

# REGULATIONS, CODES, AND STANDARDS (RCS) FOR LARGE-SCALE HYDROGEN SYSTEMS

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## ABSTRACT

Hydrogen has potential applications that require larger-scale storage, use, and handling systems than currently are employed in emerging-market fuel cell applications. These potential applications include hydrogen generation and storage systems that would support electrical grid systems. There has been extensive work evaluating regulations, codes, and standards (RCS) for the emerging fuel cell market, such as the infrastructure required to support fuel cell electric vehicles. However, there has not been a similar RCS evaluation and development process for these larger systems. This paper presents an evaluation of the existing RCS in the United States for large-scale systems and identifies potential RCS gaps. This analysis considers large-scale hydrogen technologies that are currently being employed in limited use but may be more widely used as large-scale applications expand. The paper also identifies areas of potential safety research that would need to be conducted to fill the RCS gaps. U.S. codes define bulk hydrogen storage systems but do not define large-scale systems. This paper evaluates potential applications to define a large-scale hydrogen system relative to the systems employed in emerging technologies such as hydrogen fuelling stations. These large-scale systems would likely be of similar size to or larger than industrial hydrogen systems.

## NOMENCLATURE

AHJ: Authority having jurisdiction  
ASTM: American Society of Testing Materials  
ASME: American Society of Mechanical Engineers  
CGA: Compressed Gas Association  
DOT: U.S. Department of Transportation  
FCEV: Fuel cell electric vehicle  
NFPA: National Fire Protection Association  
RCS: Regulations, codes, and standards

## 1.0 INTRODUCTION

The U.S. Department of Energy has supported the development of RCS for the deployment of hydrogen infrastructure to support fuel cell electric vehicle (FCEVs) codes and standards development as well as standards that apply to vehicle refuelling and fuel quality. The focus on infrastructure RCS has been primarily on hydrogen fuelling stations, repair garages, and eliminating restrictions on FCEVs using public roadways, tunnels, bridges, and parking garages. This RCS support effort has not yet focused on large-scale production utilizing renewable energy technologies, storage, and transport [1]. This paper describes large-scale renewable hydrogen production and storage facilities, the RCS they would be potentially subject to, and RCS issues or gaps. These gaps, in turn, will point to safety research needed to develop RCS. Hydrogen is currently produced in large amounts using steam-hydrocarbon reforming. This technology produces CO<sub>2</sub> and does not provide the same benefits as producing hydrogen using wind turbines or solar panels, which do not produce CO<sub>2</sub> emissions. Fig. 1 shows how renewable technologies such as wind turbines can produce hydrogen for vehicle applications [2]. These low-carbon energy production pathways present opportunities for energy production without potential waste capture costs.

