

MODULE 2

HYDROGEN STORAGE AND TRANSPORTATION TECHNOLOGIES

KEY COMPONENTS OF THE HYDROGEN ECONOMY



Objective: Comprehending Technology and Its Challenges

- ✓ Comparison of hydrogen storage technologies: compressed versus liquid.
- ✓ Discussion of tank classifications and procedures (compression, liquefaction).
- ✓ Analysis of security and cost-related challenges.
- ✓ Overview of hydrogen transportation methods (road, rail, sea).
- ✓ Comprehending the intricacies and technical obstacles of transportation.
- ✓ Key elements of developing an efficient logistics system



Hydrogen Storage Methods

Hydrogen: Gas or Liquid?

Hydrogen in its gaseous form (H₂)

requires compression to enhance energy density.



Liquid hydrogen (LH₂)

requires condensation at extremely low temperatures.

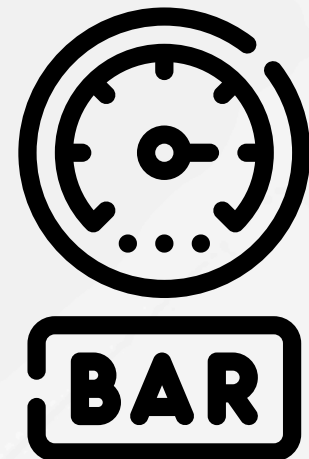


Both forms possess distinct advantages and disadvantages, which impact the selection of storage and transportation technology.

Compressed Hydrogen (CGH₂) – Properties

Hypertension

200–700 bar



Characteristics: Hydrogen is stored at high pressure (200–700 bar) in specialized tanks.



Advantages: The technology is relatively straightforward, initial costs are lower than those of LH₂, and there are no short-term evaporation losses (boil-off).



Disadvantages: Limited volumetric energy density (necessitates large tanks), elevated energy consumption for compression.

Liquid Hydrogen (LH2) – Properties

Extremely Low Temperatures

the **-253 Celsius**



Characteristics: Hydrogen is liquefied at a temperature of -253°C and stored in cryogenic tanks.



Advantages: Considerably greater volumetric energy density compared to CGH2, allowing for smaller tanks to store equivalent energy.

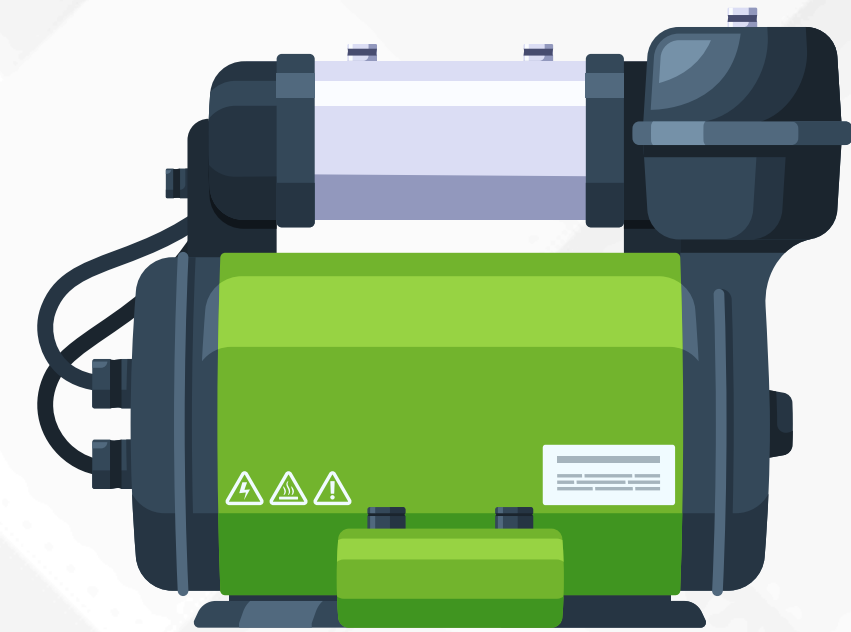


Disadvantages: Extremely high energy consumption for liquefaction, significant costs associated with cryogenic tanks, and ongoing evaporation losses (boil-off).

