H2YGCEL

HYGCEL
FINAL REPORT

HYGCEL project manager

Mari Tuomaala[1]

Contributing authors

WP1. Petteri Laaksonen, T1.1: Kim Talus[3], Sirja-Leena Penttinen[3], Moritz Wustenberg[3], T1.2: Pami Aalto[2], Sarah Kilpeläinen[2], Anna Claydon[2], Minna Hanhijärvi[2], T1.3a: Kaisu Puumalainen[1], Sanna Heinänen[1], Mariana Lyra[1], T1.3b: Antti Ylä-Kujala[1], Timo Kärri[1], Antero Tervonen[1], Maija Luukka[1].

WP2. T2.1: Jukka Lassila[1], Hannu Karjunen[1], Markus Salmelin[1], Otto-Eeti Räisänen[1]; T2.2: Christian Breyer[1], Tansu Galimova[1], T2.3: Yrjö Majanne[2], Venla Vilhonen[2], Sami Repo[2], Matti Vilkko[2].

WP3. T1.3: Esa Vakkilainen[1], Satu Lipiäinen[1]; T3.2: Kalle Lipiäinen[1], Timo Björk[1], Masoud Moshtaghi[1]; T3.3: Marika Kokko[2], Husain Patel[1], Jouni Havukainen[1].

WP4. T4.1: Hung Nguyen[1], Arto Laari[1]; T4.2: Eero Inkeri[1], Hossein Enayatizadeh[1], Tero Tynjälä[1], Jaakko Hyypiä[1], Sampo Vilve[1]; T4.3: Mehar Ullah[1], Daniel Gutierrez Rojas[1], Pedro Nardelli[1].

WP5. Tero Joronen[2], Jyrki Mäkelä[2], Miika Sorvali[2], Vesa Ruuskanen[1], Tuomas Koiranen[1], Emma Laasonen[1], Anafi Aini[1], Jero Ahola[1].

WP6. T6.1&6.2: Jani Sillman[1], Husain Patel[1], Rami Alfasfos[1], Jouni Havukainen[1], Risto Soukka[1]; T6.3: Rami Alfasfos[1], Jani Sillman[1], Esa Vakkilainen[1], Risto Soukka[1].

Indexes:
1) LUT University
2) Tampere University
3) University of Eastern Finland

LUT University   Tampereen yliopisto Tampere University   UNIVERSITY OF EASTERN FINLAND

Contents

1 Foreword

The research project titled *Hydrogen and Carbon Value Chains in Green Electrification, HYGCEL*, investigated the energy transition at the system level in Finland.

HYGCEL research was conducted from January 1, 2022, to October 30, 2024. The co-innovation project was financed by Business Finland. The research budget was €4,5 million, and the co-innovation budget around €10,5 million.

HYGCEL consortium consisted of 17 consortium members. HYGCEL research parties included Lappeenranta-Lahti University of Technology LUT (public research project lead), University of Tampere and University of Eastern Finland. HYGCEL industry partners included ABB Oy, St1 Oy, Sumitomo SHI FW Energia Oy, Gasgrid Finland Oy, Fingrid Oyj, VaasaETT Oy Ab, UPM-Kymmene Oyj, Valmet Oyj, Gasum Oy, Finnsementti Oy, Fifth Innovation Oy, Oy U-Cont Ltd, Bakelite Oy and FennoSteel Oy. The consortium was coordinated by CLIC Innovation Oy.

This final report summarizes the project's main results and refers to conclusions made in individual work packages, consisting of a total of 18 work tasks. The task reports are summaries of academic research presented on academic forums (14 theses and 37 articles). The comprehensive research reporting is available on the project's website: www.lut.fi/en/hygcel, where the results are organized into four categories: academic achievements, key messages, final results (including this document), and seminar materials.

The financial support from Business Finland is greatly acknowledged, and the project steering group is highly appreciated for their active participation.