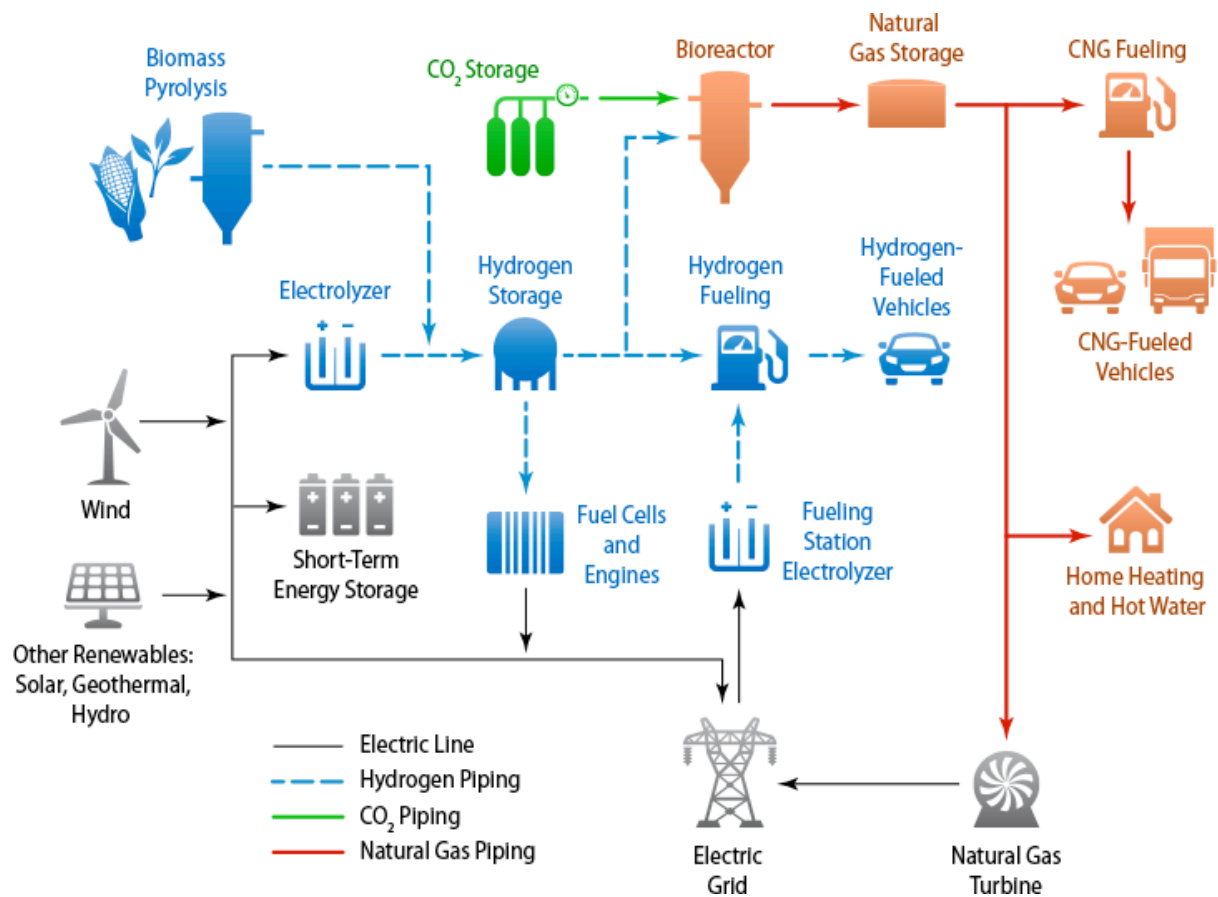


Figure 1. Renewable energy pathways

## 2.0 RENEWABLE HYDROGEN GENERATION

Hydrogen can be directly produced from such technologies as:

- Biomass gasification
- Biomass derived liquid reforming
- Natural gas reforming
- Coal gasification
- Thermochemical water splitting
- Photoelectrochemical water splitting
- Photobiological water splitting
- Microbial biomass conversion.

However, larger-scale hydrogen production using renewable electricity production technologies coupled to electrolyzers to produce hydrogen will have the incentive of potentially lower carbon emissions than steam-hydrocarbon reforming. Electricity can be produced from several renewable energy technologies including wind turbines, photovoltaic cells, and biomass. The electricity produced from these renewable technologies can then be used to produce hydrogen through electrolysis. Electrolysis is of special interest because it is a process where hydrogen is produced from electricity and water with very limited carbon usage. The electricity used to power the electrolytic hydrogen production process can come from renewable energy sources such as photovoltaic or wind electricity generation. This production can also include hydrogen produced directly from biomass. The hydrogen produced from electrolyzers is relatively pure compared to hydrogen production from natural gas, a raw chemical feedstock that may have contaminants.

Fig. 2 illustrates the process for producing hydrogen from inputs of electricity and water with outputs of hydrogen and oxygen [3]. This process can be operated at a scale that will produce substantial amounts of hydrogen. Medium-scale polymer electrolyte membrane electrolyzers can produce hydrogen at rates of up to 240  $\text{m}^3/\text{hour}$  (21.6 kg/hour). Larger-scale alkaline electrolyzers can produce hydrogen at 760  $\text{m}^3/\text{hour}$  (68.4 kg/hour) [4]. This process will produce oxygen in amounts that can potentially alter the burning characteristics of flammable and combustible materials. The oxygen production must be a part of the system design considerations. Additionally, there is the possibility for oxygen and hydrogen to form mixtures in the flammable range.