Hydrogen Compression Procedure

From Low to High Pressure

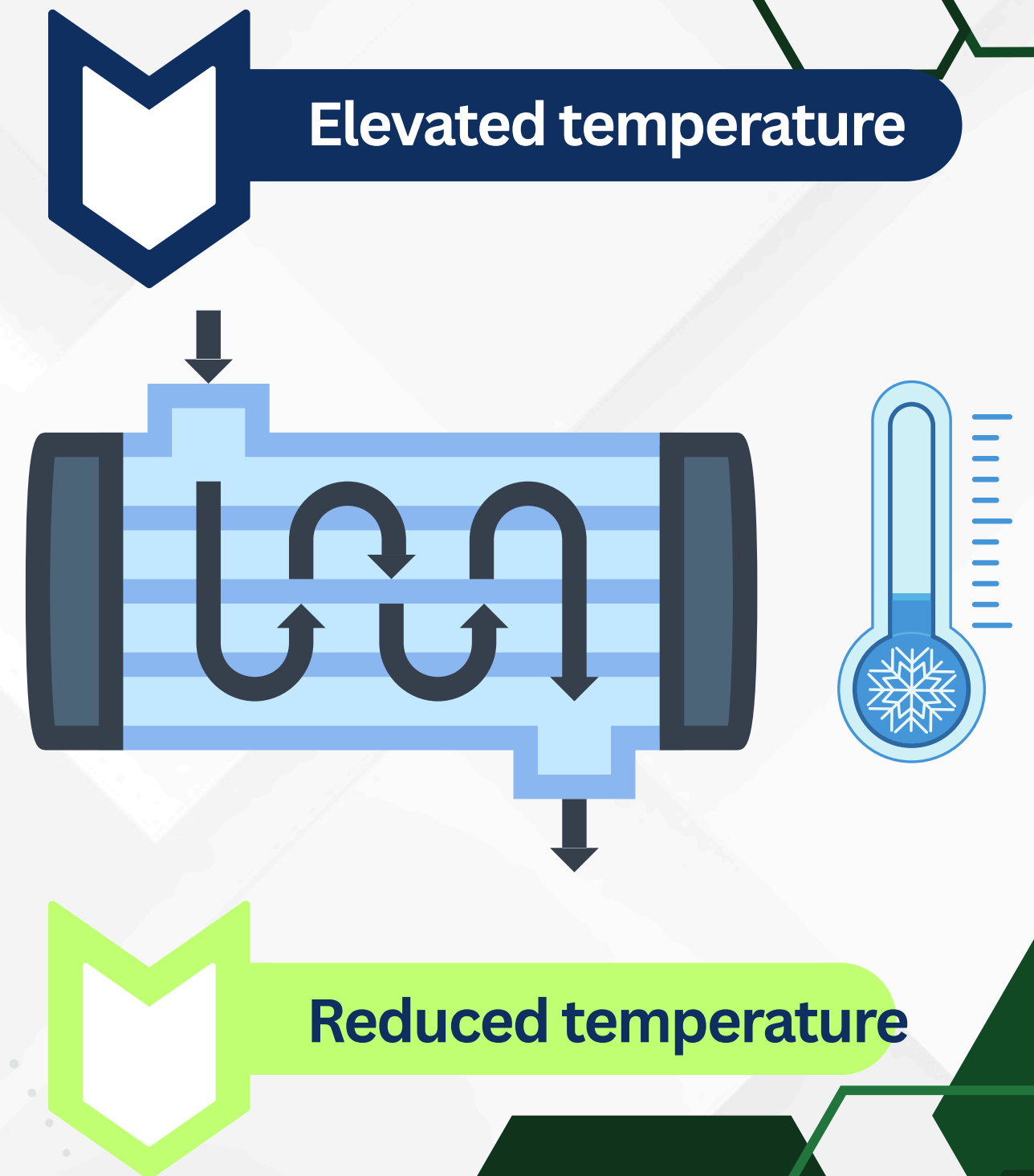
- ✓ **Compressors:** Instruments that elevate the pressure of hydrogen gas.
- ✓ **Compressor classifications:** Piston, diaphragm, ionic, electrochemical.
- ✓ **Challenges:** Elevated energy consumption, heat production, requirement for cooling, potential for high-pressure leaks.
- ✓ **Costs:** A substantial portion of overall logistics expenses.



Hydrogen Liquefaction Procedure

Cryogenic Challenge

- ✓ **Objective:** Reduce the temperature of hydrogen gas to -253°C .
- ✓ **Methods:** Refrigeration cycles (e.g., Linde-Hampson, Claude) utilizing gas expansion.
- ✓ **Challenges:** Significantly elevated energy consumption (approximately 30% of the energy contained in hydrogen), technological intricacy, and substantial capital and operational expenditures.
- ✓ **Costs:** The most costly phase in the entire LH2 supply chain.



