

Hy-EDU

Towards Sustainable Hydrogen Education and Skills

Marcin Lutyński
Silesian University of Technology , Gliwice, Poland



Silesian University
of Technology

Why do we need Hy-EDU project?

Project purpose

Integrate sustainable large-scale hydrogen transport and storage into engineering programmes as part of Europe's climate-neutral hydrogen strategy.

Today's focus

Show how the course is structured, what content is ready, and what still needs to move onto the platform.



WHAT IS HY-EDU?

Integrating sustainable large-scale Hydrogen Transport & Storage into engineering programmes as an element of hydrogen strategy for a climate-neutral Europe

A European education project preparing the hydrogen engineers Europe will need in the coming years

PROJECT PURPOSE

Integrate H₂ transport and storage knowledge into engineering education through modern, reusable course materials

EU

HYDROGEN STRATEGY

skills for a climate-neutral Europe

EDU

ENGINEERING PROGRAMMES

course content for universities

H₂

TRANSPORT & STORAGE

pipelines, carriers, UHS and safety

CC

OPEN LEARNING

MOOC, e-platform and resources

NOT A SINGLE LECTURE - A MODULAR LEARNING FRAMEWORK

from fundamentals to engineering application, safety, infrastructure and system integration

WHAT IT IS BUILDING

8 modules

structured course architecture

MOOC

online course under development

E-platform

shared access to learning resources

Assessments

beginner and advanced learning checks

CONSORTIUM SUT • TUBAF • University of Brescia • TalTech • ESG Solutions



- SILESIA UNIVERSITY OF TECHNOLOGY
- TALLINNA TEHNIKAULIKOOL
- ESG SOLUTIONS
- TECHNISCHE UNIVERSITAET BERGAKADEMIE FREIBERG
- UNIVERSITA DEGLI STUDI DI BRESCIA

TAKEAWAY

HY-EDU transforms hydrogen transition needs into teachable engineering competences