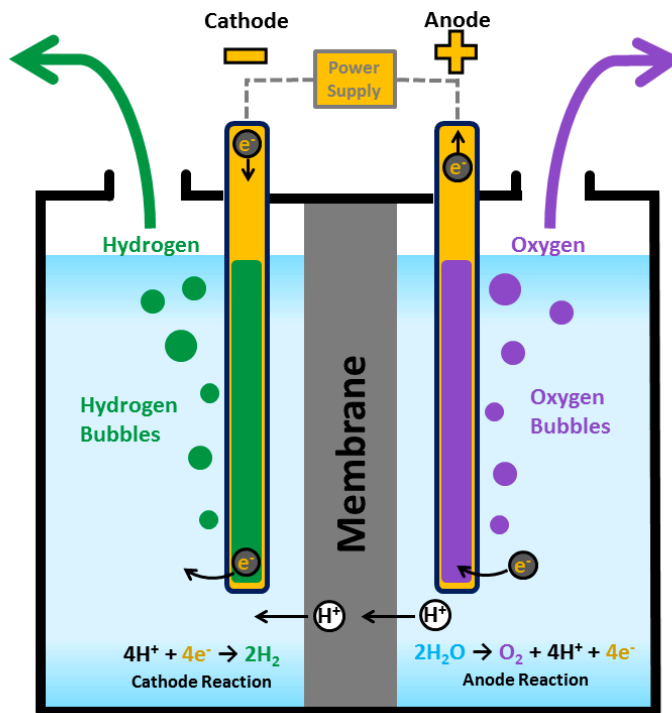
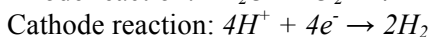
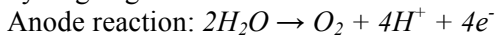


Figure 2. Electrolytic hydrogen production

In polymer electrolytic membrane hydrogen production the following steps produce hydrogen from an input at the anode of electricity and water.

- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons) ( $\text{H}^+$ ).
- The electrons flow through an external circuit and the hydrogen ions selectively move across the polymer electrolyte membrane to the cathode.
- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.



### 2.1 RCS for Large-Scale Renewable Hydrogen Generation

In the scheme described in Section 2.0, hydrogen production is accomplished through electrolysis. The electrolysis process does not result in large amounts of hydrogen in an electrolyzer device at one time. The NFPA 2 Hydrogen Technologies Code Chapter 13 sets requirements for electrolyzers. The hydrogen storage will typically present a larger risk than the hydrogen in the electrolyzer itself, although the electrolyzer will produce oxygen, which must be safely vented from the system. There is also the potential to have hydrogen/oxygen contact so that a potentially flammable atmosphere could exist. Table 1 shows representative requirements for hydrogen generation equipment in the United

States. These requirements may require modification if the number and scale of electrolyzers increases resulting in systems that present a greater risk.

Table 1. RCS for hydrogen generation

<b>RCS Document</b>	<b>Subject Matter</b>
NFPA 2 Hydrogen Technologies Code	Chapter 13 hydrogen production
NFPA 2 13.2.2 Interconnection	Requirements for connecting system to the grid
NFPA 2 13.2.4 Siting	Structural requirements, exclusion from electrical classification zone, and safe venting per Chapter 6
NFPA 2 13.3.1.2 Ventilation	Provisions for indoor venting
NFPA 2 13.3.1.5 Indoor installation	Setback distances for installations below and above the maximum allowable quantity
NFPA 70 National Electrical Code	Electrical requirements for classified areas
CGA H-5.5	Vent stack design including vent termination geometry
ASME B31 (.3 and .12)	Piping design for hydrogen piping systems including dimensions and materials
CGA S-1. 1-1.3	Pressure relief device design

### **3.0 LARGE-SCALE HYDROGEN STORAGE SYSTEMS**

Storing large quantities of hydrogen will in many locations require liquefied hydrogen in cryogenic storage systems. Gaseous hydrogen can be stored in large quantities in geologic formations [5]. Because of restrictions in the use of geologic storage and large-scale gaseous storage in general, the majority of large-scale systems will likely be liquid systems. There are two geologic storage systems in Texas but in many areas with high population density geologic storage will not be an option.

#### **3.1 Large Cryogenic Tanks**

Currently the NFPA 2 Hydrogen Technologies Code sets an upper bound for siting liquid hydrogen storage systems of (283,906 L) 75,000 gallons. Other requirements in Chapter 8 of the NFPA 2 Hydrogen Technologies Code that address bulk liquefied storage presumably would apply to any size system, so these large systems do not fall out of the regulatory applicability of the code.

However, it is likely that large hydrogen storage systems will not be treated as routine projects for permitting purposes and will be subject to a higher level of safety compliance analysis. The NFPA 2 Hydrogen Technologies Code has a chapter that sets performance-based requirements and can effectively usurp the prescriptive requirements of the code and replace them with a set of safety performance thresholds. These requirements are extremely broad and somewhat ambiguous as to what constitutes compliance. These requirements would present a large hurdle for a routine project, but an applicant might be forced to demonstrate compliance with the objectives of the code through this path for a project that represents construction far outside the norm for hydrogen storage systems. Section 5.0 summarizes key requirements of the performance-based compliance requirements.