Types of Pressure Vessels (I-IV)

Technology Evolution (Types I-IV)

TYPE I

All-metal (steel, aluminum). Heaviest, most economical, lowest pressure.

TYPE II

Metal liner encased in glass or carbon fiber along the cylindrical section. Reduced weight, increased pressure capacity.

TYPE III

Metal liner (aluminum) encased in complete carbon fiber. Considerably lighter, high pressure (350–700 bar).

TYPE IV

A polymer liner fully encased in carbon fiber. The lightest and capable of withstanding the highest pressure (700 bar). The most costly option.



Hydrogen Storage and Transportation Expenses

Costs: A Crucial Consideration in Technology Selection

- ✓ **Compression and liquefaction** costs represent the primary expense associated with the preparation of hydrogen for storage and transportation.
- ✓ **Tank costs** vary based on type, pressure, and capacity, with Type IV being the most costly.
- ✓ **Operating expenses:** Energy usage, upkeep, losses (boil-off).
- ✓ **Transport expenses:** Fuel, vehicle depreciation, charges.
- ✓ **Comparison:** LH2 incurs greater liquefaction expenses but benefits from reduced long-distance transportation costs due to its density.



Safety and Risk: Vaporization and Leaks

Boil-off and Spillage

Boil-off (for LH2)

Continuous and inevitable evaporation of liquid hydrogen resulting from heat transfer necessitates management strategies, such as reliquefaction and utilization of the evaporated gas.

Leaks

Risk of leaks in tanks, pipelines, and valves.



Threats

Formation of explosive mixtures, fires (invisible flames), cryogenic burns (liquid hydrogen).

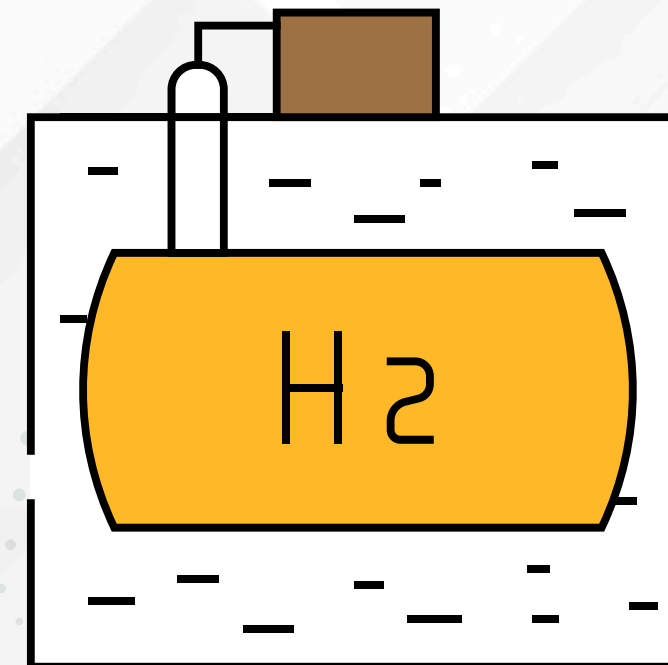
Remedies

Hydrogen detection systems, ventilation mechanisms, emergency shutdown controls, stringent protocols.

Hydrogen Storage – An Overview

Diverse Solutions

- ✓ **Storage** plays a crucial role in stabilizing the hydrogen supply chain.
- ✓ **The selection of technology** is contingent upon scale, duration of storage, and application.
- ✓ **In addition to tanks**, alternative methods are being developed.



Selection of Tanks for Applications

Selection Criteria

Application

Vehicles (Type III/IV), refueling stations (Type I/II/III), industrial warehouses (Type I, LH2 tanks), strategic storage facilities (underground).



Costs



Investment and operations.



Mass and capacity

Especially significant in transportation.

Capacity and pressure

From compact tanks in automobiles to massive industrial tanks.



Security

Adherence to standards and regulations.

Storage System Design – Small-Scale

Small-Scale (e.g., Refueling Station)

- ✓ **Objective:** Guaranteeing an uninterrupted supply of hydrogen to vehicles.
- ✓ **Components:** Pressure vessels (e.g., Types I, II, III), compressors, cooling systems, dispensers, hydrogen detectors, fire safety systems.
- ✓ **Challenges:** Restricted environments, elevated pressures, public safety.
- ✓ **Norms:** ISO 19880 (serial).



