditions for viability that are significantly different from centralized grid applications, and presumably closer to viability.

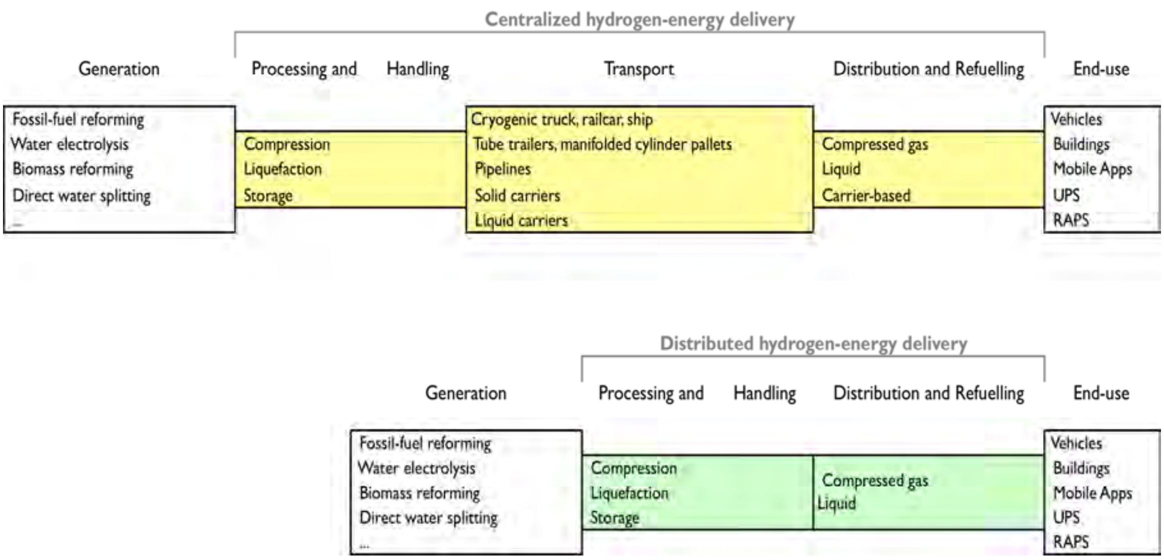
Hydrogen delivery and storage

When describing hydrogen delivery pathways it is convenient to adopt an analysis framework based on the level of decentralization in production, regardless of the particular combination of energy source and energy conversion technology which is utilized for the generation of the hydrogen (the so-called *production pathway*).

Following this structure two fundamental assumptions could be made which yield, in principle, two separate families of delivery pathways. In a *centralized pathway*, hydrogen generated at large scale facilities is then delivered to individual customers over a range of a few tens to some hundreds of kilometres, whereas in a *distributed* or *foreground pathway*, hydrogen is produced in the immediate proximity of dispensing facilities or end-use appliances.

These two separate families of generation and delivery pathways, each composed of neighbouring infrastructure stages, allow in principle the adoption of different technologies for hydrogen generation, transmission and distribution (see Figure 14 below).

FIGURE 14. CENTRALIZED AND DISTRIBUTED HYDROGEN-ENERGY DELIVERY PATHWAYS[17]



As Figure 14 clearly shows, delivery infrastructure needs at distributed facilities represent subsets of the more comprehensive delivery infrastructure that centralized facilities require.

Three families of delivery pathways are considered in this overview:

- gaseous hydrogen delivery
- liquid hydrogen delivery

The liquid and gas paths transport pure hydrogen in its molecular form (H_2) via truck, pipeline, rail, or ship/barge. Liquid or gaseous truck and gas pipelines are the primary methods by which industrial hydrogen is delivered today.

[17] Adapted from (Castello *et al.* 2005), Tab. 1.1, p.9.

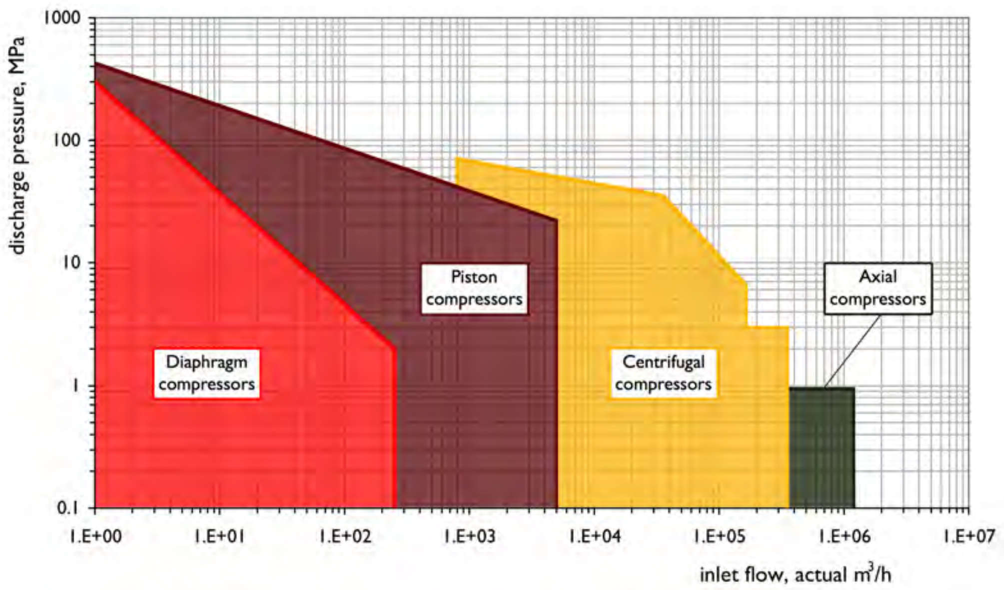
Technologies for processing and handling of hydrogen (compression, liquefaction and storage) are key components of a delivery infrastructure and are described in detail in the following three subsections. In the following subsections are described the operations and technologies which represent the state of the art for the three families of delivery pathways (compressed gaseous, liquid and carrier-based hydrogen delivery). The chapter concludes with a brief introduction to typical hydrogen refuelling station operations and technologies.

Compression

Compressors are indispensable components of any hydrogen delivery infrastructure, being used throughout the chain of hydrogen production and utilisation. Their purpose is to take a fixed quantity of hydrogen and deliver it at an increased pressure. Typically, a compressor is used in combination with a storage facility (stationary or mobile) that requires the supply of pressurised hydrogen.

The selection of the most appropriate type of compressor is based on process variables such as capacity, suction and discharge pressure, as shown in Figure 15. From an engineering point of view, the most appropriate type is the one that accomplishes the required compression with the minimum input of work.

FIGURE 15. OPERATIONAL REGIMES FOR DIFFERENT COMPRESSOR TYPES[18]



[18] Modified and adapted from (DTI 2002), Figure 6-2 p.76.

Compressors for small-scale hydrogen delivery applications

Hydrogen compressors with delivery pressures between 34.5 and 68.9 MPa are commonly adopted for small scale applications such as fuelling stations. The following types of compressors represent the state of the art in these applications (Drnevich 2003):

- V-Belt driven multi-stage reciprocating compressors
- Hydraulically driven multi-stage reciprocating compressors
- V-Belt driven diaphragm compressors

In Figure 16, below, are provided examples of the different types of small-scale compressors. These compressors have adiabatic efficiencies in the range 50-70%, which results in electricity consumption in the range 2.6-3.6 kWh_e/kg for inlet-outlet pressures of 0.7 and 48.3 MPa (Drnevich 2003). Typical manufacturers for these machines are CompAir, Fluitron, Greenfield, Hydro-Pac, Neuman-Esser, PDC and Rix.

FIGURE 16. SMALL SCALE HYDROGEN COMPRESSORS.

Compressors for large-scale hydrogen delivery applications

The state of the art for compressors for large-scale applications, such as pipeline delivery or refinery operations, is represented by multi-stage reciprocating machines with delivery pressures between 4.8 and 6.9 MPa based on the application requirements.

The reliability of compression systems is a major concern in these applications and the installation of redundant units is common practice in order to satisfy typical on-line time requirements in the order of 98-99%. The continuous operation implies high maintenance costs due to wearing of components (valves, rider bands, pistons, rings).

Adiabatic efficiencies are typically in the range 70-80% corresponding to inlet-outlet pressures of 2.1 and 6.9 MPa, respectively, for electricity consumption in the range 0.6-0.7 kWh_e/kg (Drnevich 2003). Typical manufacturers for these machines are Ariel, Dresser-Rand, Neuman-Esser and Sulzer Burckhardt.

Liquefaction

Commercial liquefiers have production capacities ranging up to 40 t/d. A concept study for a liquefier with 300 t/d capacity has been carried out in Japan as part of the WE-NET program (METI/NEDO 1998-2003).

For liquefaction processes, the reported values of energy consumption reported vary between 29 and 46 MJ/kg, hence consuming up to about 30% of hydrogen energy content. To achieve higher energy efficiencies, extra heat exchangers, multiple compressors and expansion engines (turbines) are commonly used which contribute to higher capital costs.

The size of the production facility has a great influence on both the energy demand and the costs of hydrogen liquefaction. Cost reductions from increased size and energy savings from technical developments can be expected for larger plants. Liquefaction energy efficiencies[19] of 76-79% are predicted by some sources for liquefaction plants with capacities larger than 40 t/d (Castello *et al.* 2005).

