



# MODULE 2: TECHNOLOGIES FOR HYDROGEN STORAGE AND TRANSPORTATION

## MINI LECTURE: HYDROGEN STORAGE AND TRANSPORTATION TECHNOLOGIES - INTRODUCTION

**Module 2** of the training emphasizes hydrogen storage and transportation technologies. Following an exploration of the fundamental significance of hydrogen as an energy carrier and its contribution to decarbonization, we will now examine the essential engineering and logistical elements that dictate its practical application on an industrial scale. Efficient and secure hydrogen storage and transportation are critical factors that affect its competitiveness and broader adoption within the economy.

The objective of this module is to deliver a thorough understanding of the various hydrogen storage technologies and transportation methods, considering both technical engineering aspects and rigorous safety standards. Grasping these concepts is essential for any logistics professional tasked with designing, planning, and optimizing hydrogen supply chains in the future. We will examine the distinctions in the characteristics of individual solutions, identify the related operational and technical challenges, and explore how to design systems that are both economically viable and compliant with the highest safety standards.

Hydrogen, the lightest chemical element, possesses a molar mass of approximately 2.01588 g/mol and is distinguished by its exceptionally low volumetric energy density under ambient conditions. This intrinsic characteristic presents a significant challenge regarding its storage and transportation. Consequently, the implementation of advanced technologies and meticulously developed protocols is essential to ensure both the efficient storage of substantial energy quantities in a confined space and the safe transportation on a large scale. Our focus during the next eight hours will be on these specific scientific and technical considerations.

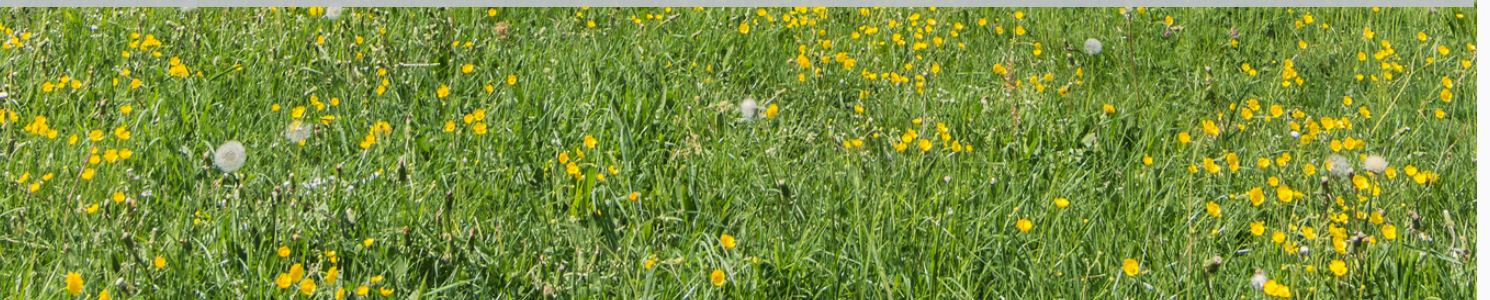
## Compressed and Liquid Hydrogen – Technological Assessment

The initial, comprehensive segment of the module will focus on the two fundamental and presently most advanced hydrogen storage technologies: Compressed Gaseous Hydrogen (CGH<sub>2</sub>) and Liquid Hydrogen (LH<sub>2</sub>). Each solution is defined by unique physicochemical and operational characteristics, leading to varied applications and differing cost and risk profiles.

Compressed hydrogen storage entails a substantial enhancement of its bulk density through the application of high pressure. Standard storage pressures, especially in both mobile and stationary applications, typically range from 350 to 700 bar (35 to 70 MPa), although systems designed to function at pressures surpassing 1,000 bar are available. A fundamental element of this technology is pressure vessels, which are categorized based on their design and materials into four primary types:

- **Type I:** All-metal tanks (e.g., steel) are distinguished by their substantial weight and economical pricing.
- **Type II:** A metal insert (liner) externally reinforced with a composite wrapping (e.g., glass or carbon fiber) in the cylindrical section.
- **Type III:** A metal insert, typically aluminum, fully encased in carbon fiber, providing substantial weight reduction.
- **Type IV:** A polymer liner entirely encased in carbon fiber, exemplifying the lightest and most contemporary design, though at the highest expense.