Storage System Design – Large-Scale

Large-Scale (e.g., Industrial Warehouse)

- ✓ **Objective:** Delivering substantial quantities of hydrogen for industrial or energy applications.
- ✓ **Components:** Large pressure vessels (Type I), cryogenic tanks (LH2), salt caverns, transfer systems (pipelines), and advanced safety systems.
- ✓ **Challenges:** Scale, expenses, integration with current infrastructure, environmental consequences.
- ✓ **Standards:** Seveso III Directive.



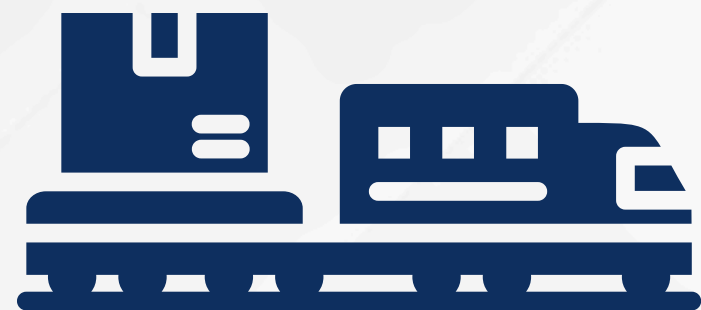
Hydrogen Transport – Assessment of Strategies

Aligning Production with Demand

Transport serves as a crucial link in the supply chain, bridging production sites with consumption locations.



The selection of transportation methods is contingent upon distance, volume, hydrogen form, and safety considerations.



Hydrogen Road Transport

Flexibility and Constraints

- ✓ **Means:** Tankers for compressed hydrogen (CGH2) or liquid hydrogen (LH2).
- ✓ **Advantages:** Flexibility, potential for door-to-door delivery, optimal for short to medium distances.
- ✓ **Disadvantages:** Restricted capacity (particularly CGH2), elevated transportation costs over extended distances, potential for road accidents.
- ✓ **Norms:** ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road).



Hydrogen-Powered Rail Transportation

Substantial Quantities for Extended Distances



Means: Specialized tank cars for CGH2 or LH2.



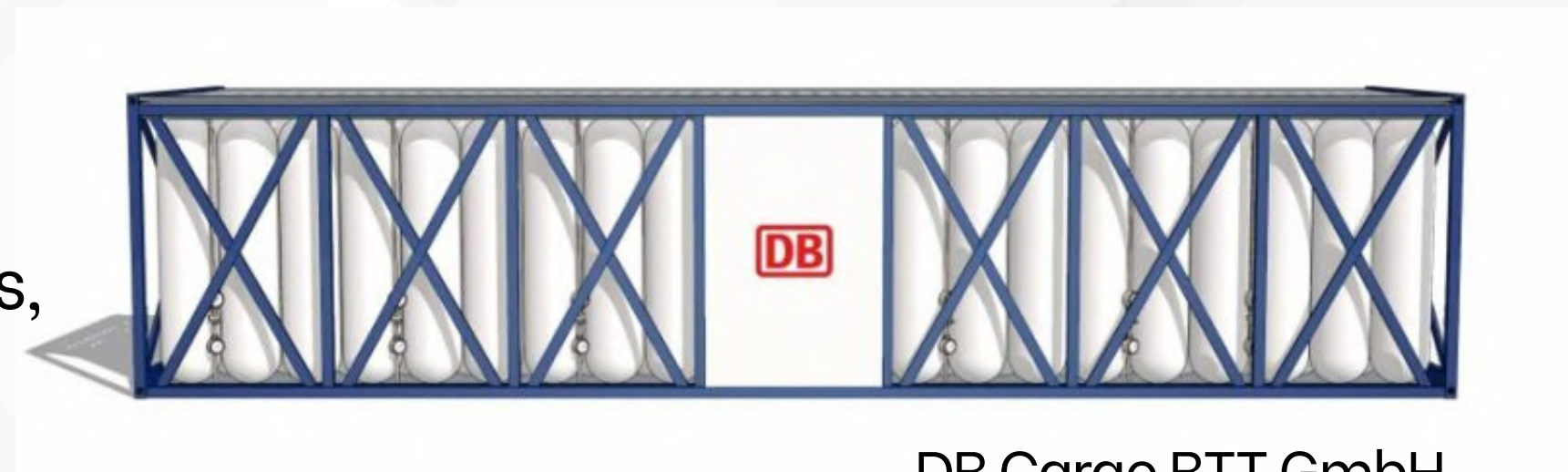
Advantages: Greater capacity compared to road transport, reduced costs over extended distances, and a diminished risk of accidents per kilometer.