Hydrogen storage

Storage is a challenging issue that cuts across production, delivery and end-use applications of hydrogen as energy carrier. Hydrogen can be stored in gaseous form (compressed gas), as a liquid at cryogenic temperatures, or in solid or liquid media. The first two methods are established technologies with some key limitations, the most important of which is the associated energy intensity. Hydrogen solid-state storage, still in its infancy, appears as a possible attractive alternative. This is particularly due to its improved safety and volumetric energy density potential.

Storage in gaseous form

High-pressure hydrogen can be stored in thick-walled tanks (mainly of cylindrical or quasi-conformable shape) made of high strength materials to ensure durability. The storage capacity available along the delivery chain plays a key role in the management of the overall hydrogen delivery infrastructure, including the choice of pressure vessel materials and design. Commonly types of compressed gas hydrogen pressure vessels include (Tzimas *et al.* 2003):

- *Type I*: all metal cylinder,
- *Type II*: load-bearing metal liner hoop wrapped with resin-impregnated continuous filament,
- *Type III*: non-load-bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament;
- *Type IV*: non-load-bearing non-metal liner axial and hoop wrapped with resin-impregnated continuous filament.

Currently, bulk hydrogen storage is commercial practice at hydrogen production plants, geologic storage sites, distribution terminals, hydrogen utilisation sites and has been demonstrated at hydrogen refuelling stations. The requirements for storage capacity vary with the application, such that thousands of tonnes of hydrogen may be stored at production sites and other large-scale storage facilities, 50-100 tonnes in distribution centres, and tens of tonnes at refuelling station and other end-use sites.

The storage of hydrogen in a compressed gaseous form offers the simplest storage solution in terms of infrastructure requirements and has become the most popular and most highly developed method. In the merchant hydrogen markets, the gas manufacturer typically makes compressed hydrogen storage vessels available on lease to the users.

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[19] These are defined as the energy content (LHV basis) of the net hydrogen output divided by the sum of the energy content (LHV basis) of the hydrogen throughput plus all other energy inputs to the liquefaction plant such as electricity requirements for the liquefaction process and plant auxiliaries.

Cylinders with hemispherical end domes, similar to those used for storing natural gas and other process gases, are commonly used to store compressed gaseous hydrogen. In stationary applications, austenitic stainless steel cylinders (e.g. AISI 316 and 304) are commonly employed to reduce material and manufacturing costs (Tzimas *et al.* 2003). Composite vessels, which are commonly adopted for on-board storage applications, present prohibitive costs for bulk stationary applications.

Small amounts of hydrogen are typically compressed to about 20 MPa and stored in standard 50-litre cylinders. For larger storage capacity, cylindrical tanks with typical diameters of 2.8 m, and lengths varying from 7 to 19 m are used with a maximum operating pressure of 5 MPa, for resulting capacities ranging from 1300 to 4500 Nm^3 of hydrogen. Vessels with capacities of about 2000 Nm^3, pressurised to about 18.5 MPa (mostly spherical containers) have been the state-of-the-art for many years and have not exhibited any major operating problems (Tzimas *et al.* 2003).

Bulk hydrogen storage facilities at hydrogen production plants, regional/local hydrogen distribution centres and end-use sites will be important to provide surge capacity for hourly, daily and seasonal demand variations.

Typical examples of stationary bulk hydrogen pressure vessels are shown in Figure 17.

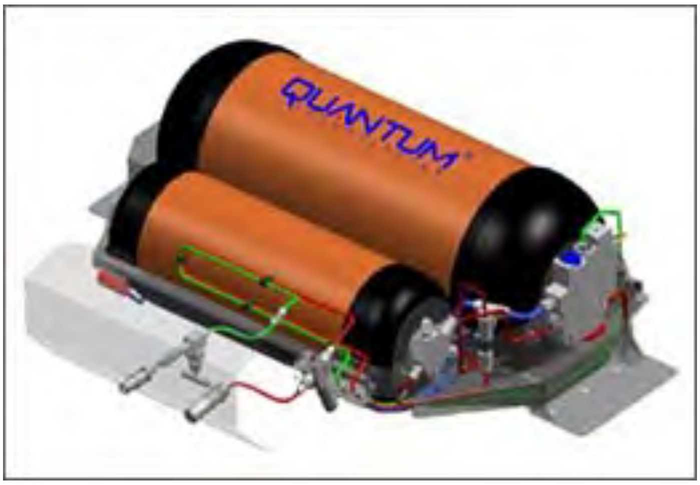
FIGURE 17. PRESSURE VESSELS FOR STATIONARY HYDROGEN STORAGE[20]

The long-term storage of large quantities of hydrogen (of the order of millions of m^3) could be made in underground storage facilities, as it occurs in the natural gas delivery infrastructure, where geologic storage is routinely used to provide seasonal surge capacity. Another option is represented by over-sized hydrogen transmission pipelines, in which the operating pressures could be adapted to meet seasonal fluctuations in demand.

More advanced lightweight gaseous hydrogen storage systems are based on composite material vessels composed of a non-load-bearing metallic (Type III) or plastic (Type IV) liner axial and hoop wrapped with resin-impregnated continuous filaments (see Figure 18). The structure of these pressure vessels, ideal for small to medium scale on-board storage in transportation applications, is based on two fundamental components: the liner, essentially a barrier for hydrogen permeation and the composite structure that ensures the mechanical integrity of the tank.

[20] Adapted from (Tzimas *et al.* 2003), Figure 25, p.53.

FIGURE 18. ON-BOARD COMPRESSED GAS STORAGE TANK[21]



Storage in liquid form

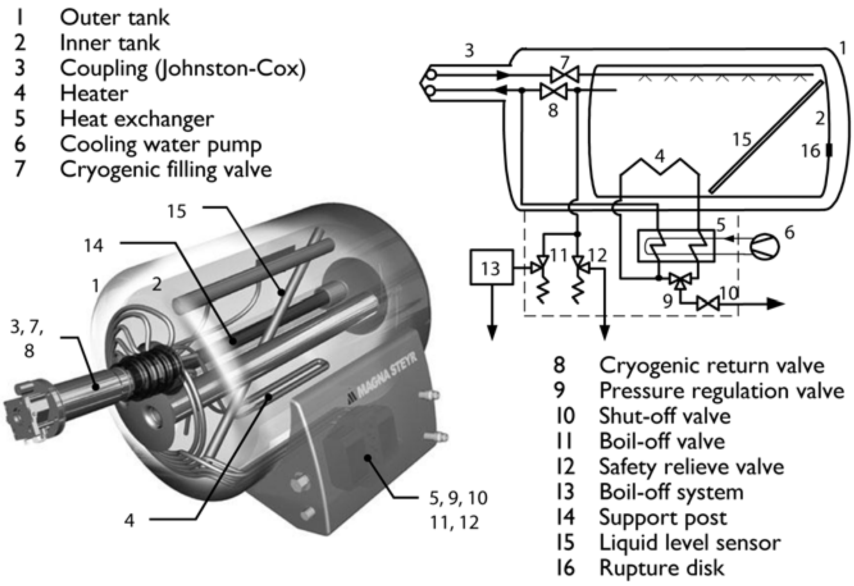
Hydrogen in liquid form has a considerably higher energy density than in its gaseous form, making it an attractive storage medium. In terms of application, liquid hydrogen and the enabling technology have already been used in space and military aircraft.

Cryogenic vessels, or dewars, designed for the storage of liquid hydrogen, are metallic double-walled containers. They are commonly composed of an aluminium alloy inner tank, surrounded by a thick walled armoured steel outer jacket for protection against third party mechanical damage. The space between the two layers is typically insulated and evacuated to minimize heat transfer and associated boil-off of liquid hydrogen (Guthrie *et al*. 2006), which is typically 2-3% per day in smaller vessels and up to 0.2% in large vessels (Tzimas *et al*. 2003). Substances with low thermal conductivity are typically employed for insulation, such as silica aerogel, diatomaceous earth, fused alumina, phenolic spheres. Radiant heat transfer is prevented by coating the interspace between the walls with multiple layers (30-100) of reflective, low-emittance heat shielding, substances such as aluminized plastic Mylar or the cheaper Perlite (colloidal silica). A further outer shell can be present, with the interspace filled with liquid nitrogen.

Because the heat transfer is proportional to the surface/volume (S/V) ratio, stationary containers are often spherical in shape; further than simply minimizing S/V, this offers advantage of higher mechanical resistance, and increased capability to withstand the pressure increases due to build-up of evaporated gaseous hydrogen in the container. The complex design of a liquid hydrogen vessel system is schematically illustrated in Figure 19.

[21] Partially modified and adapted from materials originally presented in the Quantum Technologies website

FIGURE 19. SCHEMATIC REPRESENTATION OF A CRYOGENIC VESSEL[22]



Hydrogen-energy delivery pathways

Gaseous hydrogen delivery

The widespread adoption of hydrogen as an energy carrier will require energy storage capabilities comparable to that of other fuels. However, the low density of gaseous hydrogen (0.0899 kg/Nm^3) has the consequence of a much lower volumetric energy density than other fuels. For the gaseous hydrogen pathway this means that hydrogen needs to be compressed and delivered at elevated pressures with implications for energy consumption, material requirements and operational safety.