#### **3.2 Geological Formations**

Hydrogen has been successfully stored in geologic formations in two locations in Texas. These installations are large salt caverns and the hydrogen is used to support petrochemical production. Hydrogen storage in geologic formations presents several problems for emerging hydrogen technologies, particularly for applications such as FCEVs that require high-purity hydrogen.

These problems include:

- Locating a suitable geologic formation proximate to the point of generation
- Hydrogen leakage through openings in the geologic structure
- Hydrogen reactivity that could produce undesirable reaction products including toxic materials
- Hydrogen storage material degradation and failure.

The difficulty in retaining hydrogen in other types of storage systems would be manifested in geologic formations. Hydrogen’s small molecule size would contribute to hydrogen leakage. Hydrogen would react with materials in the formation, such as sulphur compounds, to form contaminants and potential health hazards. Hydrogen attacks metals by migrating into pockets in the metal structure and then exerting pressure on the metal structure. The most vulnerable metals are high-strength steels, titanium alloys, and aluminium alloys [6].

However, there are remedies to these problems and the viability of a geologic storage structure would be based on determining the value of the hydrogen versus the cost of providing the hydrogen in the form required for the desired applications.

#### 4.0 RCS HYDROGEN TRANSPORT: PIPELINES, RAIL, AND HIGHWAY

Table 2 shows the basic RCS structure for pipeline, rail, and highway transport of hydrogen in the United States [7].

Table 2. RCS for hydrogen transport

<b>Transport Method</b>	<b>RCS Document</b>
Hydrogen pipelines – hydrogen is covered under the scope of this part of the U.S. Department of Transportation (DOT) regulations as a flammable gas	DOT 49 CFR Part 192 Subparts A–P cover: Materials Pipe design Welding, joining, and corrosion control Test requirements Operations, maintenance, and qualification of personnel Integrity management
Tanker truck	DOT 49 CFR Part 172 (provisions T75 and TP5)
Rail transport	DOT 49 CFR Part 174

#### 5.0 EXAMPLE INSTALLATION: PERFORMANCE BASED APPROACH TO LARGE-SCALE PRODUCTION AND STORAGE INSTALLATION

The basic parameters for an example large-scale system are as follows:

- Wind turbines capable of generating megawatts of power
- Electrolyzers capable of producing (combined with liquefaction plant) 5,360 kg/day (20,000 gallons/day)
- Storage system capable of holding 26,800 kg (100,000 gallons) of liquid hydrogen
- Transport capable of moving 5,360 kg/day (20,000 gallons/day)

Table 3 shows key requirements for a performance-based approach to approval for a large-scale system.

Table 3. Performance-based code design

<b>NFPA 2 Requirement</b>	<b>Application to Large-Scale Liquid Hydrogen Storage System</b>
5.1.2 Goals and Objectives. The performance-based design shall meet the goals and objectives of this Code in accordance with Section 4.3.	A large-scale system would exceed the 75,000-gallon liquid storage limit for NFPA 2 and would lie beyond the basic storage applicability.
5.1.4 Plan Submittal Documentation. When a performance-based design is submitted to the authority having jurisdiction (AHJ) for review and approval, the owner shall document, in an approved format, each performance objective and applicable scenario, including any calculation methods or models used in establishing the proposed design’s fire and life safety performance.	The focus of the performance objectives would be on establishing that a large-scale system could be safely designed, built, and operated and present a comparable level of risk to a system within the prescribed code boundaries.
5.1.6 Sources of Data. Data sources shall be identified and documented for each input data requirement that is required to be met using a source other than a required design scenario, an assumption, or a facility design specification.	Data should be from large-scale bulk liquefied hydrogen storage systems. The applicant will likely need data on both intended and unintended releases of hydrogen as well as data on the fate of these releases.
5.1.8 Operations and Maintenance Manual. An approved Operations and Maintenance (O&M) Manual shall be provided by the owner to the AHJ and the fire department [for review] and shall be maintained at the facility in an approved location.	The manual should address preventive maintenance to reduce the frequency of release as well as the impacts of planned releases.
5.1.11 Annual Certification. Where a performance-based design is approved and used, the property owner shall annually certify that the design features and systems have been maintained in accordance with the approved original performance base design and assumptions and any subsequent approved changes or modifications to the original performance-based design.	Annual certification can potentially be met through existing testing requirements in the prescriptive code text.
5.4.3.1 Explosion Design Scenario 1— Hydrogen Pressure Vessel Burst Scenario 5.4.3.2 Explosion Design Scenario 2— Hydrogen Deflagration 5.4.3.3 Explosion Design Scenario 3— Hydrogen Detonation 5.4.4 Hazardous Materials Design Scenarios 1–4	<p>The explosion impact scenarios would have to factor in the frequency of events to develop a risk for each scenario. A design scenario based solely on the impact of an explosion without taking into account the frequency (part of the risk analysis) would likely produce boundary values that would make the system difficult to site except in remote locations.</p> <p>The hazardous material design scenarios involve analysing releases under various upset conditions. These scenarios involve both accidental and intentional or malicious releases. Once again, it would be beneficial to evaluate the frequency of these events when calculating risk presented. The code requirement is for calculating impact of a release.</p>