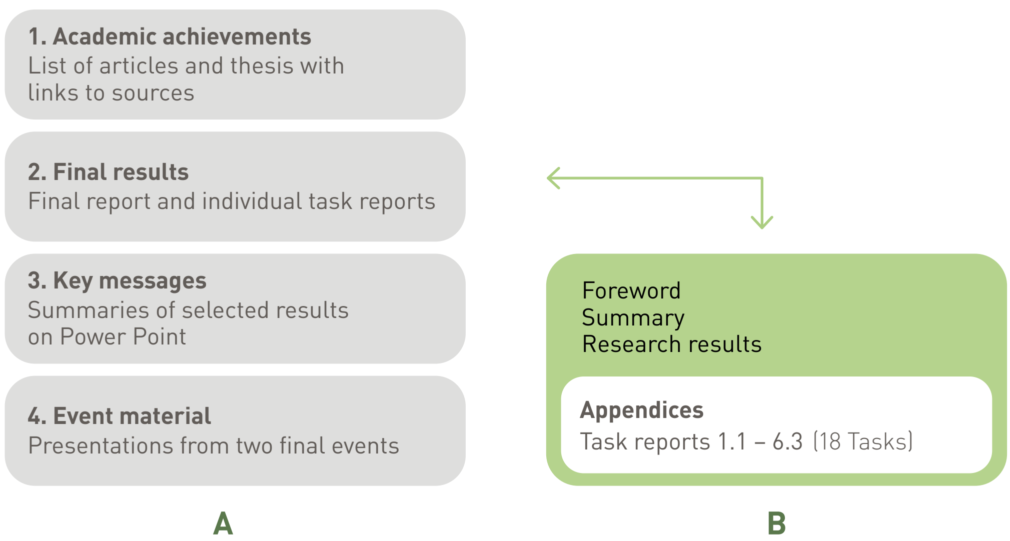

Figure 1.
a) HYGCEL reporting on project web pages www.lut.fi/en/hygcel and
b) the structure of HYGCEL final report.

2 Summary

2.1 HYGCEL project

Research on Hydrogen and Carbon Value Chains in Green Electrification (HYGCEL), conducted from January 1, 2022, to October 30, 2024, studied energy transition at the system level. **The goal of the research was to identify new PtX value chains based on Finland's renewable energy resources, and to provide guidance for building an optimal and efficient energy infrastructure that aligns with energy transition goals.** HYGCEL research was organized into six work packages, consisting of 18 work tasks and covering three perspectives: markets and regulation, techno-economy, and sustainability and safety.

2.2 Summary of findings

An energy system that is 100% based on renewables has emerged to become scientific mainstream. **Key pillars of this new energy system are solar and wind energy, energy storage, sector coupling,** and **electrification of all energy and industry sectors** and **applying power-to-X (PtX) solutions.**

New PtX value chains will differ from those based on fossil fuels and materials (Figure 2). This shift requires infrastructure adjustments, driven by regulatory measures and economic incentives.