It should also be noted that the storage capacity available along the delivery chain plays a key role in the management of the overall hydrogen delivery infrastructure. Bulk hydrogen storage facilities at hydrogen production plants, regional/local hydrogen distribution centres and end-use sites will be important to provide surge capacity for hourly, daily and seasonal demand variations.

Compressed gaseous hydrogen delivery by trucks

In present industrial applications, when small quantities of hydrogen (up to about 300-500 kg) need to be delivered over short distances (<200-300 km), compressed hydrogen gas is commonly delivered in steel pressure vessels. Pressure vessels of different sizes and configurations are available which suppliers use to meet customers' needs across a wide range of hydrogen quantities to be delivered. Various companies operate in this market, including all the major international industrial gas producers, including Air Liquide, Air Products, BOC Gases, Linde Gas, and Praxair.

Smaller quantities of hydrogen (from 5 g up to 1 kg) are delivered in single cylinders of different sizes, filled typically to pressures of 12-18 MPa. Manifolded cylinder pallets filled to 18 MPa are used for larger quantities of hydrogen (up to 10-20 kg, at 18 MPa), whereas bulk quantities of gaseous hydrogen (100-300 kg) are delivered by means of tube trailers filled with hydrogen at typical pressures of 15-23 MPa (Castello et al. 2005).

[22] Partially modified and adapted from (Krainz *et al.* 2003), Figure 2, p.3.

The different types of vessels are filled at the production site or at a major distribution point, generally by means of small reciprocating compressors. Single cylinders or manifolded pallets are then loaded, trucked to destination and off-loaded, while tube trailers consisting of several steel cylinders mounted to a protective framework, are often left in place and replaced when empty (see Figure 20).

FIGURE 20. COMPRESSED GASEOUS HYDROGEN DELIVERY BY TUBE TRAILER TRUCKS[23]

Compressed gaseous hydrogen delivery by pipelines

In general terms two options exist for gaseous delivery of hydrogen by pipeline: either as pure hydrogen in dedicated hydrogen transmission and distribution networks, or as a blend of hydrogen and natural gas, to be separated at the delivery point or to be used as a mixture depending on the requirements of the application.

Hydrogen delivery via pipeline is the lowest cost option when large quantities of hydrogen are to be transported over long distances. Today's hydrogen pipelines deliver hydrogen to a few large industrial users (more commonly refineries) by means of steel pipelines. The operating hydrogen pipeline networks in the USA and Europe have an extension of 900 and 1500 km, respectively.

The oldest existing system is found in Germany in the Ruhr area, it is 220 km long and distributes hydrogen between 18 producers and consumers. The single longest hydrogen pipeline, operated by Air Liquide, runs for 400 km between France and Belgium. In the United States, Praxair operates the longest pipeline network, which connects 11 hydrogen production sites to refinery facilities along the Gulf Coast through a system of pipelines with a total length of 500 kilometers. The network also includes the first commercial large-scale cavern hydrogen storage system (PRAXAIR 2006).

While significant experience exists with the development and operation of hydrogen pipelines for the delivery of pure hydrogen, the adoption of hydrogen as a major energy carrier will require the development, along the main transmission pipelines, of distribution networks with a higher degree of branching.

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[23] Partially modified and adapted from materials originally presented in the Air Products website.

The opportunity to deliver hydrogen and natural gas mixtures through the existing natural gas infrastructure is a potential solution to this problem because it could enable early hydrogen markets to reach a suitable level of branching, by piggybacking on the existing natural gas infrastructure, thus avoiding the large capital investments that the development of new pipeline networks require. Cost-effective technologies for the selective separation of hydrogen and natural gas will need to be developed and issues related to safety, life cycle and socio-economic aspects, durability of the system, gas quality management and performance of end-user appliances. The European Integrated Project NaturalHy (Florisson *et al.* 2005) is the first RD&D programme focussed on the use of the existing natural gas infrastructure for the early delivery of hydrogen. Activities within the Japanese project WE-NET and the U.S. D.o.E. Hydrogen Program are also aimed at investigating these issues.

Liquid hydrogen delivery

Liquid hydrogen delivery is another commercially available option, made attractive by a much higher energy density when compared to gaseous hydrogen. The liquefaction process, however, is energy intensive and liquid hydrogen handling requires the adoption of cryogenic technologies.

As mentioned previously, liquefaction is achieved by bringing hydrogen below its boiling point through a combination of cooling, compression and expansion stages. Hydrogen, liquefied and stored at atmospheric pressure in cryogenic tanks below this temperature, is characterized by a density of 70.96 kg/m^3, some 780 times higher of that of gaseous hydrogen at standard conditions (0.0899 kg/Nm^3) and nearly twice that of gaseous hydrogen compressed at 70 MPa (39.6 kg/m^3).

Liquid hydrogen delivery by trucks

The higher density of liquid hydrogen translates into higher volumetric energy density, a clear advantage when considering alternative hydrogen storage and transmission options. As an example, a liquid hydrogen tank with a water volume of 50 m^3 (see Figure 21), fitted to a truck with vehicle mass of 40 tonnes, can carry 3000 kg of liquid hydrogen, or 10 times the carrying capacity of a compressed gaseous hydrogen tube trailer (300 kg at 23 MPa).

FIGURE 21. LIQUID HYDROGEN DELIVERY IN TANKER TRUCKS[24]

[24] Partially modified and adapted from materials originally presented in the Linde website.

On trucks, tanks of cylindrical shape are normally used for carrying liquid hydrogen. The adoption of spherical containers on trucks will result in a poor utilization of the available space, with the maximum diameter of the vessel being limited by the maximum cross section of the trailer allowed by applicable road rules. The increase in the surface/volume ratio of the cylinder shape with respect to a sphere is partly countered by adopting larger tanks that use the full width and length of the trailer (for a given shape S/V decreases with increasing volumes).

APPENDIX B. ANNOTATED REVIEW OF INTERNATIONAL STANDARDS

HYDROGEN REFUELLING STATION and FUEL CELL VEHICLES

THE HYDROGEN UTILITY

Overview

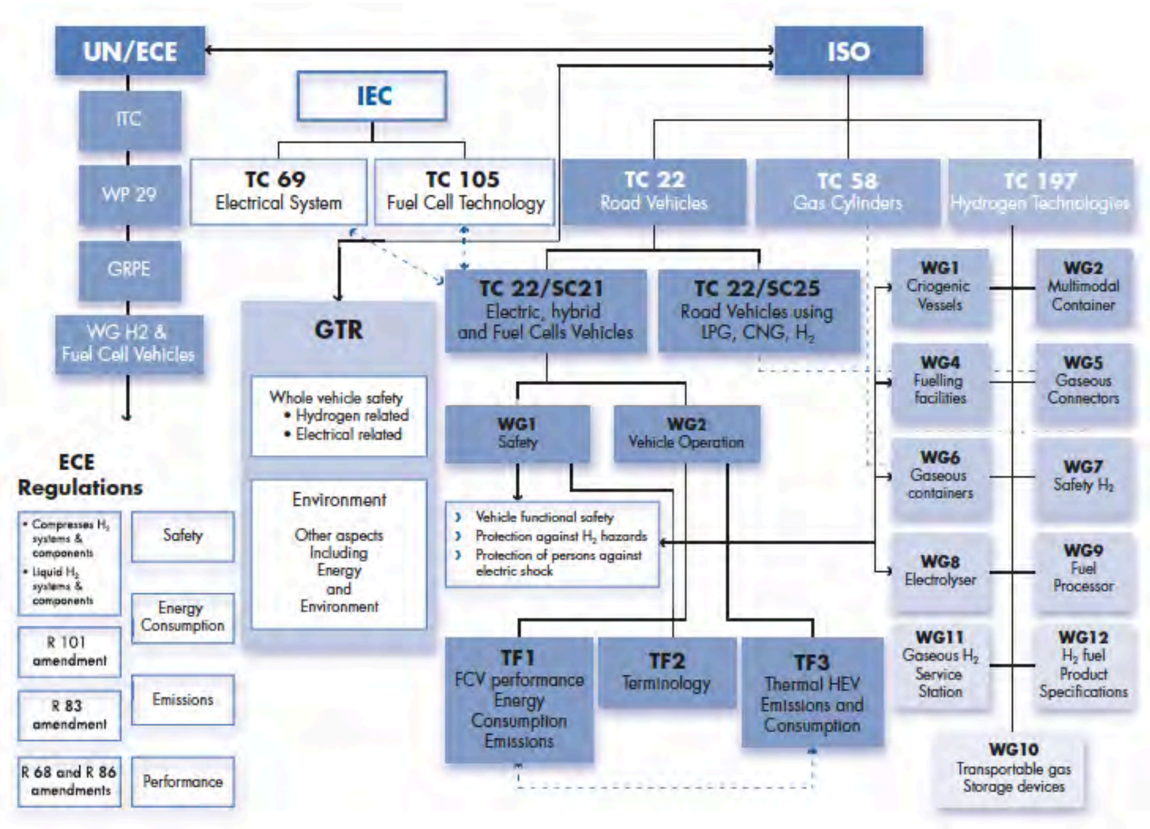
The increased focus on fuel cell vehicle technology development over the last decade has resulted in the establishment of a new harmonised set of international standards specific to hydrogen-energy applications. This represents a marked improvement over the past, where hydrogen installations have been built to a number of different codes & standards, primarily based on national and local specific requirements. Some codes and standards applied have been derived from experiences with the Compressed Natural Gas (CNG) industry.

