MODULE 3: HYDROGEN LOGISTICS AND SUSTAINABILITY AND ECOLOGY

MINI LECTURE: HYDROGEN LOGISTICS AND SUSTAINABLE DEVELOPMENT – BETWEEN POTENTIAL AND CHALLENGES

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Mini-lecture: Hydrogen logistics and sustainable development – between potential and challenges

The mini-lecture will have the following structure:

1. Introduction: Hydrogen – hope or challenge?
   A short anecdote from the history of the technology or implementation (e.g. Toyota Mirai or the H2Haul project).
   Global and local context.
2. Types of hydrogen – energy colours and their consequences
   Description of grey, blue, green, turquoise, white – data, costs, emissions, application examples.
3. Hydrogen supply chain – where do we lose the most?
   Production, storage, transport – showing where energy losses and emissions occur. Example from industry or research (e.g.Air Liquide).
4. Statistics and numbers that make an impression
   – 900 million tons of CO_2 from hydrogen per year
   – 10 kg CO_2 per 1 kg H_2 – comparison with aviation
   – EU Investments and Goals by 2030
5. Hydrogen transport – an expensive luxury?
   Gas pipelines, cryogenic tanks, LOHC – advantages, disadvantages, numbers, examples (e.g. Hydrogenious Technologies).
6. Does ecology pay off? Green hydrogen and renewable energy sources The use of renewable energy sources in cooling and compression systems – opportunities, challenges, implementation examples (H2 Green Steel).
7. Digital revolution – how AI and IoT are changing hydrogen logistics AI in route optimization (H2Haul, Siemens), Big Data, IoT – the future of intelligent logistics.
8. Conclusions and reflections: Can hydrogen be truly green?
   Summary: What needs to happen for hydrogen logistics to support sustainable development? What can we do today?

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1. Introduction: Hydrogen – hope or challenge?

In 2014, Japanese carmaker Toyota presented the Mirai model – the first mass-produced hydrogen-powered car. For many, it was a symbol of a future without emissions, and for skeptics – a costly experiment. Today, a decade later, the world no longer has any doubts: hydrogen has huge potential, but its popularization is not only a matter of technology, but above all, logistics.

Rising energy prices, climate change and the need to reduce greenhouse gas emissions are forcing governments and industries to look for alternative energy sources. Hydrogen is seen as a universal energy carrier that can power vehicles, industry and even homes. At the same time, it is difficult to produce, store and transport – it requires specialist infrastructure, huge energy inputs and safety measures.

The debate over the potential of hydrogen is no longer about whether? but rather how? How to produce it emission-free, how to transport it cheaply and safely, how to store it without losses? The key to the answer is well-planned and optimized logistics, the importance of which grows with each passing year.

Projects such as H2Haul, HySynergy and H2 Green Steel show that Europe treats hydrogen logistics as one of its priorities. Without it, climate goals will not be achieved, "green" supply chains will not be created and hydrogen will not become a real alternative to fossil fuels.

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What's more, hydrogen logistics is not just the domain of engineers - it is a space for specialists in management, planning, finance, IT, safety and ecology. The interdisciplinarity of this area makes it exceptionally attractive professionally. Therefore, education in this area must be comprehensive, practical and future-oriented. The aim of this mini lecture is not only to present challenges, but also to inspire solutions. It is an invitation to act in one of the most dynamic sectors of the energy transformation of the 21st century.

2. Types of Hydrogen – Energy Colors and Their Consequences

The color of hydrogen is not just marketing – it is specific data: emissions, costs, efficiency. In reality, each color of hydrogen symbolizes a different method of production and carries different environmental, economic and technological consequences. The most common is currently gray hydrogen, produced in the steam methane reforming (SMR) process, which leaves a huge carbon footprint – about 10 kg of CO_2 for every kilogram of H_2. This means that industrial-scale hydrogen production is responsible for as much as 2% of global carbon dioxide emissions.

The alternative is blue hydrogen, which uses the same technology but with the addition of CCS (Carbon Capture and Storage). This allows for the capture of up to 90% of CO_2 emissions. However, implementing this technology is associated with high costs, lack of infrastructure and additional energy challenges.

Green hydrogen is produced using renewable energy through water electrolysis. It is the only truly emission-free form of hydrogen, but it is very expensive – from 4 to 7 euros per kilogram. This technology is gaining importance with the development of wind and solar farms, but requires huge investment and scaling.