NEXT

How the course was designed

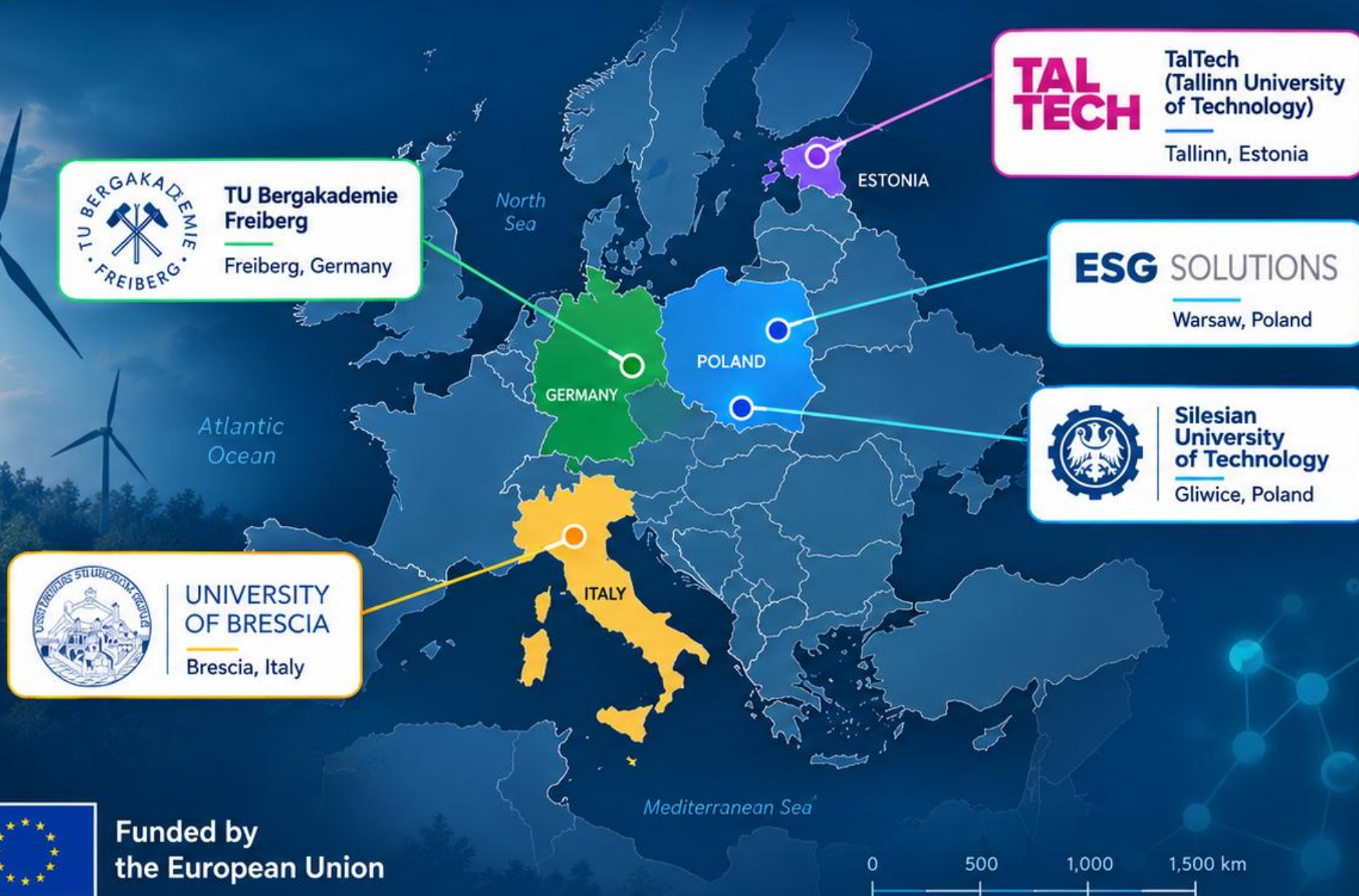


Higher Education
for a Greener
Hydrogen Economy

Consortium Partners

WORKING TOGETHER FOR SUSTAINABLE HYDROGEN EDUCATION

CLEAN ENERGY
BRIGHTER TOMORROW



Our Partners



Silesian University
of Technology

📍 Gliwice, Poland



TU Bergakademie
Freiberg

📍 Freiberg, Germany



UNIVERSITY
OF BRESCIA

📍 Brescia, Italy



TalTech
(Tallinn University
of Technology)

📍 Tallinn, Estonia



ESG Solutions

📍 Warsaw, Poland



Funded by
the European Union

EDUCATION
INNOVATION
SUSTAINABLE IMPACT

H₂

FROM SKILLS GAPS TO COURSE DESIGN

The course structure is designed from evidence: what universities already teach, what experts expect, and what engineers will actually need

WHY THIS MATTERS

Students do not just see hydrogen as a topic –
they learn it as an engineering system

Physics, infrastructure, storage, safety, regulation, system integration



DESIGN PRINCIPLES

Beginner-first

clear concepts before complex modelling

Applied engineering

transport, storage and safety in real systems

Flexible use

modules usable in different university programmes

Built-in assessment

simple YES/NO checks plus advanced tasks

TAKEAWAY

The HY-EDU course is evidence-based, modular and built for real teaching use

NEXT

What did the Delphi study show?

WHAT DID THE DELPHI STUDY SHOW?

A two-round expert survey used to identify priorities and build consensus

Round 1: identify priorities

Round 2: rate and validate

21
experts
Round 1

17
experts
Round 2

5
European
countries

84%
agreement
achieved

2
Delphi
rounds

Evidence-based
Course design

WHAT EXPERTS PRIORITISED

Most frequently selected elements and aspects for engineering education



Storage received the strongest support; safety and production were also ranked very highly

KEY MESSAGE

The course should be modular, system-oriented and aligned with the real competence needs of future hydrogen engineers

HOW IT SHAPED HY-EDU

Recommendations from the Delphi study that directly influenced the course design

01 Dedicated modules

H₂ content should be implemented mainly through postgraduate studies and dedicated subjects/modules

02 Emerging topics

Include natural H₂, Power-to-X, storage and distribution, material challenges and case studies

03 System perspective

Understand H₂ as part of the whole energy system - linked to renewables, storage, transport, markets and other energy carriers

04 EU strategy content

Content linked to the EU Hydrogen Strategy should be included as compulsory programme content

TAKEAWAY The Delphi study confirmed the need for structured, modular and competence-based hydrogen education

NEXT
HY-EDU course structure

THE HY-EDU COURSE:

8 MODULES

A modular learning framework covering the hydrogen value chain, storage, safety and system integration

STRUCTURE

The course moves from fundamentals and hydrogen sources to transport, storage, safety, policy and synergies

[Beginners level]

TUBAF, Germany

1 Hydrogen properties and production

Hydrogen fundamentals, production routes and the role of hydrogen in future energy systems

TalTech, Estonia

2 Natural and stimulated hydrogen

Emerging hydrogen resources, geological contexts and the growing interest in natural hydrogen

SUT, Poland

3 Hydrogen transport and transformation

Pipelines, trucks, ships, rail and transformation processes across the hydrogen value chain

TalTech, Estonia

4 Underground H₂ storage options and case studies

Salt and rock caverns, saline aquifers, depleted oil and gas fields, and real storage cases

UoB, Italy

5 Storage-site modelling and selection

Capacity, site screening, reservoir and caprock behaviour, and key subsurface interactions

UoB, Italy

6 Monitoring, safety and risk assessment

Monitoring concepts, safety principles and risk-based thinking for real hydrogen systems

UoB, Italy

7 Policy, regulations and techno-economics

Regulatory frameworks, policy context, market logic and economic dimensions of hydrogen

TalTech, Estonia

8 Synergies with carbon-neutral technologies

How hydrogen connects with wider decarbonisation pathways and other low-carbon solutions

[Advanced level]

TAKEAWAY

HY-EDU offers a complete learning pathway from hydrogen basics to storage, safety, policy and system integration