The purpose of regulations, standards and codes is to ensure safe and reliable design and operation of a product or facility. Authorities, e.g. local, national, or international governments, provide compelling legal regulations to protect the public, workers, and the environment.

Codes (also referred to as codes of practice) and standards serve as guidelines developed by interested parties to support free exchange of goods and services, and to promote safety and common understanding. Interested parties are typically companies and associations. While standards are developed by standardisation organisations through a thorough development processes involving workgroups consisting of a wide range of interested parties, codes may be developed by a few or only a single company or association. Because of the more rigorous development process, standards generally have a wider acceptance than codes.

Unlike regulations, standards and codes are not legal documents, yet standards may be included or referred to in regulations and through the regulation be made legally binding. In this case the standard is said to be harmonised with the regulation and becomes a harmonised standard.

FIGURE 4: OVERVIEW OF INTERNATIONAL WORK ON STANDARDISATION OF HYDROGEN EQUIPMENT AND TECHNOLOGIES[25]



. 2000).

[25] Adapted from (Riis
et al. 2005).

[25] Reproduced from ADDIN PAPERS2_CITATIONS <citation><uuid>AD4AD24B-322C-47F9-A95C-937F64855D6C</uuid><priority>0</priority><publications><publication><publication_date>99200600001200000000200000</publication_date><title>Introducing hydrogen as an energy carrier </title><uuid>965A652C-001C-4DB7-930B-EB610A70F302</uuid><subtype>700</subtype><publisher>Directorate-General for Research and Innovation, European Commission</publisher><type>700</type><url>http://bookshop.europa.eu/is-bin/INTERSHOP.enfinity/WFS/EU-Bookshop-Site/en_GB/-/EUR/ViewPublication-Start?PublicationKey=KINA22002</url><authors><author><lastName>EC</lastName></author></authors></publication></publicat

ISO standards

The International Standardisation Organisation (ISO) is actively engaged in the development of international standards for hydrogen equipment and technologies through the following technical committees (TC):

- ISO/TC 197 – Hydrogen technologies;
- ISO/TC 22 – Road vehicles; and
- ISO/TC 58 – Gas cylinders.

ISO/TC 197 – Hydrogen technologies

ISO/TC 197 covers standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen, through the following working groups (WG):

- ISO/TC 197/WG 5, Gaseous hydrogen land vehicle refuelling connection devices;
- ISO/TC 197/WG 15, Gaseous hydrogen - Cylinders and tubes for stationary storage;
- ISO/TC 197/WG 17, Pressure swing adsorption system for hydrogen separation purification;
- ISO/TC 197/WG 18, Gaseous hydrogen land vehicle fuel tanks;
- ISO/TC 197/WG 19, Gaseous hydrogen fuelling station dispensers;
- ISO/TC 197/WG 20, Gaseous hydrogen fuelling station valves;
- ISO/TC 197/WG 21, Gaseous hydrogen fuelling station compressors;
- ISO/TC 197/WG 22, Gaseous hydrogen fuelling station hoses;
- ISO/TC 197/WG 23, Gaseous hydrogen fuelling station fittings;
- ISO/TC 197/WG 24, Gaseous hydrogen fuelling stations. General requirements;
- ISO/TC 197/WG 25, Hydrogen absorbed in reversible metal hydride;
- ISO/TC 197/WG 26, Hydrogen generators using water electrolysis;
- ISO/TC 197/WG 27, Hydrogen fuel quality; and
- ISO/TC 197/WG 28, Hydrogen quality control.

ISO/TC 22 – Road vehicles

ISO/TC 22 covers all questions of standardization concerning compatibility, interchangeability and safety, with particular reference to terminology and test procedures (including the characteristics of instrumentation) for evaluating the performance of road vehicles and their equipment. Work related to hydrogen fuel cell vehicles and hydrogen refuelling applications is covered by the following sub-committees (SC):

- ISO/TC 22/SC 37, Electrically propelled vehicles; and
- ISO/TC 22/SC 41, Specific aspects for gaseous fuels.

ISO TC 58 Gas cylinders

ISO TC 58 covers standardization of gas cylinders, their fittings and characteristics relating to their manufacture and use. Work related to hydrogen applications is covered by the following sub-committees (SC):

- ISO/TC 58/SC 2, Cylinder fittings;
- ISO/TC 58/SC 3, Cylinder design;
- ISO/TC 58/SC 4, Operational requirements for gas cylinders.

General

ISO/TR 15916:2015(en) Basic considerations for the safety of hydrogen systems	
Type:	Guidelines
Relevant to:	Hydrogen systems and technologies
Status:	Published
Application:	Safety guidelines
Scope:	Guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage in either of these or other forms (hydrides). It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety.

Fuel quality

ISO 14687-2:2012 Hydrogen fuel -- Product specification -- Part 2: PEM fuel cell applications for road vehicles	
Type:	Standard
Relevant to:	Hydrogen refuelling (gaseous)
Status:	Published
Application:	Product quality
Scope:	This International Standard specifies the quality characteristics of hydrogen fuel in order to assure uniformity of the hydrogen product as produced and distributed for utilization in vehicular, appliance or other fuelling applications. Part 2 of ISO 14687 specifies the quality characteristics of hydrogen fuel in order to ensure uniformity of the hydrogen product as dispensed for utilization in proton exchange membrane (PEM) fuel cell road vehicle systems.

Hydrogen production

ISO 16110 (group) Hydrogen generators using fuel processing technologies	
Type:	Standard
Relevant to:	Hydrogen production
Status:	Published
Application:	Product certification
Scope:	Set of standards covering hydrogen generators intended for indoor and outdoor commercial, industrial, light industrial and residential use, with a capacity of less than 400 Nm^3/h at STP[26], using a variety of fossil and renewable (biomass) fuels, alone or in combination. • ISO 16110-1:2007 -- Part 1: Safety • ISO 16110-2:2010 -- Part 2: Test methods for performance

ISO 22734-1:2008 Hydrogen generators using water electrolysis process -- Part 1: Industrial and commercial applications	
Type:	Standard
Relevant to:	Hydrogen production
Status:	Published, ongoing development under ISO/AWI 22734
Application:	Product certification
Scope:	ISO 22734-1:2008 is applicable to hydrogen generators intended for indoor and outdoor commercial and industrial use (non-residential use). This International Standard defines the construction, safety and performance requirements of hydrogen generators based on water electrolysis, including generators that use the following types of ion transport medium: • Group of aqueous bases; • Solid polymeric materials with acidic function group additions such as acid proton exchange membrane (PEM).

ions><cites></cites></citation
>(EC, 2006)
[26] Standard Tem

Hydrogen storage and transport

ISO 11114 (group) Gas cylinders -- Compatibility of cylinder and valve materials with gas contents	
Type:	Standard
Relevant to:	Hydrogen storage/transport (gaseous)
Status:	Published
Application:	Safety guidelines
Scope:	Set of standards providing guidance in the selection and evaluation of compatibility between gas cylinder and valve materials, and the gas content, including: • ISO 11114-1:2012 -- Part 1: Metallic materials • ISO 11114-2:2013 -- Part 2: Non-metallic materials • ISO 11114-3:2010 -- Part 3: Autogenous ignition test for non-metallic materials in oxygen atmosphere • ISO 11114-4:2005 -- Part 4: Test methods for selecting metallic materials resistant to hydrogen embrittlement

ISO 16111:2008 TRANSPORTABLE GAS STORAGE DEVICES -- HYDROGEN ABSORBED IN REVERSIBLE METAL HYDRIDE	
Type:	Standard
Relevant to:	Hydrogen storage/transport (gaseous)
Status:	Published
Application:	Product certification
Scope:	ISO 16111:2008 defines the requirements applicable to the material, design, construction, and testing of transportable hydrogen gas storage systems, referred to as "metal hydride assemblies" (MH assemblies) which utilize shells not exceeding 150 l internal volume and having a maximum developed pressure (MDP) not exceeding 25 MPa (250 bar). It only applies to refillable storage MH assemblies where hydrogen is the only transferred media. Storage MH assemblies intended to be used as fixed fuel-storage onboard hydrogen fuelled vehicles are excluded.

Refuelling station installations

ISO 19880 (group) GASEOUS HYDROGEN – FUELLING STATIONS	
Type:	Standard
Relevant to:	Hydrogen refuelling (gaseous)
Status:	Under development
Application:	Product certification
Scope:	Set of standards covering all equipment and operations of refuelling stations dispensing gaseous hydrogen: • ISO/DTR 19880-1 -- Part 1: General requirements • ISO/CD 19880-2 -- Part 2: Dispensers • ISO/CD 19880-3 -- Part 3: Valves • ISO/AWI 19880-4 -- Part 4: Compressors • ISO/AWI 19880-5 -- Part 5: Hoses • ISO/AWI 19880-6 -- Part 6: Fittings • ISO/AWI 19880-8 -- Part 8: Hydrogen quality control

ISO 26142:2010 HYDROGEN DETECTION APPARATUS -- STATIONARY APPLICATIONS	
Type:	Standard
Relevant to:	Hydrogen refuelling (gaseous)
Status:	Published
Application:	Product certification
Scope:	This International Standard defines the performance requirements and test methods of hydrogen detection apparatus that is designed to measure and monitor hydrogen concentrations in stationary applications. This International Standard sets out only the requirements applicable to a product standard for hydrogen detection apparatus, such as precision, response time, stability, measuring range, selectivity and poisoning.