The hydrogen compression process necessitates the utilization of specialized compressors, which represent a considerable source of energy consumption across the supply chain, thereby directly influencing operating costs. We will examine the operational principles and energy efficiency of various compressor types.



An alternative and complementary method involves the storage of hydrogen in its liquid form (LH2). Hydrogen attains its liquid state at extremely low temperatures, below  $-253^{\circ}\text{C}$  (approximately 20 K), nearing absolute zero. The liquefaction process, known as cryogenics, is highly energy-intensive, consuming 30% to 40% of the energy contained in the hydrogen, which presents a considerable economic challenge. Nevertheless, liquid hydrogen boasts a significantly higher volumetric energy density (approximately  $10.1 \text{ MJ}/\text{dm}^3$ , corresponding to a physical density of about  $71 \text{ kg}/\text{m}^3$ ) compared to compressed hydrogen, which at pressures up to 700 bar has a volumetric density of approximately  $4.1 \text{ MJ}/\text{dm}^3$  ( $41 \text{ kg}/\text{m}^3$ ), and at pressures up to 350 bar, approximately  $2.3 \text{ MJ}/\text{dm}^3$  ( $23 \text{ kg}/\text{m}^3$ ). This characteristic enables the storage of larger quantities of energy within a confined space.

LH2 is stored in specialized cryogenic tanks (Dewars) designed to offer superior thermal insulation, typically achieved through vacuum and multi-layer superinsulation. Despite these advanced insulation techniques, slow hydrogen evaporation resulting from heat transfer from the surrounding environment is unavoidable, a phenomenon referred to as boil-off. Effectively managing this occurrence, including the recovery or safe release of hydrogen gas, is essential for the safety and economic efficiency of LH2 storage and transportation.

From a logistics standpoint, it is essential to comprehend the costs, safety considerations, and risks associated with both technologies. We will evaluate the capital and operational cost structure, factoring in equipment, infrastructure, and energy consumption. Regarding safety, we will examine the risks related to high pressure (for CGH2) and extremely low temperatures, as well as the flammability of hydrogen (for both forms, with particular emphasis on the boil-off phenomenon for LH2). Hydrogen, being a colorless and odorless gas, necessitates sophisticated leak detection systems, and its extensive flammability range (from 4% to 75% by volume in air) and low ignition energy (0.017–0.02 mJ) impose considerable demands on leak prevention and management.

## Hydrogen Storage: An Analysis and Design of Systems

Upon gaining a comprehensive understanding of the fundamentals of the technology, we will progress to the practical dimensions of analyzing and designing hydrogen storage systems. This segment of the module will consist of intensive exercises and a mini-workshop, focused on cultivating practical application skills.

A crucial aspect will be the capacity to select suitable tank types (Type I-IV) according to the specific application. We will examine scenarios such as hydrogen storage at vehicle refueling stations, within large industrial facilities (e.g., refineries or ammonia production), or as energy storage for intermittent renewable sources (e.g., wind or photovoltaic). Each of these scenarios presents distinct requirements concerning capacity, filling and emptying rates, available space, and budget, which will serve as the foundation for case studies and collaborative identification of optimal solutions.

The conclusion of this section will involve the independent design of a storage system for a chosen application. Collaborating in groups, you will be responsible for creating a conceptual design that considers not only the technical specifications of the tanks but also their integration with existing infrastructure, safety requirements (such as explosion-hazard zones, ventilation, and detection systems), location factors, and a preliminary assessment of capital and operating costs. This exercise aims to replicate the real-world design challenges that logistics professionals may encounter in the future.

## Hydrogen Transportation – Details and Protocols

Storage is intrinsically connected to transportation. In this section of the module, we will concentrate on hydrogen transportation through primary modes: road, rail, and sea. We will examine the particulars of each mode in relation to hydrogen's physicochemical properties.