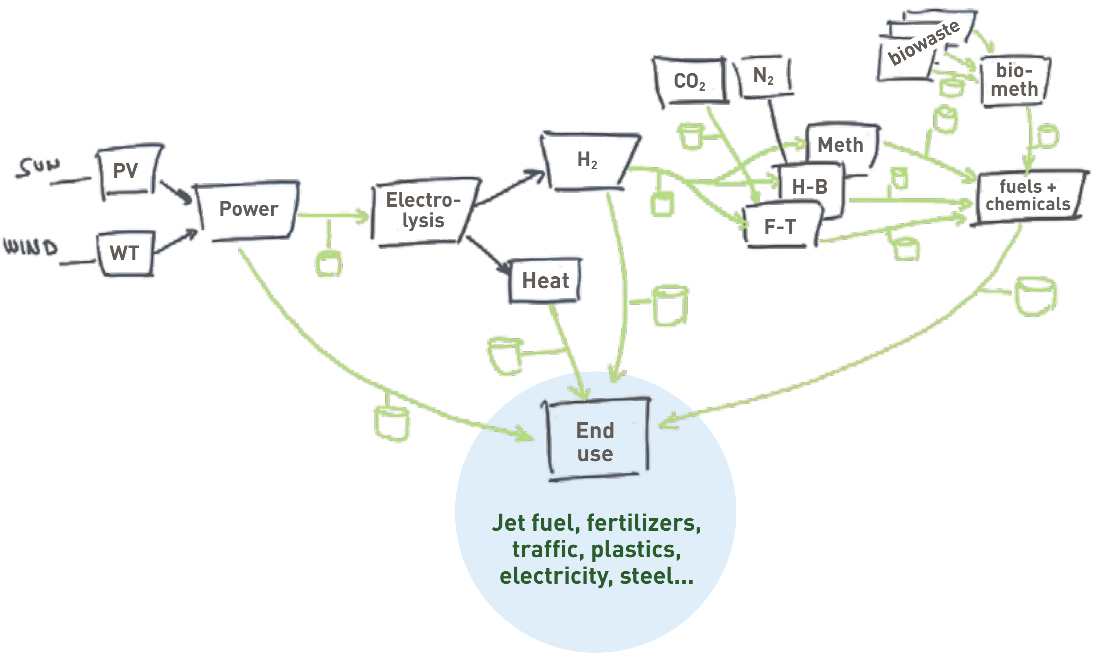

Figure 2. Schematic picture of PtX value chains (Matti Vilkko, TAU)

The transition towards sustainable energy and PtX systems begins with the production of renewable electricity. HYGCEL research indicates that **Finland has significant potential to produce renewable electricity**. The study found that the theoretical maximum wind power potential reached 1600 TWh, with the sensitivity analysis ranging between 700 and 2500 TWh. The theoretical maximum solar PV potential reached 1300 TWh of which the majority is on agricultural land. With these figures Finland would have the potential to produce about 10% of the EU's renewable electricity.

The calculated potential can be compared to the prospects published by Fingrid Oyj, Finland's transmission system operator. Their Q3/2024 forecast for 2035 is 160 TWh (Figure 2), with the industry's share being 101 TWh. For reference, utilizing Finland's bio-CO_2 resources of around 24 Mt could be used, for example, to produce a total 20 Mt of e-methanol with 175 TWh of electricity.

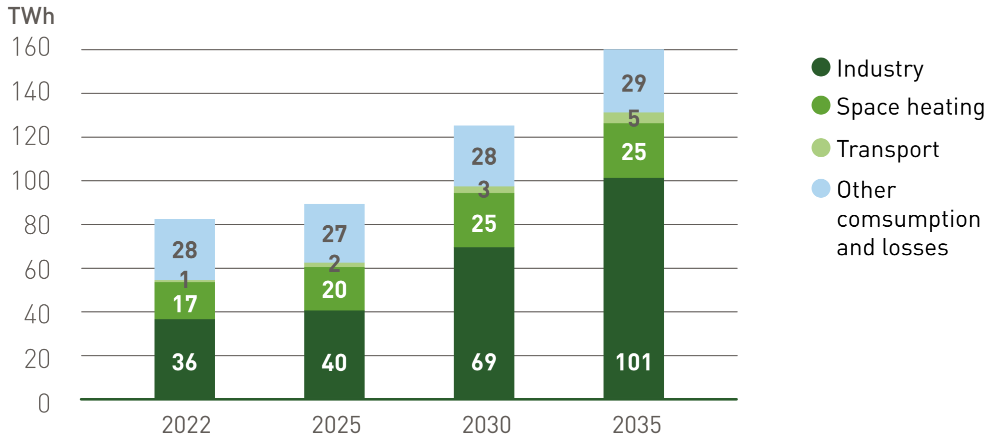

Figure 3. Electricity consumption in Finland between 2025 and 2035
(source: Fingrid, modified – Fingrid Oyj, prospects for future electricity production and consumption, Fingrid's forecast Q3/2024).

The potential for renewable electricity is substantial, but **the study also underscores the need to balance this maximum potential with biodiversity, nature values, and landscape**. Additionally, it is important to align production with the needs of various stakeholders, such as local inhabitants. **Acceptance of projects was found to be higher if the project is seen to positively influence the well-being of the area** – for example, through job creation.