Vehicle/refuelling interface

ISO/TS 15869:2009 GASEOUS HYDROGEN AND HYDROGEN BLENDS -- LAND VEHICLE FUEL TANKS	
Type:	Standard
Relevant to:	Hydrogen storage (gaseous)
Status:	Published
Application:	Product certification
Scope:	ISO 15869:2009 specifies the requirements for lightweight refillable fuel tanks intended for the on-board storage of high-pressure compressed gaseous hydrogen or hydrogen blends on land vehicles. ISO 15869:2009 applies to the following types of fuel tank designs: • Type 1: metal fuel tanks; • Type 2: hoop-wrapped composite fuel tanks with a metal liner; • Type 3: fully wrapped composite fuel tanks with a metal liner; • Type 4: fully wrapped composite fuel tanks with no metal liner.

ISO 17268:2012 GASEOUS HYDROGEN LAND VEHICLE REFUELLING CONNECTION DEVICES	
Type:	Standard
Relevant to:	Hydrogen dispensing (gaseous)
Status:	Published, ongoing development under ISO/AWI 17268
Application:	Product certification
Scope:	ISO 17268:2012 defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refuelling connectors consisting of receptacle and protective cap (mounted on vehicle), and nozzle. This International Standard applies to refuelling connectors which have working pressures of 11 MPa, 25 MPa, 35 MPa and 70 MPa, referred to as the following: • H11 – 11 MPa at 15 °C; • H25 – 25 MPa at 15 °C; • H35 – 35 MPa at 15 °C; • H35HF – 35 MPa at 15 °C (high flow for commercial vehicle applications); • H70 – 70 MPa at 15 °C.

Vehicles - safety

ISO 6469 (group) ELECTRICALLY PROPELLED ROAD VEHICLES -- SAFETY SPECIFICATIONS	
TYPE:	Standard
RELEVANT TO:	Vehicle powertrain
STATUS:	Published
APPLICATION:	Safety guidelines
SCOPE:	Set of standards covering requirements for the on-board rechargeable energy storage systems (RESS) of electrically propelled road vehicles, including battery-electric vehicles (BEVs), fuel-cell vehicles (FCVs) and hybrid electric vehicles (HEVs), for the protection of persons inside and outside the vehicle and the vehicle environment, including: • ISO 6469-1:2009 -- Part 1: On-board rechargeable energy storage system (RESS) • ISO 6469-2:2009 -- Part 2: Vehicle operational safety means and protection against failures • ISO 6469-3:2011 -- Part 3: Protection of persons against electric shock • ISO 6469-4:2015 -- Part 4: Post crash electrical safety

ISO 23273:2013 FUEL CELL ROAD VEHICLES -- SAFETY SPECIFICATIONS -- PROTECTION AGAINST HYDROGEN HAZARDS FOR VEHICLES FUELLED WITH COMPRESSED HYDROGEN	
TYPE:	Standard
RELEVANT TO:	Vehicle powertrain
STATUS:	Published
APPLICATION:	Safety guidelines
SCOPE:	ISO 23273:2013 specifies the essential requirements for fuel cell vehicles (FCV) with respect to the protection of persons and the environment inside and outside the vehicle against hydrogen-related hazards. It applies only to such FCV where compressed hydrogen is used as fuel for the fuel cell system, under normal operating (fault-free) and single-fault conditions.

Vehicles – fuel system

ISO 12619 (group) ROAD VEHICLES -- COMPRESSED GASEOUS HYDROGEN (CGH2) AND HYDROGEN/NATURAL GAS BLEND FUEL SYSTEM COMPONENTS	
TYPE:	Standard
RELEVANT TO:	Vehicle fuel system
STATUS:	Published/Draft
APPLICATION:	Product certification
SCOPE:	Set of standards covering compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel system components for use on road motor vehicles, including: • ISO 12619-1:2014 -- Part 1: General requirements and definitions • ISO 12619-2:2014 -- Part 2: Performance and general test methods • ISO 12619-3:2014 -- Part 3: Pressure regulator • ISO/DIS 12619-4 (draft) -- Part 4: Check Valve • ISO/DIS 12619-5 (draft) -- Part 5: Manual cylinder valve • ISO/DIS 12619-6 (draft) -- Part 6: Automatic valve

ISO/NP 21266 ROAD VEHICLES -- COMPRESSED GASEOUS HYDROGEN (CGH2) AND HYDROGEN/NATURAL GAS BLENDS FUEL SYSTEMS	
TYPE:	Standard
RELEVANT TO:	Vehicle fuel system
STATUS:	Under development
APPLICATION:	Product certification
SCOPE:	New proposed set of international standards covering system configurations for compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel system components for use on road motor vehicles, including: • ISO/NP 21266-1 -- Part 1: Safety requirements • ISO/NP 21266-2 -- Part 2: Performance and general test methods

Vehicles – fuel cell powertrain

ISO/TR 11954:2008(en) FUEL CELL ROAD VEHICLES – MAXIMUM SPEED MEASUREMENT	
TYPE:	Standard
RELEVANT TO:	Fuel cell powertrain
STATUS:	Published
APPLICATION:	Performance testing
SCOPE:	Technical Report describing test procedures for measuring the maximum road speed of fuel cell passenger cars and light duty trucks which use compressed hydrogen and which are not externally chargeable, in accordance with national or regional standards or legal requirements.

ISO 23828:2013 FUEL CELL ROAD VEHICLES -- ENERGY CONSUMPTION MEASUREMENT -- VEHICLES FUELLED WITH COMPRESSED HYDROGEN	
TYPE:	Standard
RELEVANT TO:	Fuel cell powertrain
STATUS:	Published
APPLICATION:	Product certification
SCOPE:	International Standard specifying procedures for measuring the energy consumption of fuel cell passenger cars and light-duty trucks that use compressed hydrogen and which are not externally chargeable.

IEC standards

The International Electrotechnical Commission (IEC) is actively engaged in the development of international standards relevant to hydrogen equipment and technologies through the following technical committees (TC):

- IEC/TC 105 – Fuel cell technologies;
- ISO/TC 69 – Electric road vehicles and electric industrial trucks; and
- IEC/TC 31 – Equipment for explosive atmospheres.

IEC/TC 105 – Fuel cell technologies

IEC/TC 105 covers development of international standards regarding fuel cell (FC) technologies used in stationary, transport, auxiliary power and portable applications. Work related to hydrogen fuel cell vehicles and hydrogen refuelling applications is covered by the following working groups (WG):

- IEC/TC 105/WG 4, Performance of Fuel Cell Power Systems; and
- IEC/TC 105/WG 6, Fuel cell system for propulsion and auxiliary power units (APU).

IEC/TC 69 – Electric road vehicles and electric industrial trucks

IEC/TC 69 covers development of international standards for road vehicles, totally or partly electrically propelled from self-contained power sources, and for electric industrial trucks.

IEC/TC 31 – Equipment for explosive atmospheres.

IEC/TC 31 covers development of international standards relating to equipment for use where there is a hazard due to the possible presence of explosive atmospheres of gases, vapours, mists or combustible dusts.

Vehicles – fuel cell powertrain

IEC 62282 (group) FUEL CELL TECHNOLOGIES	
TYPE:	Standard
RELEVANT TO:	Fuel cell powertrain (industrial trucks)
STATUS:	Published
APPLICATION:	Safety guidelines, Product certification
SCOPE:	Set of international standards specifying general safety requirements for fuel cell systems for stationary, portable, auxiliary power and transport applications. • IEC 62282-2:2012 - Part 2: Fuel cell modules • IEC 62282-4-101:2014 - Part 4-101: Safety of electrically powered industrial trucks

Electrical systems

IEC 60079 (group) ELECTRICAL APPARATUS FOR EXPLOSIVE GAS ATMOSPHERES	
TYPE:	Standard
RELEVANT TO:	Hydrogen installations
STATUS:	Published
APPLICATION:	Safety guidelines, Product certification, System compliance
SCOPE:	Set of international standards specifying general requirements for construction, testing and marking of electrical apparatus and components intended for use in explosive gas atmospheres. • IEC 60079-0:2011 – Part 0: Equipment - General requirements • IEC 60079-29-1:2007 – Part 29-1: Gas detectors - Performance requirements of detectors for flammable gases • IEC 60079-29-2:2015 – Part 29-2: Gas detectors - Selection, installation, use and maintenance of detectors for flammable gases and oxygen • IEC 60079-29-4:2009 – Part 29-4: Gas detectors - Performance requirements of open path detectors for flammable gases • IEC TS 60079-40:2015 – Part 40: Requirements for process sealing between flammable process fluids and electrical systems

SAE Standards

The Society for Automotive Engineers (SAE) is the leading global association of engineers and related technical experts in the aerospace, automotive and commercial-vehicle industries.

The Fuel Cell Standards Committee is responsible for establishing standards for hydrogen and fuel cell vehicles covering safety aspects of hydrogen, fuel cell, and electrical systems in the vehicle, test procedures to establish the performance of the vehicle, system/components, and interface requirements.