Disadvantages: Restricted flexibility (necessitates railway infrastructure), requirement for reloading at the “last mile.”



Norms: RID (Regulations on the International Transport of Dangerous Goods by Rail).



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Hydrogen in Maritime Transport

Global Connections

- ✓ **Means:** Vessels for the transportation of LH2 or hydrogen carriers (e.g., ammonia, LOHC).
- ✓ **Advantages:** Largest capacities, optimal for international and intercontinental transportation.
- ✓ **Disadvantages:** Elevated expenses associated with port infrastructure, extended transportation durations, and the intricacy of transshipment procedures.
- ✓ **Normy:** IMDG Code (International Maritime Dangerous Goods Code).



The Suiso Frontier



Hydrogen Pipeline Transportation

The Foundation of the Hydrogen Network

- ✓ **Measures:** Specialized hydrogen pipelines or modified natural gas pipelines.
- ✓ **Advantages:** Highly effective and cost-efficient for substantial volumes and permanent connections, minimal operating expenses, and a superior level of security.
- ✓ **Disadvantages:** Elevated initial construction expenses, limited routing flexibility, and challenges associated with hydrogen embrittlement (for existing pipelines).

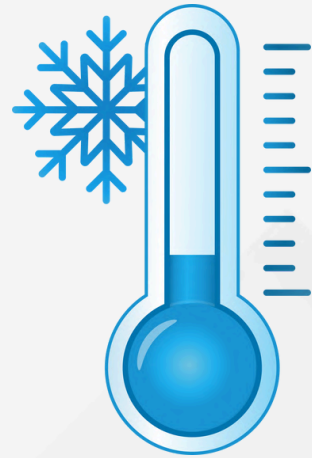


Technical Challenges in Hydrogen Transportation

Safety and Efficiency

High pressure/low temperature

They necessitate specialized materials and construction techniques.



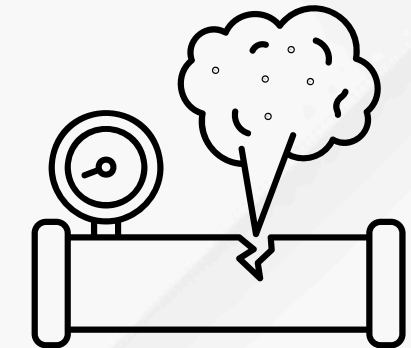
Hydrogen embrittlement

Degradation of materials due to hydrogen exposure



Tightness

Essential for safety and loss reduction.



Mass and capacity

Limitations on road and rail transportation.



Maintaining cleanliness

Ensuring the necessary hydrogen purity across the entire chain.

Operational Protocols and Transportation Standards

Secure Transit

Loading and unloading procedures

Stringent safety regulations, pressure and temperature management, ventilation

Employee development

Compulsory training for drivers, operators, and handling personnel (ADR, IMDG).



Marking and documentation

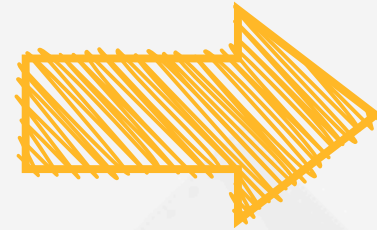
Accurate labeling, safety data sheets, and shipping documentation.

Standards

ADR (road transport), RID (rail transport), IMDG Code (maritime transport) – comprehensive regulations for hazardous materials.

Designing a Hydrogen Logistics Framework From Concept to Execution

Needs analysis: Identification of volume, production and consumption sites, and quality specifications.



Technology Selection: Optimal Selection of Hydrogen Form (CGH2/LH2/Carriers) and modes of transportation.

Risk analysis: Evaluating potential threats and formulating contingency plans.



Modeling and simulation: Employing tools to enhance networks, routes, and warehouse locations.