NEXT

Beginner vs Advanced

BEGINNER VS ADVANCED: TWO LEARNING PATHWAYS

The HY-EDU course is designed to support different learner needs and levels of depth

DESIGN IDEA

Start with essential hydrogen knowledge, then move into deeper technical, safety, policy and system-level content

2

learning
pathways

8

total
modules

1-4

core modules
for beginners

1-8

full pathway
for advanced

3-4

submodules
per module

60+

slides
per module

BEGINNER PATHWAY

INTRODUCTORY

ACCESSIBLE

- Covers the core concepts needed to understand the H₂ field.
- Focus on Modules 1–4: **properties, sources, transport and underground storage**.
- Built for newcomers, mixed audiences and broad engineering orientation.
- Assessment: simple Yes/No questions and introductory knowledge checks.

ADVANCED PATHWAY

DEEPER

COMPREHENSIVE

- Includes the **full 8-module** architecture for deeper technical learning.
- Extends into site **selection, safety, monitoring, policy and techno-economics**.
- Suitable for learners seeking a more comprehensive professional skill set.
- Assessment: more advanced questions, exercises and deeper applied discussion.

LEARNING FLOW

Beginner: Modules 1–4 - strong foundation | Advanced: Modules 1–8 - complete course journey

NEXT

Example modules

MODULE

01

UNDER
DEVELOPMENT

MODULE 1

Hydrogen Properties and Production

Hydrogen in the value chain and future energy systems

ERASMUS+ HY-EDU PROJECT

UNDER DEVELOPMENT

MODULE CONTENT IN PREPARATION

This part of the HY-EDU course is currently being developed
and will be integrated into the final learning pathway



PLANNING



DEVELOPMENT



INTEGRATION

COMING SOON

NEXT

Module 2 example

MODULE

02

READY EXAMPLES

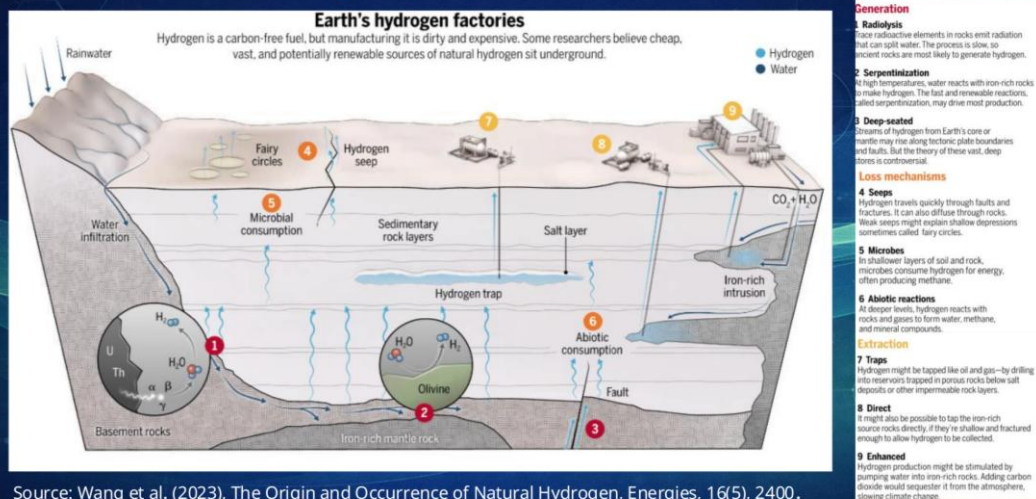
MODULE 2

Natural and Stimulated Hydrogen

From geological hydrogen generation to engineered stimulation and commercial potential

Submodule 1. Natural Hydrogen

The mechanisms for hydrogen generation in the subsurface



GEOLOGY

Natural H₂ generation mechanisms in the subsurface

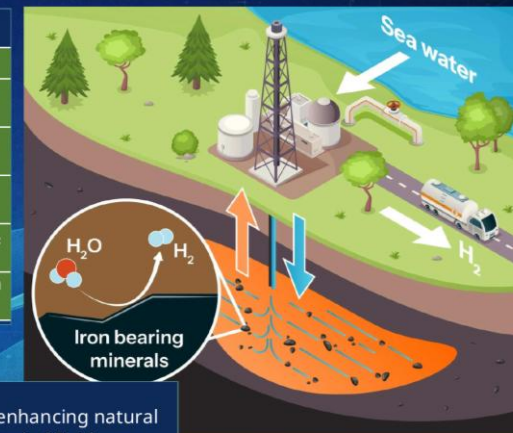
Submodule 2. Stimulated Hydrogen

What is stimulated hydrogen?

	NATURAL H ₂	STIMULATED H ₂
H ₂ generation	Naturally occurring	Deliberately accelerated
Human intervention	Exploration/production	Required for generation
Main mechanism	Serpentinization, radiolysis, etc.	Enhancement of these reactions
Analogy	Conventional geothermal system	Engineered geological H ₂ system
Goal	Extract existing H ₂	Generate additional H ₂ in situ

DEFINITION:

Stimulated hydrogen is hydrogen generated by deliberately enhancing natural geological H₂-producing processes, through engineered control of fluid access, reactive surface area, temperature, pressure and/or fluid chemistry.