The work of the Committee has been instrumental in the establishment of a single harmonised refuelling protocol across all hydrogen vehicle applications.

Vehicles – safety

J1766_201401 RECOMMENDED PRACTICE FOR ELECTRIC, FUEL CELL AND HYBRID ELECTRIC VEHICLE CRASH INTEGRITY TESTING	
TYPE:	Recommended practice
RELEVANT TO:	Fuel cell powertrain
STATUS:	Published
APPLICATION:	Safety guideline, Product certification
SCOPE:	Electric, Fuel Cell and Hybrid vehicles may contain many types of high voltage systems. Adequate barriers between occupants and the high voltage systems are necessary to provide protection from potentially harmful electric current and materials within the high voltage system that can cause injury to occupants of the vehicle during and after a crash. This SAE Recommended Practice is applicable to Electric, Fuel Cell and Hybrid vehicle designs that are comprised of at least one vehicle propulsion voltage bus with a nominal operating voltage greater than 60 and less than 1,500 VDC, or greater than 30 and less than 1,000 VAC. This Recommended Practice addresses post-crash electrical safety, retention of electrical propulsion components and electrolyte spillage.

J2578_201408 RECOMMENDED PRACTICE FOR GENERAL FUEL CELL VEHICLE SAFETY	
TYPE:	Recommended practice
RELEVANT TO:	Fuel cell powertrain
STATUS:	Published
APPLICATION:	Safety guideline, Product certification
SCOPE:	Requirements relating to the safe integration of the fuel cell system, the hydrogen fuel storage and handling systems (as defined and specified in SAE J2579) and high voltage electrical systems into the overall Fuel Cell Vehicle. The document may also be applied to hydrogen vehicles with internal combustion engines. This document relates to the overall design, construction, operation and maintenance of fuel cell vehicles.

Vehicles – fuel cell powertrain

J2572_201410 RECOMMENDED PRACTICE FOR MEASURING FUEL CONSUMPTION AND RANGE OF FUEL CELL AND HYBRID FUEL CELL VEHICLES FUELLED BY COMPRESSED GASEOUS HYDROGEN	
TYPE:	Recommended practice
RELEVANT TO:	Fuel cell powertrain
STATUS:	Published
APPLICATION:	Product certification
SCOPE:	Uniform procedures for testing fuel cell and hybrid fuel cell electric vehicles, excluding low speed vehicles, designed primarily for operation on the public streets, roads and highways. Standard tests that will allow for determination of fuel consumption and range based on the US Federal Emission Test Procedures, using the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HFEDS).

Vehicles – fuel system

J2579_201303 STANDARD FOR FUEL SYSTEMS IN FUEL CELL AND OTHER HYDROGEN VEHICLES	
TYPE:	Standard
RELEVANT TO:	Vehicle fuel system
STATUS:	Published
APPLICATION:	Safety guideline, Product certification
SCOPE:	SAE J2578 includes requirements relating to crashworthiness and vehicle integration for fuel cell vehicles. It defines recommended practices related to the integration of hydrogen storage and handling systems, fuel cell system, and electrical systems into the overall Fuel Cell Vehicle.

Vehicle/refuelling interface

J2600_201510 COMPRESSED HYDROGEN SURFACE VEHICLE FUELLING CONNECTION DEVICES	
Type:	Standard
Relevant to:	Hydrogen dispensing (gaseous)
Status:	Published
Application:	Product certification
Scope:	SAE J2600 applies to the design and testing of Compressed Hydrogen Surface Vehicle (CHSV) fuelling connectors, nozzles, and receptacles with pressure classes of H11, H25, H35, H50 or H70.

J2799_201404 HYDROGEN SURFACE VEHICLE TO STATION COMMUNICATIONS HARDWARE AND SOFTWARE	
TYPE:	Standard
RELEVANT TO:	Hydrogen dispensing (gaseous)
STATUS:	Published
APPLICATION:	System compliance
SCOPE:	This standard specifies the communications hardware and software requirements for fuelling Hydrogen Surface Vehicles (HSV), such as fuel cell vehicles, but may also be used where appropriate, with heavy duty vehicles (e.g., busses) and industrial trucks (e.g., forklifts) with compressed hydrogen storage. It contains a description of the communications hardware and communications protocol that may be used to refuel the HSV. The intent of this standard is to enable harmonized development and implementation of the hydrogen fuelling interfaces.

Fuel quality

J2719_201511 HYDROGEN FUEL QUALITY FOR FUEL CELL VEHICLES	
TYPE:	Standard
RELEVANT TO:	Hydrogen refuelling (gaseous)
STATUS:	Published
APPLICATION:	Product quality
SCOPE:	Background information and a hydrogen fuel quality standard for commercial proton exchange membrane (PEM) fuel cell vehicles.

Refuelling protocols

J2601 (GROUP) FUELLING PROTOCOLS FOR GASEOUS HYDROGEN POWERED SURFACE VEHICLES	
TYPE:	Standard
RELEVANT TO:	Hydrogen dispensing (gaseous)
STATUS:	Published
APPLICATION:	System compliance
SCOPE:	Family of standards establishing the protocol and process limits (fuel temperature, the maximum fuel flow rate, rate of pressure increase and end pressure) across hydrogen vehicle fuelling applications, including: • J2601_201407 – Light Duty Vehicles • J2601/2_201409 – Heavy Duty Vehicles • J2601/3_201306 – Industrial Trucks

EIGA Codes

The European Industrial Gases Association (EIGA) is an organization representing the majority of European (and some non-European) companies producing and distributing industrial, medical and food gases. The activities of the organization are focused on the technical, safety and environmental aspects concerning the handling of gases. Since 2002, EIGA has been a major contributor to the development of international standards and the dissemination of knowledge related to hydrogen-energy systems.

To date 5 Industrial Gas Codes (IGC) code of practice documents have been published by EIGA related to various aspects of hydrogen delivery covering general safety aspects, hydrogen and syngas pipelines, hydrogen production plants, cylinders and vessels for hydrogen transport and refuelling station designs.

Hydrogen production

IGC 155/09/E Best available techniques for hydrogen production by Steam Methane Reforming	
Type:	Code of practice
Relevant to:	Hydrogen production
Status:	Published
Application:	Safety/Best practice guidelines
Scope:	Guidance to site managers, technical managers, and company environmental specialists on some best available techniques for hydrogen production by steam methane reforming.

IGC 122/11/E Environmental impacts of hydrogen plants	
Type:	Code of practice
Relevant to:	Hydrogen production
Status:	Published
Application:	Best practice guidelines
Scope:	General guide for hydrogen plant operations to assist in putting in place a formal environmental management system that can be certified by an accredited third party. It aims to provide a guide for operating managers for identifying and reducing the environmental impacts of these operations.

Hydrogen storage and transport

IGC 100/11/E Hydrogen cylinders and transport vessels	
Type:	Code of practice
Relevant to:	Hydrogen storage and transport
Status:	Published
Application:	Safety/Best practice guidelines
Scope:	Industry experiences with hydrogen cylinders and transport vessels and provides a number of recommendations for the specification, manufacture, testing, maintenance and mounting of the cylinders and vessels. Applications of hydrogen with working pressure more than 300 bar and using composite cylinders are not covered by this document.

IGC 171/12/E Storage of hydrogen in systems located underground	
Type:	Code of practice
Relevant to:	Hydrogen storage and transport
Status:	Published
Application:	Safety/Best practice guidelines
Scope:	Safety requirements specific to the installation of a hydrogen storage system in an underground space with top or side access, hereafter called a vault, including liquid hydrogen storage and ancillary systems and compressed hydrogen storage composed of a single container, or multiple cylinders or tubes.

Refuelling station installations

IGC 15/06/E Gaseous hydrogen stations	
Type:	Code of practice
Relevant to:	Hydrogen refuelling (gaseous)
Status:	Published
Application:	Safety/Best practice guidelines
Scope:	Guidance/best practices of designers and operators of gaseous hydrogen stations.

Appendix C. GUIDELINE TOOLS

ESTABLISHED APPROVAL GUIDELINE TOOLS FOR HYDROGEN REFUELLING STATIONS IN Germany and California

THE HYDROGEN UTILITY

Germany – NOW Approval Guidelines

A set of guidelines for approval of hydrogen refuelling stations in Germany has been developed by the National Organisation for Hydrogen and Fuel Cell Technology (NOW).

The NOW Approval Guidelines, published on a dedicated website[27], are presented as an interactive tool enabling project developers to identify relevant licensing and technical authorities based on the proposed location of the hydrogen refuelling station, and to access a list of list of all authorised inspection bodies (Zugelassenen Überwachungsstellen, ZÜS) of the Federal Institute for Occupational Safety and Health (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, BAuA).

The NOW Approval Guidelines organize the approval process in three stages: Application, Review, and Commissioning. The key steps involved at each stage are listed in the table presented below.