The potential for renewable electricity exists throughout Finland. Scenario analysis identified **distinct energy imbalances across regions**, highlighting areas of surpluses and deficits. These regional disparities underscore the **importance of developing strategies and mechanisms to minimize energy transportation or transmission needs, thereby avoiding costly investments.** The placement of hydrogen conversion facilities can be considered a strategic decision, as it significantly impacts requirements for transportation and transmission infrastructure.

The **PtX production typically requires the transportation of some production factors** (electricity, H_2, CO_2, feedstocks, intermediates, or end products). The feasibility of transportation depends on multiple variables, and a detailed study is always required for each investment decision. However, **the study suggests that e-ammonia and e-methanol can be economically feasible for transportation**. On the other hand, **e-hydrogen should only be transported for short distances** of not more than a few hundreds of kilometres, and it is not economically attractive for long-distance transportation. An example case study indicated that **transporting CO_2 to an electricity production site for methanol synthesis resulted in the lowest product costs**, compared to electricity and hydrogen transportation for e-methanol production at a CO_2 source. **Power grids may be the more valuable infrastructure** in terms of flexibility and diverse use cases.

A lot more research should be done to understand the various actor roles in the value chain in specific investment cases. **In the preliminary studies based on NCF (net cashflow) analysis, the H_2 production step, as such, was not feasible**. This is noteworthy as all PtX value chains will involve this role. In a methanol production case study, the discounted **net cash flow** (NCF) **of a value chain came profitable with sufficiently low electricity prices** (less than 37€/MWh) and **considerable investment subsidies for hydrogen producer. Making hydrogen production attractive is important for the successful development of the hydrogen economy**.

Ensuring safety will be crucial for the success of PtX. It was found that **components, such as valves, fittings, and other connection points, are most vulnerable due to hydrogen's physical properties**, such as high diffusivity. **Human error accounted for 87% of the incidents analyzed**. Therefore, adhering to strict safety practices is mandatory. The **transition from small-scale to large-scale hydrogen usage amplifies the potential for accidents**. Even **1 bar of hydrogen overpressure can significantly reduce transport pipe toughness and accelerate fatigue crack growth** (for more information, see the key takeaways Safety and hydrogen materials in this report). Emerging geopolitical conditions and security practices indicate that **Finland should carefully consider the export routes** (for more information, see the key takeaways Infrastructure resiliency in this report).

Finally, the research indicates **that PtX products are always beneficial for the climate compared to their fossil counterparts**. By exporting these products, Finland could help other countries meet their climate targets, enabling so-called 'positive handprint' for Finland.

Solar photovoltaics are projected to dominate electricity supply in most regions, **providing abundant power for global PtX demands**. Greenland and Egypt were studied as reference countries. The study reveals that **the reference countries also have the potential to become significant exporters of e-fuels and e-chemicals**, benefiting from their abundant renewable resources. This encourages also Finland to **move forward with determination and efficiency in its efforts on the energy transition** in order to gain a foothold on the market.

2.3 List of key takeaways

The key findings raised by the individual work groups are the following:

Markets and regulation

EU regulation

- The EU framework is detailed and may risk overregulation. Changes to the regulation may be necessary, creating uncertainty for investors.

Support for investments

- Various types of public sector and regulatory support are needed to grow the market.
- Due to high investment uncertainty, the regulatory support must be addressed to foster market growth.
- For further suggestions, see the key takeaways Role of hydrogen and the value chain economics in this report.

Investment acceptance

- Acceptance of hydrogen projects is closely linked to information and knowledge.
- Acceptance is higher if the project is seen to positively influence the living and well-being in the area.