CONCEPT

Natural vs stimulated H₂ - concept and definition

LEARNING VALUE

Explains where natural H₂ comes from, the main geological generation mechanisms, and why understanding the subsurface is essential for exploration and future resource development

NEXT

Module 3 example

MODULE

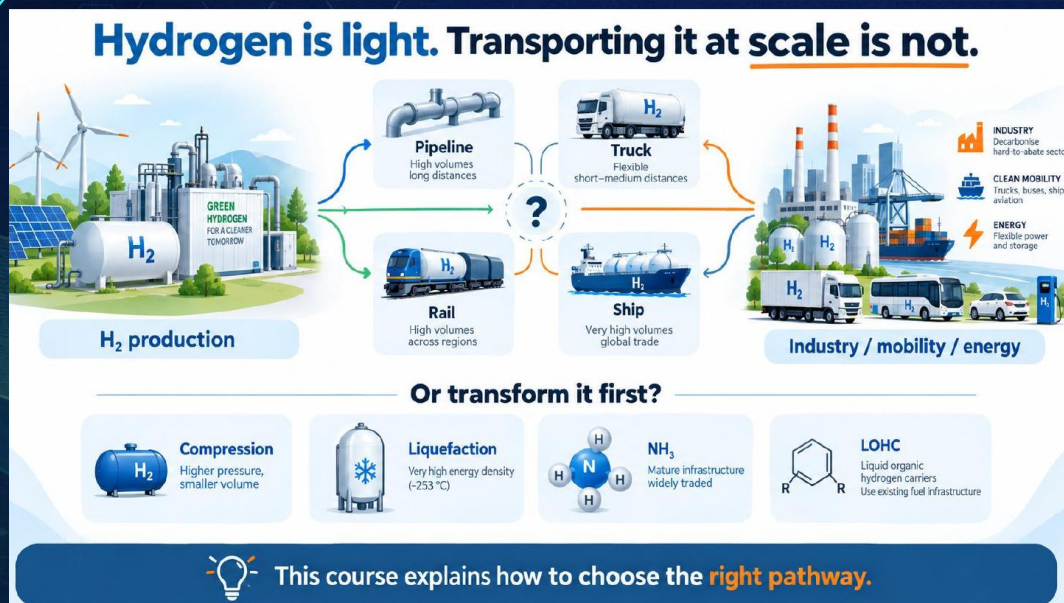
03

READY EXAMPLES

MODULE 3

Hydrogen Transport and Transformation

How hydrogen is transported by pipeline, road, rail and ship, and transformed into chemical carriers



SYSTEM

Why transport and logistics are central to the H₂ value chain

LEARNING VALUE

Explains how hydrogen is transported and transformed across the value chain and why its physical properties determine the choice of transport and carrier options

Why is hydrogen difficult to transport?

Hydrogen has a very high energy content **per unit of mass**, but a very low energy density **per unit of volume** under ambient conditions.

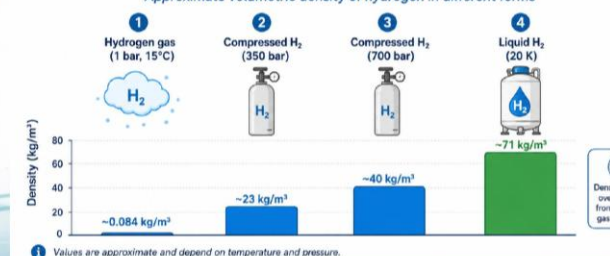
This means that transporting useful quantities of hydrogen generally requires one of three approaches:

- increasing its pressure through compression;
- reducing its volume through liquefaction;
- converting hydrogen into a more easily transported chemical compound.

All these approaches require additional equipment and energy.

Example Hydrogen Densities

Approximate volumetric density of hydrogen in different forms



Key message: Hydrogen has high energy content by mass, but low energy density by volume in gaseous form. This is why compression or liquefaction is often needed for transport.

U.S. DOE (2022), Liquid Hydrogen Technologies Workshop Report; U.S. DOE HFTO (2021), Importance of Liquid Hydrogen for Decarbonizing the Energy Sector.

Source: [2], [8]

DISCLAIMER - Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the National Agency (PRSE). Neither the European Union nor the granting authority can be held responsible for any use of the information provided.