TABLE 3. NOW APPROVAL GUIDELINES FOR HYDROGEN REFUELLING STATIONS

STAGE 1 – APPLICATION INTENTION TO CONSTRUCT AND OPERATE A PUBLIC H_2 FUELLING STATION	
1	IDENTIFICATION OF THE RELEVANT LICENSING AUTHORITY
2	STUDY OF THE COMPLETE APPROVAL PROCESS AND RELEVANT DOCUMENTS
3	ARRANGEMENT OF A PRELIMINARY MEETING WITH THE LICENSING AUTHORITY
4	DISCUSSION OF PLANS WITH THE LICENSING AUTHORITY
5	DETAILED CONCEPT OF THE FACILITY (TECHNOLOGY AND LICENSING STAKEHOLDER) AS A FIRST DRAFT
6	ARRANGEMENT OF A KICK-OFF MEETING WITH THE STAKEHOLDERS
7	DISCUSSION OF THE DRAFT IN THE KICK-OFF MEETING, COORDINATION WITH STAKEHOLDERS
8	ARRANGING A FOLLOW-UP MEETING WITH THE ZÜS EXPERTS AND THE EQUIPMENT SUPPLIERS
9	MEETING WITH ZÜS EXPERTS AND EQUIPMENT SUPPLIER
10	COMMISSIONING OF AN EXPERT OPINION
11	MAKING A LICENSE APPLICATION ACCORDING TO PREVIOUSLY ESTABLISHED FACILITY TYPE (H2-DELIVERED FUELLING STATION VS. H2 PRODUCTION STATION)
12	SUBMISSION OF THE LICENSING APPLICATION

[27] English version of the NOW Approval Guidelines is available at http://www.h2-genehmigung.de/english

TABLE 3. (CONT'D)

STAGE 2 – REVIEW REVIEW OF APPLICATION FOR INDUSTRIAL FACILITIES BY THE LICENSING AUTHORITY	
13	RECEIPT OF THE LICENSING APPLICATION
14	CHECKING THE COMPLETENESS OF THE APPLICATION DOCUMENTS
15	INVOLVEMENT OF THE TECHNICAL AUTHORITIES
16	CONSULTATION WITH THE APPLICANT
17	PROCESSING THE APPLICATION
18	GRANTING OF THE PERMIT FOR THE CONSTRUCTION AND OPERATION OF THE H2 FACILITY (WITH CONDITIONS, WHERE APPLICABLE)
STAGE 3 – COMMISSIONING THE INTENTION TO OPEN A PUBLIC H_2 FUELLING STATION (FACILITY OPERATOR)	
19	THE START OF BUILDING PLANNING/ CONSTRUCTION/ INSTALLATION OF THE H_2 FACILITY
20	COMPILATION OF DOCUMENTS FOR COMMISSIONING
21	PREVIEW OF H2 FACILITY BY ZÜS EXPERTS
22	ZÜS INSPECTION OF THE H2 FACILITY BEFORE THE INITIAL COMMISSIONING
23	THE ZÜS EXPERT MUST FORWARD THE TEST CERTIFICATE TO THE AUTHORITY
24	CLEARANCE FOR THE START OF THE TEST/ NORMAL OPERATION
25	INVESTIGATION/CHECKING OF THE INSPECTION INTERVALS OF THE H2 FACILITY (FACILITY OPERATOR & ZÜS)
26	COMMUNICATION OF THE INSPECTION INTERVALS TO THE LICENSING AUTHORITIES
27	SEPARATE INSPECTION BY VEHICLE MANUFACTURER
28	OPENING OF H2 FUELLING STATION TO THE PUBLIC

California – Hydrogen Station Permitting Guidebook

The *Hydrogen Station Permitting Guidebook – Best practices for planning, permitting and opening a hydrogen fuelling station* (Eckerle & Jones, 2015), is a resource published in November 2015 by the Governor's Office of Business and Economic Development (GO-Biz) of the State of California.

The *Guidebook* provides a comprehensive overview of technical, safety and operational considerations in regard to the development process for hydrogen refuelling stations, and outlines key regulatory requirements applicable to permitting of hydrogen refuelling stations in California.

The *Guidebook* organizes the permitting process in five phases:

1. Pre-application outreach
2. Planning review
3. Building review
4. Construction
5. Commissioning

The key steps involved at each stage are listed in the table presented below.

TABLE 4. CALIFORNIA HYDROGEN STATION PERMITTING PROCESS

STAGE 1 – PRE-APPLICATION OUTREACH	
1	SECURING SITE CONTROL
2	ESTABLISHING A PERMITTING PATHWAY UNDERSTANDING
3	PRE-APPLICATION MEETING WITH AUTHORITIES HAVING JURISDICTION (AHJ)
STAGE 2 – PLANNING REVIEW	
4	ZONING COMPATIBILITY ASSESSMENT
5	ARCHITECTURAL REVIEW
6	REVIEW OF COMPLIANCE UNDER CALIFORNIA ENVIRONMENTAL QUALITY ACT (CEQA)
7	FIRE DEPARTMENT APPROVAL
8	UTILITY POWER CONSIDERATIONS

TABLE 4. (CONT'D)

STAGE 3 – BUILDING REVIEW	
9	SITING, LAYOUT and SAFETY DISTANCES COMPLIANCE
10	MECHANICAL EQUIPMENT COMPLIANCE
11	ELECTRICAL EQUIPMENT COMPLIANCE
12	MAINTENANCE PLAN
13	EMERGENCY RESPONSE PLAN
14	SENSORS EQUIPMENT and LOCATION COMPLIANCE
STAGE 4 – CONSTRUCTION	
15	ENCROACHMENT PERMITS
16	WORK-IN-PROGRESS INSPECTIONS
17	NOTICE OF COMPLETION
18	FINAL INSPECTION
STAGE 5 – COMMISSIONING	
19	STATION DEVELOPER COMMISSIONING
20	FINAL OCCUPANCY PERMIT ISSUED BY AUTHORITY HAVING JURISDICTION (AHJ)
21	FUELLING PROTOCOL CONFIRMATION
22	COMMERCIAL TESTING
23	STATION OPENING FOR PUBLIC USE

Appendix D. CASE STUDIES

HYDROGEN REFUELLING STATIONS

Europe

IIT HYDROGEN REFUELLING STATION

BOLZANO, ITALY

OPERATOR	**H2 Alto Adige/H2 South Tyrol**
LOCATION and CONTACTS	H2 ALTO ADIGE c/o IIT, Uscita Autostradale Bolzano Sud Via Enrico Mattei 1, 39100 Bolzano, Italy Tel. +39 0471 050444, info@iit.bz.it
STATION LAYOUT	**TYPE:** standalone hydrogen refuelling station
	H2 SUPPLY: On-site (electrolysis)
	DISPENSING PRESSURES: 70/35 MPa **COMPRESSOR-STORAGE-DISPENSER:** 1x Linde Gas IC 90, 2x Linde Gas IC 45 **ELECTROLYSER:** 3x Hydrogenics HyStat™ 60
FLEET COMPOSITION	**PASSENGER VEHICLES:** 10 x Hyundai ix35 FCEV (local business + rental service), capacity for up to 700 **BUSES:** 5x Daimler EvoBus Citaro FuelCELL Hybrid (City service), capacity for up to 15
DESCRIPTION	H2 Alto Adige/H2 South Tyrol is a trading name of IIT (Istituto per Innovazioni Tecnologiche Bolzano) a consortium of local businesses and government agencies supported by the European Commission Regional Development Fund. The station complex, and the adjoining innovation center, opened in 2013, with the commencement of a 5-year bus trial program under the CHIC (Clean Hydrogen In European Cities) program in fall 2013. The buses are on normal city service, and run approximately 200-250 km/day. Since 2014, IIT has acquired 10 Hyundai ix35 FCEV some of which are leased for local businesses, the balance available for rent to the general public.
STATUS	**OPEN to GENERAL PUBLIC**

OMV INNSBRUCK HYDROGEN REFUELLING STATION

INNSBRUCK, AUSTRIA

OPERATOR	**OMV Aktiengesellschaft**
LOCATION and CONTACTS	Egger-Lienz-Straße 3d, 6020 Innsbruck, Austria +43 512 582345
STATION LAYOUT	**TYPE:** hosted on existing forecourt, non-integrated (separate H2 dispensing area)
	H2 SUPPLY: Delivered (compressed gaseous hydrogen tube trailer trucks)
	DISPENSING PRESSURES: 70/35 MPa **COMPRESSOR-STORAGE-DISPENSER:** 1x Linde Gas IC 90
DESCRIPTION	The hydrogen filling station in Innsbruck is part of a major European Union initiative to introduce hydrogen on the road. A total of 15 international partners are taking part in the so-called demo project "HyFIVE", one of which is OMV. The filling station in Tyrol is part of "Hydrogen Cluster South", which runs from Stuttgart via Munich to Verona. Four hydrogen stations have already been built in these cities. OMV opened the first public hydrogen filling station in Vienna in 2012 and the expansion of further stations is planned for the coming years. OMV is a member of H2-Mobility Deutschland GmbH, whose goal is to build around 400 hydrogen filling stations in Germany by 2023. Innsbruck is the first HRS to be deployed through HyFIVE.
STATUS	**OPEN to GENERAL PUBLIC**