Techno-economy

The renewable energy potential

- The theoretical maximum land-use based wind power potential is 1600 TWh, with the sensitivity analysis ranging between 700 and 2500 TWh. The theoretical maximum solar PV potential reached 1300 TWh of which the majority is on agricultural land.
- 70% of the wind power potential is clustered in Northern Ostrobothnia and Lapland.
- Although the solar PV sites are scattered into small segments, a significant portion of the potential is located along the coastal area in Southern and Southwest Finland.
- Large CO_2 point sources release about 41 Mt of CO_2 annually and about 50% of it, 24 Mt (2022), is bio-based CO_2 i.e. originating from biomass.
- Full utilization of bio-based CO_2 could produce 20 Mt of MeOH (e-methanol), requiring about 175 TWh of electricity i.e., twice the amount currently used in Finland.
- Biomethanation of biogas and bioethanol CO_2 streams could increase the methane production by 30%, resulting in methane production of around 5.4 TWh/a by 2030. Biogas processes play an additional important role in nutrient recycling.

Regional energy needs and cross-regional transportation needs

- Scenario analysis identified distinct energy imbalances across regions of Finland, highlighting areas of surpluses and deficits.
- Energy imbalances need to be compensated through energy transfers. However, potential disparities between regions highlight the importance of developing strategies and mechanisms to minimize energy transportation/transmission needs to avoid costly investments.
- Energy is trasferred as hydrogen via gas grids, or transmitted as electricity via electric grids, or as other forms of energy products. Thus, the strategic placement of hydrogen conversion significantly impacts the requirements for the transportation/transmission infrastructure.
- Scenario analysis also identified the need for peak energy transfer capacity, emphasizing the importance of developing flexibility, as well as strategies and mechanisms to minimize peak power energy transfer between regions.

- Further research should combine the location of bio-based CO_2 sources to the strategic thinking related to balancing energy surplus and defict areas.
- The study also emphasized the importance of flexible operation of electrolyzers, energy storages (mainly hydrogen and heat), and import and export electricity transmission capacity to optimize energy production and usage in the Nordic and northern European areas.

Transportation feasibility studies

- CO_2 transportation is a proven technology and CO_2 will be a potential resource to transport alongside electricity and hydrogen. CO_2 pipelines were the lowest-cost transport option, although they also require high initial investment.
- e-Ammonia and e-methanol can be economically feasible for transport, with shipping being more advantageous than pipelines for long distances.
- e-Hydrogen should be transported for short distances of not more than a few hundred kilometres. e-Hydrogen transportation seems economically unattractive for long-distance transportation due to high additional costs and required initial investment. Long-distance shipping of hydrogen over thousands of kilometres is highly expensive.
- An example case study of e-methanol production in Finland found that transporting CO_2 to an electricity production site for methanol synthesis resulted in the lowest product costs for all scenarios studied, compared to electricity and hydrogen transportation for e-methanol production at a CO_2 source. However, power grids, in general, may be the more valuable infrastructure in terms of flexibility and diverse use cases. CO_2 pipelines are a proven technology, although they also require high initial investments.
- An example case compared five different hydrogen delivery pathways to a hypothetical steel mill located in Southern Finland. The pathway options included mill site electrolysis (i.e., hydrogen manufacturing at the site), hydrogen transportation in new and repurposed pipelines, transportation of hydrogen in a pipeline as synthetic methane, and hydrogen delivery by shipping. Findings indicate that mill site electrolysis and hydrogen pipeline transportation (both new and repurposed) were the most feasible in terms of costs, energy consumption, and greenhouse gas emissions. The transportation of synthetic methane (involving methane pyrolysis back to H_2 and solid carbon on site) and hydrogen shipping were both found to be less feasible due to higher costs and energy consumption, but the methane route provided a pathway to store carbon.
- Studies emphasize that the feasibility of transportation options depends on various partly local factors, and detailed studies are required for each investment decision. It must be noted that the feasibility of each investment depends on several variables, including hydrogen volumes, transportation distances, and the location of hydrogen producers and users.

Flexibility to add value

- Flexibility was found to bring significant benefits, allowing for the production of green products while managing fluctuations in renewable energy production and prices.
- Compared to full-load operation, the flexible operation of power-to-methanol production enabled a cost reduction of 1.2–46.1% relative to the grid-only scenario, depending on the price volatility.
- Hydrogen storage was identified as a key factor for flexibility, with both small dedicated storages and large-scale shared storages being viable options. The study found that the design of hydrogen storage is highly case-specific, influenced by factors such as pressure levels and production-consumption profiles. Levelized cost of the compressor-tank combination was 0.14–2.72 €/kgH_2.
- The development of dynamic process models for methanol production under variable feed conditions supports the integration of renewable energy sources into industrial processes. Improving the minimum operating load of the synthesis from 80% to 20% could reduce the optimized hydrogen storage capacity by 44.7–71.7%.