PHYSICS

Low volumetric energy density explains why H₂ needs conditioning

NEXT

Module 4 example

MODULE

04

READY EXAMPLES

MODULE 4

Underground Hydrogen Storage Options

Salt/rock caverns, saline aquifers, depleted oil & gas fields and case studies

MODULE ROADMAP

01

Slides 3–14

UHS INTRODUCTION & FUNDAMENTALS

- Introduction to UHS options & why underground storage?
- UHS in the hydrogen value chain / system context
- H₂ vs conventional gases
- Main storage options
- Working vs cushion gas
- Operational cycle
- Pressure management
- Thermodynamic behaviour underground
- Capacity, deliverability & cycling
- Geological controls
- Selection of UHS options
- Comparative overview



02

Slides 15–16

GLOBAL & EUROPEAN UHS PROJECTS

- Global underground H₂ storage projects
- European H₂ infrastructure & storage projects
- Current status and planned developments
- Key initiatives and consortia



03

Slides 17–19

HYDROGEN PHYSICS & THERMODYNAMICS

- Why H₂ is NOT natural gas
- Key physical and thermodynamic properties
- Implications for underground storage
- Compression, density and phase behaviour
- Behaviour under high pressure and temperature

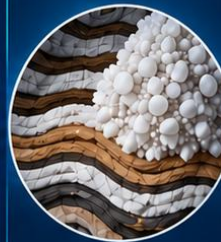


04

Slides 20–23

SALT CAVERNS: GEOLOGY & DEVELOPMENT

- Why salt for H₂ storage
- Salt formations and characteristics
- Salt domes vs bedded salt
- Site selection criteria
- Solution mining process
- Operational considerations



05

Slides 24–29

SALT CAVERNS: ENGINEERING & OPERATION

- Geomechanics and well design
- Cavern construction and completion
- Operational flexibility
- H₂ embrittlement and materials
- Surface infrastructure
- Thermodynamic cycling
- Monitoring and safety



06

Slides 30–35

SALT CAVERNS: PERFORMANCE, CONSTRAINTS & CASE STUDIES

- Key advantages
- Geological scarcity
- Brine management
- Environmental aspects
- Economics
- HyStock case study
- Moss Bluff / Spindletop case study
- Lessons learned

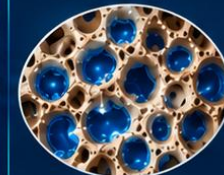


07

Slides 36–59

POROUS-MEDIA UHS, LRC & FINAL SYNTHESIS

- Porous-media storage (depleted fields & saline aquifers)
- Multiphase flow and trapping
- Gas mixing and purity
- Caprock and well integrity
- Injection, withdrawal and monitoring
- Austria case studies
- Lined rock caverns (LRC)
- Technology comparison
- Site-selection framework
- Demonstrated evidence
- Challenges and outlook
- Module summary



LEARNING VALUE

Understand the key geological, technical, and operational principles of underground hydrogen storage and evaluate suitable storage options

NEXT

Module 4 example

MODULE

04

READY EXAMPLES

MODULE 4

Underground Hydrogen Storage Options

Salt/rock caverns, saline aquifers, depleted oil & gas fields and case studies

INTRODUCTION TO UNDERGROUND HYDROGEN STORAGE OPTIONS

Variable renewable energy leads to periods of surplus electricity, while hydrogen demand exists year-round. Underground storage enables large-scale, long-duration and flexible hydrogen supply.

1. THE SYSTEM CHALLENGE
Renewable electricity supply and energy demand do not always coincide in time.
Variable renewable electricity → Electrolysis converts electricity to hydrogen → Hydrogen is transported and stored → Hydrogen supports industry, transport and power.

2. WHY STORE HYDROGEN UNDERGROUND?

- LARGE STORAGE CAPACITY**
 - Geological formations provide substantial subsurface volumes suitable for large-scale H_2 storage.
 - Enables national and regional energy security and system resilience.
- LONG-DURATION STORAGE**
 - UHS can support medium- to long-duration storage (from weeks to seasons).
 - Complements other flexibility options (e.g. batteries, demand response).
- SYSTEM FLEXIBILITY**
 - Stored H_2 can be withdrawn when demand exceeds contemporaneous production.
 - Supports multiple end-uses (industry, transport, power generation, heating).
- DECARBONISATION POTENTIAL**
 - Helps integrate high shares of renewable energy.
 - Contributes to emission reductions in hard-to-abate sectors.

STORAGE NEEDS EXIST AT MULTIPLE TIME SCALES

- HOURS – DAYS**: Balance short-term fluctuations
- WEEKS – MONTHS**: Bridge longer imbalances
- SEASONS**: Enable seasonal energy storage

3. WHERE CAN H_2 BE STORED UNDERGROUND? – THE MAIN GEOLOGICAL OPTIONS

- SALT CAVERNS**
 - High purity storage
 - High injection and withdrawal rates
 - Commercial maturity
- DEPLETED GAS RESERVOIRS**
 - Reuse of existing infrastructure
 - Large storage capacities
 - Potentially cost-competitive (site-specific)
- DEEP SALINE AQUIFERS**
 - Very large theoretical potential
 - Wide geographic availability
 - Limited pure- H_2 field experience
- HARD-ROCK LRC**
 - Engineered solution in competent rock
 - High containment due to liner
 - Flexible siting (not dependent on salt)
 - Key challenges: liner integrity, H_2 embrittlement, thermomechanical cycling