New production methods are also emerging: turquoise hydrogen, produced by pyrolysis of methane (instead of CO_2, solid carbon is produced), and white hydrogen, which occurs naturally in the Earth's crust. Although they sound promising, they are still experimental and not commercially available.

Key question for participants: Which type of hydrogen should be a priority in national and European policies in the next decade?

International solutions:

- Germany has a national hydrogen strategy that provides strong financial support for green hydrogen.
- France is investing in blue hydrogen with CCS technology in the petrochemical sector.
- Australia is researching turquoise hydrogen, while Mali and the US are exploring natural deposits of white hydrogen.

It is crucial to understand that no one colour of hydrogen is universally "better" – it all depends on the local context, available resources, climate goals and technological capabilities.

3. The hydrogen supply chain – where are we losing the most?

Hydrogen logistics encompass all stages of hydrogen movement – from production, through storage and transport, to final use. Each of these stages brings specific challenges – technological, economic and ecological – that affect the overall efficiency and sustainability of the entire supply chain.

At the production stage, the dominant SMR (Steam Methane Reforming) technology is characterized by low efficiency and high CO_2 emissions. Although this method is the cheapest, it is not in line with EU climate goals. Alternatives, such as electrolysis with renewable energy, are promising but expensive and dependent on unstable energy sources.

Hydrogen storage requires complex and expensive technologies. In the case of compressed hydrogen, 15–20% of its energy is used in the compression process itself. Liquid hydrogen, although more compact, is associated with losses in the form of evaporation and the need to maintain extremely low temperatures (-253°C).

Hydrogen transportation is one of the biggest barriers – regardless of the method. Gas pipelines need to be modernized to avoid hydrogen embrittlement. Cryogenic tankers are expensive and associated with the risk of leaks and losses. LOHC technology is still not commercially scalable.
Finally, there is distribution and use, where reliability and purity of the final product count. Hydrogen must be delivered in the right parameters to the industry, energy or transport sectors.
Key question for participants: At what stage of the hydrogen supply chain do you see the greatest losses or risks – and how to minimise them?

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International solutions:

- Northern Lights Project (Norway) – integration of CCS with industrial logistics.
- Hydrogen Backbone Plan (EU) – development of a pan-European hydrogen pipeline network.
- Air Liquide develops mobile H_2 transport systems based on cryogenic and LOHC infrastructure.

Supply chain analysis allows for the identification of bottlenecks that are crucial to the success of the entire sector. Optimizing logistics is not just a matter of costs – it is a fight for a climate-neutral energy future.

4. Statistics and numbers that make an impression

In the context of hydrogen as the fuel of the future, it is worth looking at the figures that show both the scale of the challenge and the potential. Annual CO_2 emissions related to hydrogen production worldwide amount to 900 million tons, which is greater than the emissions of the entire aviation industry. This level of pollution makes it impossible to treat current hydrogen production as a pro-ecological solution.

The European Union has set itself an ambitious goal: by 2030, it wants to produce 10 million tons of green hydrogen per year and import another 10 million tons. This is a huge technological, logistical and financial challenge. The production of green hydrogen requires huge amounts of energy from renewable sources – according to some estimates, as much as 500 TWh per year.

For comparison, the emissions associated with the production of individual types of hydrogen are as follows:

- Grey hydrogen: 9–11 kg CO_2 per 1 kg H_2,
- Blue hydrogen: 2–4 kg CO_2 per 1 kg H_2,
- Green hydrogen: 0 kg CO_2 per 1 kg H_2 (ignoring the carbon footprint associated with the construction of the installation).

Production costs range from €1.5–2.5 for grey hydrogen, €2.5–4 for blue, and €4–7 for green. Energy efficiency also varies: the lowest for blue (55–65%), the highest for turquoise (up to 85%).

Key question for participants: Which of these numbers surprised you the most and why? How might they impact investment decisions in your organization or region?

International solutions:

- In the Netherlands and Denmark, special "hydrogen clusters" have been created that concentrate production, storage and distribution in one place, which reduces costs and emissions.
- Japan and South Korea are investing in mass production of electrolyzers, driving down the cost of green hydrogen.
- In Spain, the "HyDeal Ambition" project was created, which aims to sell green hydrogen at a price of €1.5/kg by 2030.

These data show that the transition to low-emission hydrogen requires, on the one hand, investment and, on the other, smart economic and technological analysis. Statistics can be an impulse to act – or an excuse. It all depends on political decisions and the social will to transform.