<b>NFPA 2 Requirement</b>	<b>Application to Large-Scale Liquid Hydrogen Storage System</b>
5.4.5.1* Building use design scenario 1. 5.4.5.2 Building use design scenario 2.	These design scenarios involve an event during maximum occupant load and during construction or demolition. Because a storage system is not an occupancy these would not typically apply. A storage system may have associated buildings that would have occupancy issues and these might be considered under these scenarios.
5.5.3.1.1 Input data for computer fire models shall be obtained in accordance with ASTM E1591, standard guide for data for fire models.	This guide is intended primarily for users and developers of mathematical fire growth models. It is also useful for people conducting fire tests, making them aware of some important applications and uses for small-scale fire test results. The guide contributes to increased accuracy in fire growth model calculations, which depend greatly on the quality of the input and matching the input demands to the model.
5.5.3.2 Data Requirements. A complete listing of input data requirements for all models, engineering methods, and other calculation or verification methods required or proposed as part of the performance-based design shall be provided.	A tabular presentation of this information will make it easy for the AHJ to verify that all required data have been provided.
5.6* Safety Factors. Approved safety factors shall be included in the design methods and calculations to reflect uncertainty in the assumptions, data, and other factors associated with the performance-based design.	Safety factors should be based on factors assigned to similar installations.
5.7.1.1 All aspects of the design, including those described in 5.7.2 through 5.7.14, shall be documented.	The clearer the documentation the easier for the AHJ to review. All supplied documentation should identify what requirements it supports.
5.7.11.1 Assumptions made by the model user, and descriptions of models and methods used, including known limitations, shall be documented.	Assumptions should be presented in a context to allow the AHJ determine whether the assumption is conservative and consistent with industry practice.
5.7.10 Prescriptive Requirements. Retained prescriptive requirements shall be documented.	This is an important requirement because it gives the applicant the flexibility to use existing prescriptive requirements where they can clearly show compliance. This option can significantly reduce the performance compliance burden and focus the performance compliance on the more critical aspects of the project.

## 6.0 CONCLUSION

Many of the RCS that would allow the deployment of large-scale hydrogen production and storage systems are in place. There are potential RCS gaps that have become apparent when reviewing existing RCS. These RCS gaps include:

- More comprehensive requirements for below-grade hydrogen storage for both bulk liquefied and bulk gaseous systems

- A comprehensive risk analysis for electrolyzers accounting for the scale required to support the H2@Scale projects
- A proven methodology to using performance-based approvals for large hydrogen storage systems
- Successful demonstration of hydrogen transport in existing pipelines used for other gases in compliance with U.S. DOT regulations.

Current requirements for below-grade storage found in NFPA codes and CGA standards provide very limited safety requirements and do not address many areas including equipment access, electrical classifications, setback distances for venting systems, maintenance schedules, and delivery/tank filling procedures. NFPA codes currently allow for liquid storage systems of up to 75,000 gallons (283,906 L). Systems larger than 75,000 gallons (283,906 L), and likely large systems close to 75,000-gallon (283,906 L) volume, will require a performance-based compliance approach. The performance-based compliance methodology in the NFPA 2 Hydrogen Technologies Code has not been demonstrated in field applications. Large gaseous systems employing storage in geologic formations also would likely require a performance-based code compliance approach. This lack of defined precedent likely will result in a lengthy review and approval process for the initial performance-based installation.

The DOT Pipeline and Hazardous Materials Administration has regulations that address flammable gas pipelines that would include hydrogen. Hydrogen pipelines exist for hydrogen usage in industrial operations (see reference below). [7} However, a widespread system of hydrogen pipelines does not exist and there is not a well-defined compliance path for hydrogen usage.

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