SELECTED REFERENCES

- Davoudi, S. M., et al. (2025). Underground hydrogen storage: A review of technological developments, challenges, and opportunities. *Applied Energy*, 381, 125172. <https://doi.org/10.1016/j.apenergy.2024.125172>
- Sadhu, V. A., & Al-Murshid, W. I. (2024). Key aspects of underground hydrogen in depleted hydrocarbon reservoirs and saline aquifers: A review & future understanding. *Energy Conversion*, 54(4), 100239. <https://doi.org/10.1016/j.encon.2024.100239>
- Muller, M. L., et al. (2024). A critical review of underground hydrogen storage: From fundamentals to applications, unveiling future frontiers in energy storage. *International Journal of Hydrogen Energy*, 79, 1305–1334. <https://doi.org/10.1016/j.ijhydene.2024.07.076>

OVERVIEW

Why underground storage is needed and where H_2 can be stored

LEARNING VALUE

Understand the key geological, technical, and operational principles of underground hydrogen storage and evaluate suitable storage options

WHY SALT CAVERNS ARE A LEADING OPTION FOR UNDERGROUND H_2 STORAGE

Key advantages, proven performance and remaining considerations

- 01 EXCELLENT SEALING**
Very low permeability of halite ($\approx 10^{-21}$ – 10^{-19} m²) minimises leakage risk.
- 02 SELF-HEALING BEHAVIOUR**
Salt creep promotes stress redistribution and can contribute to self-healing of minor damage.
- 03 HIGH OPERATING FLEXIBILITY**
Fast injection and withdrawal rates, suitable for seasonal storage and grid balancing.
- 04 LARGE STORAGE CAPACITY**
Individual caverns can store hundreds of thousands to millions of m³ of H_2 .
- 05 LOWER CUSHION GAS REQUIREMENT**
Typically ~20–30% in salt caverns; commonly ~40–80% in porous storage, depending on reservoir type and operation.
- 06 WELL-ESTABLISHED TECHNOLOGY**
Decades of experience from natural gas storage, with several hydrogen pilot projects in Europe.
- 07 HIGH HYDROGEN PURITY POTENTIAL**
Limited gas-rock interaction compared with porous reservoirs. Field test in the Rüdersdorf salt cavern showed **Demonstrated H_2 purity >99.95% after storage.** However, trace N_2 , H_2O and halogenated compounds were detected. Gas conditioning may still be required depending on end-use specifications.

KEY CONSIDERATIONS

- Potential contaminants: residual brine, initial gases (e.g. N_2), mineral impurities and microbial activity.
- Gas conditioning may be required to meet specific end-use standards (e.g. EN 17024 for fuel cell mobility).
- Site-specific geological, geomechanical and operational assessment is essential.

PROVEN IN PRACTICE
Field demonstration in the Rüdersdorf salt cavern (Germany) achieved >99.95% H_2 purity after storage, confirming the high purity potential of salt caverns (Scholz et al., 2025).

SALT CAVERN FOR HYDROGEN STORAGE

Surface facilities (compression, conditioning, metering)
Well (injection/withdrawal)
Salt cavern (H_2 storage)
Halite (salt) (low permeability, self-healing)
Brine sump (brine)

Scholz et al. (2025). Assessment of the feasibility of hydrogen storage in salt caverns: Implications for purity and contamination pathways for fuel cell mobility. *Int. J. Hydrogen Energy*, 170, 151236. <https://doi.org/10.1016/j.ijhydene.2025.151236>

CASE

Salt caverns as a leading option for underground H_2 storage

NEXT

Module 5 example

MODULE

05

UNDER
DEVELOPMENT

MODULE 5

Storage-Site Modelling and Selection

Capacity, reservoir/caprock interactions and site-screening logic

ERASMUS+ HY-EDU PROJECT

UNDER DEVELOPMENT

MODULE CONTENT IN PREPARATION

This part of the HY-EDU course is currently being developed
and will be integrated into the final learning pathway



PLANNING



DEVELOPMENT



INTEGRATION

COMING SOON

NEXT

Module 6 example

MODULE

06

READY EXAMPLES

MODULE 6

Monitoring, Safety and Risk Assessment

Hydrogen hazards, control measures and risk-based system thinking

Hazards related to gaseous hydrogen 1

Project-only version with logo and no EU funding footer

- Gaseous Hydrogen: Properties and Safety
 - Gaseous hydrogen is colorless and odorless and is the lightest gas (≈ 14.4 times lighter than air).
 - It diffuses rapidly, easily permeates materials and small leaks, and has high buoyancy.
 - It tends to rise and disperse, but in enclosed spaces it can accumulate at high points and reach ignition sources (e.g., ceiling lights).
- Risks and Leaks
 - Requires well-sealed vessels and piping systems; leaks are a key concern.
 - Hazards include jet fires or unignited high-pressure jets.
 - Leaks are difficult to detect without instruments (often not visible or audible).