The specific characteristics and technical challenges associated with transport. Hydrogen transport, irrespective of the selected method and state of matter, poses logistics with several distinct technical challenges.

**We will elaborate on these in detail:**

- Design specifications for specialized pressure tankers (tube trailers) for CGH2 and cryogenic tankers for LH2. Pressure tankers are engineered to endure elevated pressures, whereas cryogenic tankers must offer superior thermal insulation to reduce boil-off losses.
- The influence of the tare weight of transport equipment on payload and economic efficiency is significant. High-pressure and cryogenic tanks are intrinsically heavy, thereby constraining the effective mass of hydrogen that can be transported.
- Managing the boil-off phenomenon in LH2 transport involves strategies to minimize losses and ensure the safe release of gas.
- Material compatibility challenges for pipelines and fittings with hydrogen. Hydrogen can induce hydrogen embrittlement (HEM) in certain materials, necessitating the use of specialized alloys and protective coatings.
- The necessity of employing advanced leak detection and ventilation systems in confined spaces arises from the colorless, odorless, and flammable characteristics of hydrogen.

Operating Procedures and International Standards. The transport of hydrogen, characterized by its safety and efficiency, is governed by a range of international standards and regulations. We will examine the operating procedures for each mode of transport in detail, with a particular focus on the following regulations:

- **ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road):** A European accord addressing the international transport of hazardous materials by road. This discussion will encompass the classification of hydrogen (UN 1049 for compressed, UN 1966 for liquid, Class 2), the specifications for the construction and approval of tank vehicles, labeling, transport documentation (such as ADR vehicle approval certificates and written instructions), and the training requirements for drivers and other participants in the transport process.
- **RID (Regulations concerning the International Carriage of Dangerous Goods by Rail):** Regulations governing the International Transport of Hazardous Materials by Rail. We will outline analogous guidelines for the transportation of hydrogen by rail, with a specific focus on the stipulations for tank wagons and containers.
- **IMDG Code (International Maritime Dangerous Goods Code):** The International Maritime Dangerous Goods Code. We will explore the particulars of hydrogen transportation by sea, including the regulations for vessels transporting liquefied

gases and for tank containers (MEGC – Multiple Element Gas) and cryogenic vessels.

Comprehending and rigorously following these standards is essential for any logistician tasked with planning and managing the international transportation of hydrogen.

## Logistics System Architecture

The final, yet essential, component of the module is an intensive simulation workshop where we will develop a comprehensive hydrogen logistics system. This will serve as the culmination of the knowledge gained throughout the module and provide an opportunity to apply it in practical, realistic scenarios.

In groups, you will encounter specific logistics scenarios—such as the requirement to transport a designated quantity of hydrogen to a newly established refueling station in a remote area, supply energy to a large factory manufacturing green steel, or manage a fleet of heavy-duty hydrogen-powered vehicles along a specified route. Your objective will be to determine the most effective transportation method (or a combination of methods, such as road and rail) and suitable storage technologies, considering all essential factors:

- **Cost analysis:** comprehensive calculations of the capital and operational expenses associated with various transportation and storage alternatives, encompassing fuel expenditures, equipment depreciation, labor costs, insurance, and safety expenses.
- **Risk assessment** involves the identification and evaluation of the operational and technical risks linked to each transportation option, along with the formulation of strategies to mitigate and manage these risks during emergency situations.
- **Efficiency assessment:** an evaluation of the effectiveness of individual solutions concerning delivery time, throughput, supply chain reliability, and the optimization of resource utilization (e.g., vehicle fleet, warehouse capacity).

You will be expected to conduct accurate calculations and prepare professional group presentations in which you will articulate and justify your logistics system proposals. This exercise is designed not only to apply your knowledge in practice but also to cultivate analytical, decision-making, and presentation skills, which are essential in the field of logistics.

Module 2 will provide you with the essential scientific and practical skills required to proficiently design and manage hydrogen supply chains within the swiftly evolving hydrogen economy. Prepare for an intensive and fulfilling learning experience!

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