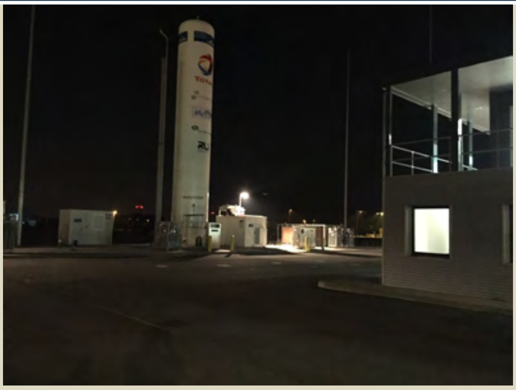
TOTAL SACHSENDAMM HYDROGEN REFUELLING STATION

BERLIN, GERMANY

OPERATOR	**Total GmbH**
LOCATION	10829 BERLIN, SACHSENDAMM 90-92
STATION LAYOUT	**TYPE:** hosted on existing forecourt, car dispenser integrated in existing dispensing area, separate dispenser area for bus filling
	H2 SUPPLY: Delivered (liquid hydrogen tanker trucks)
	DISPENSING PRESSURES: 70/35 MPa **COMPRESSOR-STORAGE-DISPENSER:** 1x Linde Cryopump
FLEET CAPACITY	**PASSENGER VEHICLES:** Up to 100 fills per day **BUSES:** Up to 10 fills per day
DESCRIPTION	The Sachsendamm station is based on the application of Linde Cryopump technology, where the hydrogen is compressed in its liquid form, and the gaseous boil-off is then delivered to a high-pressure gaseous storage buffer ready for dispensing. To fit within the constraints of the site, and limit the overall footprint dedicated to hydrogen refuelling equipment part of the Cryopump and storage tank installation is underground. The station opened in 2011 was originally developed to support a bus program.
STATUS	**OPEN to GENERAL PUBLIC**

TOTAL SCHÖNEFELD HYDROGEN REFUELLING STATION

BERLIN, GERMANY



OPERATOR	**Total GmbH**
LOCATION and CONTACTS	Elly-Beinhorn-Ring 2a, 12529 Schönefeld, Germany +49 30 609156230
STATION LAYOUT	**TYPE:** hosted on existing forecourt, integrated in existing dispensing area
	H2 SUPPLY: On-site (electrolysis)
	DISPENSING PRESSURES: 70/35 MPa **COMPRESSOR-STORAGE-DISPENSER:** 1x Linde Gas IC 90, 1x Linde Gas IC 45 **ELECTROLYSER:** McPhy/Enertrag
FLEET CAPACITY	**PASSENGER VEHICLES:** Up to 100 fills per day **BUSES:** Up to 10 fills per day
DESCRIPTION	The "Hub for green hydrogen" (H2BER) at the TOTAL multi-energy refuelling station in Schönefeld, Berlin, adjoining the new airport, was opened in May 2014. The station features green hydrogen produced from an on-site electrolyser using wind power from a nearby wind farm.
STATUS	**OPEN to GENERAL PUBLIC**

VATTENFALL HAFEN CITY HYDROGEN REFUELLING STATION

HAMBURG, GERMANY

OPERATOR	**Vattenfall/Shell**
LOCATION	Poggenmühlen-Brücke, HafenCity, Hamburg
STATION LAYOUT	**TYPE:** standalone hydrogen refuelling station
	H2 SUPPLY: On-site (electrolysis)
	DISPENSING PRESSURES: 70/35 MPa **COMPRESSOR-STORAGE-DISPENSER:** 2x Linde Gas IC 90 **ELECTROLYSER:** 2x Hydrogenics HyStat™ 60
DESCRIPTION	The Vattenfall hydrogen refuelling station is a local landmark in the historic HafenCity area of Hamburg. Built as a standalone installation alongside one of the HafenCity canal bridges with direct access from a public footpath. the station features a very small footprint and an architectural design to suit with the requirements of the heritage-listed precinct. The station opened in February 2012, has been the first installation of Linde Gas IC90 compressor technology. Designed to supply hydrogen to a fleet of buses and cars, the station features on-site production from two HyStat-60 electrolysers from Hydrogenics (with the potential for a third installation), for a combined capacity of over 100 kg of hydrogen per day. Power for the electrolysers is provided by local utility Vattenfall which operates a large portfolio of wind farms.
STATUS	**OPEN to GENERAL PUBLIC**

Japan

HySUT HANEDA HYDROGEN REFUELLING STATION

YOKOHAMA, JAPAN


OPERATOR	**Tokyo Gas**
LOCATION	Haneda Airport, Yokohama Japan
STATION LAYOUT	**TYPE:** integrated on existing CNG station, with separate H_2 dispensing area
	H2 SUPPLY: On-site (steam methane reforming)
	DISPENSING PRESSURES: 35 MPa **COMPRESSOR-STORAGE-DISPENSER:** Tokyo Gas, Haji, NItto **STEAM METHANE REFORMER:** Tokyo Gas
DESCRIPTION	The Haneda station was developed by Tokyo Gas in 2009 within the scope of the Hydrogen Supply/Utilization Technology (HySUT) programme, to support the demonstration of two shuttle buses developed by Hino for service at Tokyo Haneda airport. The station, installed at an existing CNG refuelling site, features on-site production of hydrogen from steam reforming of natural gas, CO2 from the process is separated, liquefied and stored for delivery to industrial users, mainly from the beverage industry.
STATUS	**OPEN to GENERAL PUBLIC**

SHIBA-KOEN HYDROGEN REFUELLING STATION

TOKYO, JAPAN

OPERATOR	**Iwatani Corporation**
LOCATION	Shiba-Koen, Tokyo Japan
HRS OPERATION	**TYPE:** Public
	LAYOUT: Standalone
	H2 SUPPLY: Delivered (liquid hydrogen tanker trucks)
	DISPENSING PRESSURES: 35/70 MPa **COMPRESSOR-STORAGE-DISPENSER:** Iwatani/Linde IC90
DESCRIPTION	Iwatani Hydrogen Refuelling Station in Shibakoen represents one of the best examples of integration within the urban landscape. Built on the former site of Toyota's first ever showroom in Tokyo, the station sits on a corner at the foothill of the Tokyo Tower complex. Located at a busy intersection, the station is built with adjoining residential and commercial properties, and across the road from a kindergarten. The station complex is also host to a showroom for the Toyota Mirai FCV. Hydrogen is delivered to the station in liquid form by Iwatani corporation, where its is stored on a 24,000 liters liquid hydrogen tank. Boil-off gaseous hydrogen is then compressed and stored at dispensing pressure in version of the IC90 designed by Linde in collaboration with Iwatani in order to comply with Japanese standards and regulations. According to local regulations, the dispensing area is located at a minimum set-back distance of 8 m from road entrance and general use footpaths, whereas the hydrogen storage and compression equipment complex is contained by a 6 in thick steel firewall as a mitigation measure to the reduced set-back distance from adjoining properties.

NERIMA HYDROGEN REFUELLING STATION

TOKYO, JAPAN

OPERATOR	**Tokyo Gas**
LOCATION	Nerima District, Tokyo Japan
HRS OPERATION	**TYPE:** Public
	LAYOUT: Hosted on existing CNG station, integrated in general dispensing area
	H2 SUPPLY: Delivered (compressed gaseous hydrogen cylinder bundles)
	DISPENSING PRESSURES: 35/70 MPa **COMPRESSOR-STORAGE-DISPENSER:** Tokyo Gas, Haji, Kobelco, Nitto
DESCRIPTION	The Nerima Station, located in the northern area of Tokyo was opened by Tokyo Gas in 2014. The station, located alongside an existing CNG station, dispenses hydrogen delivered to the site via hydrogen cylinder bundles.

TOYOTA-CITY ECOFUL HYDROGEN REFUELLING STATION TOYOTA-CITY, JAPAN	
	
OPERATOR	**Toho Gas**
LOCATION	Toyota-City, Japan
STATION LAYOUT	**TYPE:** standalone public
	H2 SUPPLY: On-site (steam methane reforming)
	DISPENSING PRESSURES: 35/70 MPa **COMPRESSOR-STORAGE-DISPENSER:** 1x Linde IC45, 1x Linde IC90
DESCRIPTION	The Toho-Gas hydrogen refuelling station is integrated as part of the EcoFul City demonstration site, featuring an education center, renewable energy installations and an eco-efficent demo house. The station, developed originally within the HySUT programme, was opened in 2010 to support a Hino bus demonstration trial, and is now open to the general public.
STATUS	**OPEN to GENERAL PUBLIC**

AMAGASAKI HYDROGEN REFUELLING STATION

AMAGASAKI-CITY, JAPAN

OPERATOR	**Iwatani Corporation**
LOCATION	Amagasaki-city, japan
STATION LAYOUT	**TYPE:** standalone public
	H2 SUPPLY: Delivered (liquid hydrogen tanker trucks)
	DISPENSING PRESSURES: 35/70 MPa **COMPRESSOR-STORAGE-DISPENSER:** 1x Linde IC45, 1x Linde IC90
DESCRIPTION	The Amagasaki station is located within the Iwatani Corporation R&D Centre in Amagasaki city. It is a standalone station, located on a general use footpath. Hydrogen is delivered to the station in liquid form by Iwatani corporation, where its is stored on a 24,000 l liquid hydrogen tank. Boil-off gaseous hydrogen is then compressed and stored at dispensing pressure in version of the IC90 designed by Linde in collaboration with Iwatani in order to comply with Japanese standards and regulations.
STATUS	**OPEN to GENERAL PUBLIC**

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