SAFETY

Gaseous H_2 : leakage, buoyancy, detection and jet-fire risk

Hazards related to liquid hydrogen 1

Project-only version with logo and no EU funding footer

- Properties and Safety
 - Liquid hydrogen is clear with a slight blue tint.
 - Extremely low boiling point (20.3 K) and very low density ($\sim 70 \text{ kg/m}^3$).
 - Large expansion when vaporizing (≈ 850 times volume increase).
- Behavior and Pressure Risks
 - Rapidly boils or flashes into gas when exposed to ambient conditions.
 - When confined and warmed, can generate very high pressures.



CRYOGENIC

Liquid H_2 : cryogenic hazards, boil-off and pressure risks

LEARNING VALUE

The safety module makes the engineering consequences of hydrogen properties visible to students

NEXT

Module 7 example

MODULE

07

READY EXAMPLES

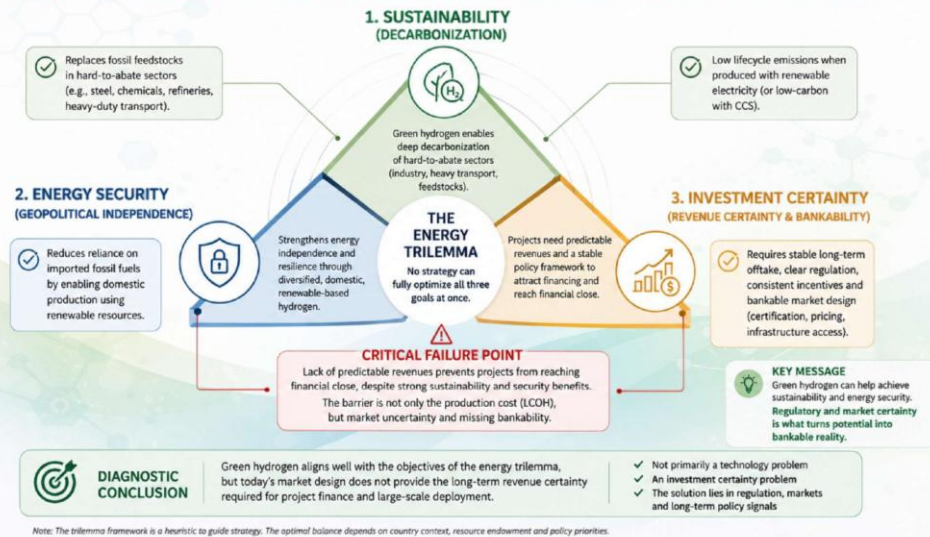
MODULE 7

Policy, Regulations and Techno-Economics

From EU hydrogen strategy to market design, finance and regulatory implementation

The Green Hydrogen Trilemma: Balancing Three Essential Goals

Hydrogen contributes to energy security and decarbonization, but investment certainty is the missing piece.



POLICY

The green H₂ trilemma: sustainability, security and investment certainty

SMR Based H₂ Plant: sensitivity analysis on NG price



TECHNO-ECONOMICS

H₂ production costs and competitiveness depend strongly on energy prices and production pathways

LEARNING VALUE

This module shows why H₂ deployment is also a regulatory, financial and market-design challenge

NEXT

Module 8 example

MODULE

08

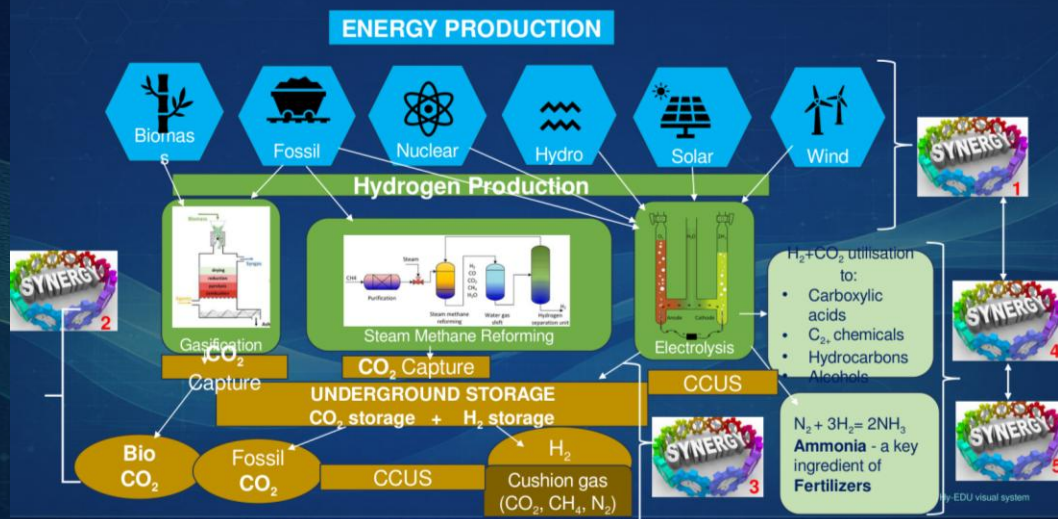
READY EXAMPLES

MODULE 8

Synergies with Carbon-Neutral Technologies

Hydrogen integration with renewables, CCUS, CO₂ utilisation, ammonia and Power-to-X pathways