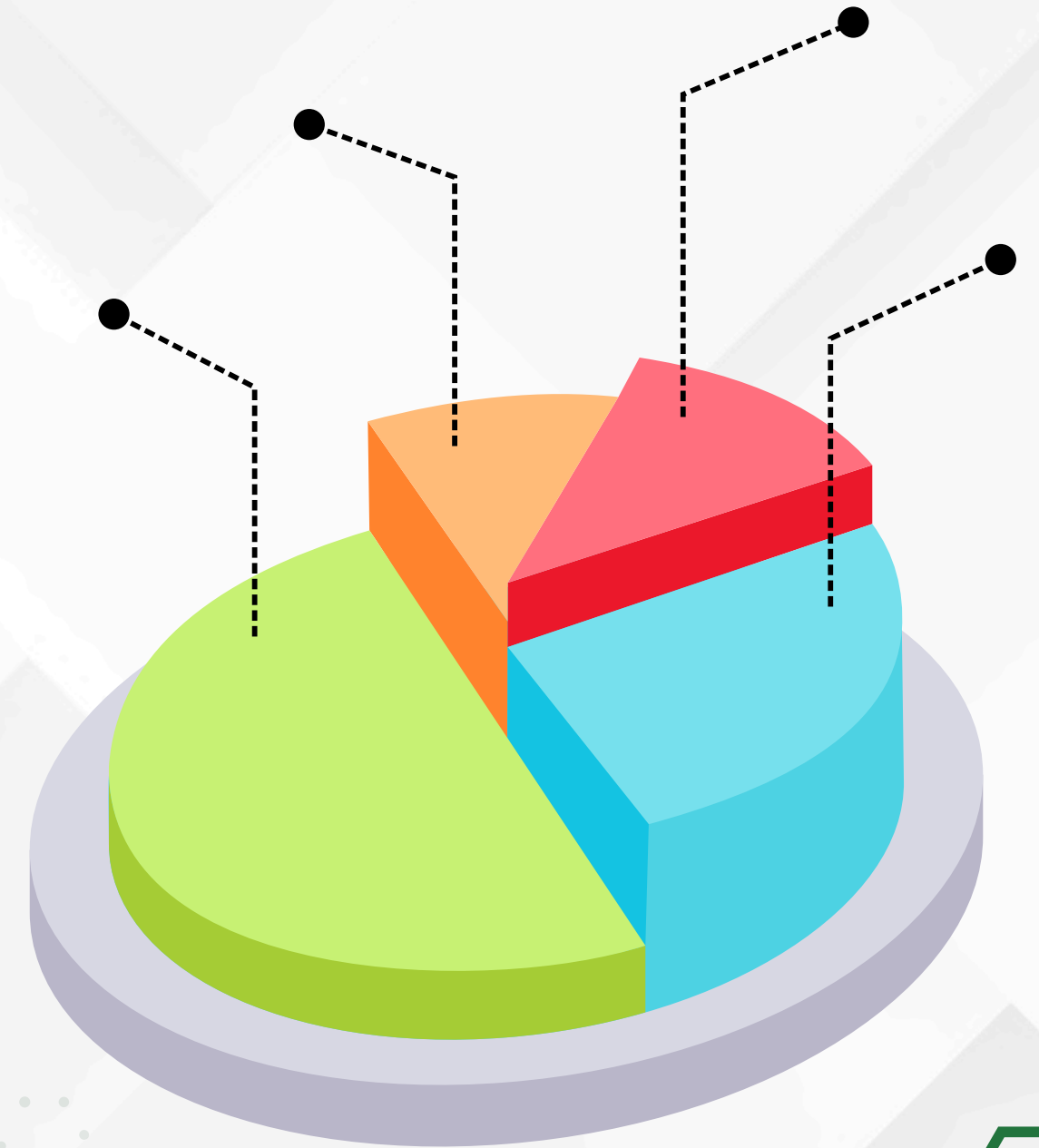
Regulatory considerations: Ensuring adherence to relevant regulations and standards.



Cost, Risk, and Efficiency in Design

Key Design Considerations

- ✓ **Costs:** Reducing total life cycle costs (LCC) – CAPEX (capital expenditure) and OPEX (operational expenditure).
- ✓ **Risk:** Identification, assessment, and management of risks (technical, operational, security, and regulatory).
- ✓ **Efficiency:** Optimization of processes, reduction of losses (boil-off, leaks), and maximization of resource utilization.
- ✓ **Sustainability:** Considering environmental and social dimensions.



Summary of Principal Messages

The Future of Hydrogen Transportation

The selection of storage technology (CGH2 versus LH2) involves a trade-off among density, cost, and complexity.

Different modes of transportation (road, rail, maritime, pipelines) possess distinct applications.

Safety and adherence to standards (ADR, IMDG) are of utmost importance.

The advancement of technology and infrastructure is essential for expanding the hydrogen economy.

Effective logistics system design necessitates a thorough analysis of costs and risks, alongside the optimization of processes.

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