5. Hydrogen transport – an expensive luxury?

Hydrogen transport is one of the most complicated and expensive elements of the entire logistics chain. It requires the use of advanced technologies and meeting strict safety standards. Hydrogen is the smallest and lightest molecule, which means that it penetrates materials very easily and is difficult to encapsulate. In addition, it is flammable and explosive in contact with air, requiring special storage and transport conditions.

The most commonly used transportation methods are:

- Gas pipelines: Hydrogen can be transported through pipelines, but this requires special adaptation – so-called "hydrogen embrittlement" leads to a weakening of materials.
- Cryogenic tanks: Transporting liquid hydrogen at a temperature of -253°C involves enormous energy consumption (up to 40% of the energy content of hydrogen).
- LOHC (Liquid Organic Hydrogen Carriers): transport of hydrogen chemically bound to a liquid, which does not require cooling or pressure, but requires energy to release it (dehydrogenation).

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Key question for participants: Which hydrogen transport method has the greatest potential to be scaled up – and what conditions must be met to make it profitable?

International solutions:

- The European Union plans to create a European Hydrogen Backbone by 2030 – 28,000 km of pipelines.
- Air Liquide delivers liquid hydrogen by tanker to hydrogen stations in Europe.
- The German company Hydrogenious Technologies is commercially implementing LOHC using dibenzyltoluene as a carrier.

Efficiency in hydrogen transport requires both infrastructure and technology investments. Intelligent management of routes, cooling, decompression and safety must go hand in hand with digitalization and process automation.

6. Is ecology worth it? Green hydrogen and renewable energy

Green hydrogen production is one of the key challenges, but also opportunities in the context of sustainable development. Water electrolysis using renewable energy (RES) is a zero-emission process, provided that the energy comes from installations such as wind farms, photovoltaic or hydro farms.
However, implementing RES technology in hydrogen logistics systems poses numerous challenges, including the need to ensure continuity of energy supply, integration with the power grid, and high investment costs. For example, the process of compressing hydrogen to 700 bar consumes 15 to 20% of its energy, which is why the use of wind turbines to power compressors is becoming increasingly popular.

Key question for participants: Are investments in green hydrogen and renewable energy a real alternative for the industrial and transport sectors in your region?
International solutions:

- H2 Green Steel (Sweden) – a plant producing steel exclusively using green hydrogen and renewable energy.
- HySynergy (Denmark) – integration of electrolysers with renewable energy and transport infrastructure.
- Port of Rotterdam – developing green hydrogen storage infrastructure from renewable energy sources for maritime shipping.

Green hydrogen has the potential to become the foundation of a zero-emission economy. But its profitability depends on energy costs, scale of production and legislative support.

7. Digital revolution – how AI and IoT are changing hydrogen logistics

Digital transformation is one of the pillars of modern hydrogen logistics. The implementation of artificial intelligence (AI), the Internet of Things (IoT) and Big Data allows for the optimization of processes, reduction of losses and increased safety.

AI enables real-time data analysis – from demand forecasts to the selection of optimal delivery routes. Big Data allows for predicting energy demand, analyzing the efficiency of cooling and compression systems, and monitoring the environmental effects of logistics. IoT, in turn, provides ongoing supervision of tanks, pipelines, and filling stations – sensors transmit data on pressure, temperature, humidity, and system tightness.

Key question for participants: What digital solutions would be possible to implement in your company or institution?

International solutions:

- H2Haul – a European project to optimize H_2 truck routes using AI.
- Siemens Digital Logistics – integrated tracking and management systems for hydrogen transport.
- Shell Energy Hub – a platform for monitoring the carbon footprint of H_2 logistics in real time.

Digitalisation is not an option – it is a necessity if hydrogen logistics are to be efficient, safe and sustainable.

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8. Conclusions and reflections: Can hydrogen really be green?

Hydrogen as the fuel of the future is gaining importance – but its greenness depends on the entire value chain: production, storage, transport and consumption. To make a real contribution to climate protection, it must be produced from renewable energy sources, transported emission-free and used in energy-sustainable systems.

It is a huge challenge, but also an opportunity for industry, education, politics and society. It requires joint action, supranational coordination and a vision of long-term transformation. The challenges are real – but so are the technological solutions that are already being implemented around the world.
Key question for participants: What role can you and your organization play in developing the hydrogen economy?

International solutions:

- REPowerEU – the European Union plan to support the development of green hydrogen and energy independence.
- IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) – intergovernmental cooperation platform for standards and regulations.
- Green Hydrogen Catapult – a global industrial initiative accelerating the large-scale deployment of green hydrogen.

Hydrogen logistics is not the future – it is the present.
And we are the ones who co-create it.

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