The synergy of hydrogen with main energy technologies



SYSTEM

H₂ synergies with energy technologies, CCUS, storage and use

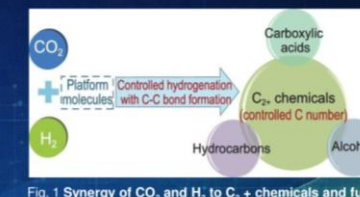
H₂ use together with CO₂ for chemicals and fuel production- SM4

Synergy of CO₂ and H₂ to C₂ + chemicals and fuels¹

- The joint utilization of captured CO₂ and low-carbon hydrogen (H₂) enables carbon recycling into C₂+ hydrocarbons and oxygenates (olefins, liquid fuels, aromatics, ethanol, higher alcohols).
- This synergy underpins power-to-X pathways that integrate renewable electricity with chemical and fuel production.

Why CO₂ + H₂ Synergy Matters:

- Decarbonization: CO₂ becomes a feedstock, while H₂ (from electrolysis) supplies reducing power.
- Energy storage: Converts intermittent electricity into dense chemical energy.
- Value upgrade: C₂+ products have higher energy density and market value than C₁ products (CO, CH₄, MeOH).



POWER-to-X

CO₂ + H₂ synergies: carbon recycling into chemicals and fuels

LEARNING VALUE

This module closes the loop by showing hydrogen as part of an integrated carbon-neutral technology system

NEXT

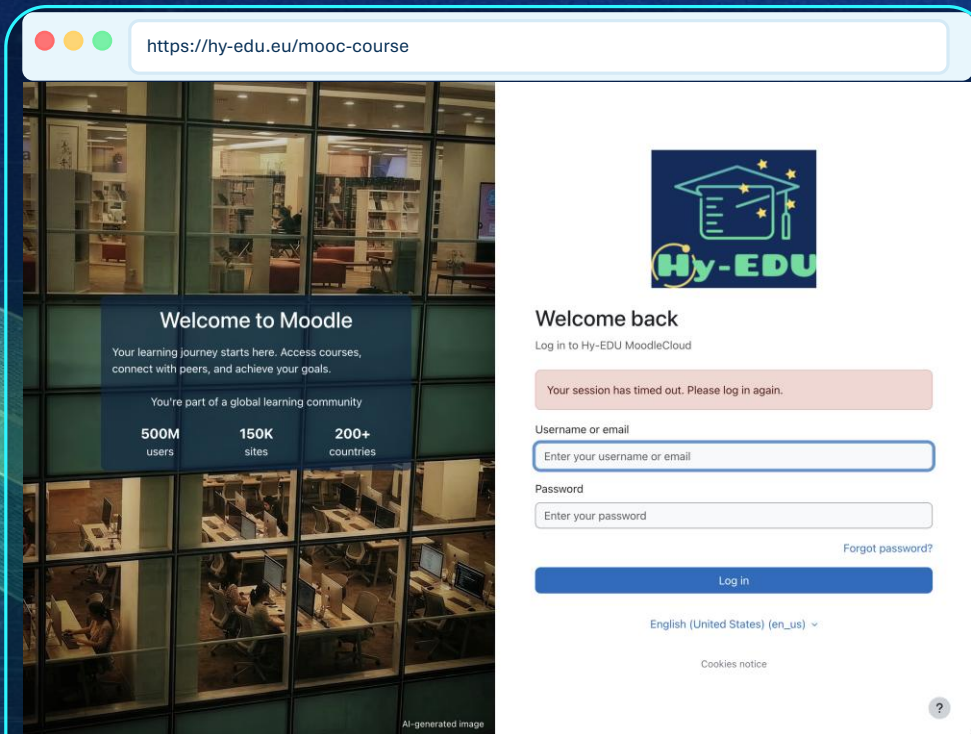
MOOC platform

MOOC ACCESS

[ONLINE PAGE](#)

Access the HY-EDU MOOC

Moodle course access and login page



SCREENSHOT

Course landing page and module pathway preview

MOOC ADDRESS

<https://hy-edu.eu/mooc-course>

SCAN TO OPEN

Use the QR code or type
the address directly in
the browserhy-edu.eu



HIGHER EDUCATION FOR A GREENER HYDROGEN ECONOMY

CLEAN ENERGY
BRIGHTER TOMORROW

*Same
energy.
More
opportunities.*



*Knowledge
fuels a
cleaner
tomorrow*

Thank you!

Now let's store a few questions.

*No hydrogen leaked during this presentation —
only knowledge.*



Marcin Lutynski

Full Professor at Silesian University
of Technology



Scan to connect

Marcin Lutyński | Silesian University of Technology



EDUCATION
SKILLS



PRODUCTION



STORAGE



TRANSPORT



A CLEANER
TOMORROW