- Results from methanol production simulation indicate that the minimum load is around 20%, with maximum allowable ramping rates of 3.25% per minute for ramp-down and 2.10% per minute for ramp-up between full and minimum load. The main limitation for the minimum load point is the operational lower limit of the compressors.
- IoT technology enables the collection, transmission, and processing of vast amounts of data from various points in the PtX process chain, including renewable energy generation, electrolysis, and chemical synthesis. The study developed a theoretical architecture integrating IoT, big data, and machine learning technologies, demonstrating how these technologies can enhance the efficiency and flexibility of PtX operations.

Use of existing natural gas infrastructure

- The suitability of existing natural gas pipelines for hydrogen transportation must be analyzed and several issues such as leakage, leakage detection, effects of hydrogen on pipeline assets and end users, corrosion, maintenance, and metering of gas flow must be considered.
- The blending of hydrogen into a natural gas grid has been found to be harmful for some end users, and de-blending can be expensive.
- The results concerning the applicable hydrogen odorants conflict. Some sources claim that there are already products available on the market, and others claim that there are still some challenges to be tackled before application.

Role of hydrogen and the value chain economics

- Hydrogen is expected to emerge as an important energy carrier constituting some of the final energy demand. However, its most important role will be as feedstock for further processing to e-fuels, e-chemicals, and e-steel.
- The study highlighted that H_2 production is the key factor determining the risks and costs in PtX value chains due to high capital expenditure (CAPEX) and operational expenditure (OPEX) costs.
- NCF (net cashflow) of H_2 production is critically dependent on the price of electricity consumed. In general, to reduce H_2 production costs, the price of electricity needs to be feasible, the weighted average cost of capital should be low, and investment subsidies may be necessary. Discount rates naturally also influence the results.
- In an NCF (net cash flow) study when the price of H_2 was set at 1200 €/t, the H_2 production was never feasible. This is noteworthy as all PtX value chains will involve this role. Thus making hydrogen production attractive is important for the successful development of the hydrogen economy. In other words, hydrogen production was identified as the least viable part of the value chain (value chain role) across different scenarios.
- Also a study was made to analyze the use of CO_2 point sources and atmospheric CO_2. The findings indicate that e-methanol production using point source CO_2 is more economically feasible than using atmospheric CO_2.
- A one-time investment generates greater cash flow, while being more capital-intensive and involving higher risks, when compared to the alternative approach of investing in phases. Phasing investments may reduce economic risks but may postpone some emission reductions compared to heavy one-time investments. This in turn will slower achieving the climate targets.

Future technologies

- A novel technology, molten carbonate electrolysis (CO_2 electrolysis), was showcased and further developed as part of the project. This technology can be used to transform carbon dioxide into valuable products such as graphene and carbon nanotubes.

Safety and sustainability

Safe use of hydrogen

- Human error is a significant factor, accounting for 87% of the incidents analyzed. It is often linked to insufficient training, inadequate safety procedures, and poor operational oversight.
- The most hydrogen-related incidents occur during the storage and distribution phases of the hydrogen value chain. Components, such as valves, fittings, and other connection points, are most vulnerable due to hydrogen's physical properties, such as high diffusivity and low molecular weight, which make it prone to leaks and failures.
- Transition from small-scale to large-scale hydrogen usage amplifies the potential for accidents.
- Safety studies highlight the need for safety assessments and management strategies.

Safety and hydrogen materials

- The studies highlight the risk for hydrogen embrittlement and fatigue, as the crack growth can be 100 times faster in hydrogen than in air. This amplifies the necessity for comprehensive studies on the materials and fatigue design for green energy infrastructure.
- The findings indicate that hydrogen exposure leads to significant material degradation, resulting in accelerated fatigue crack growth. Already 1 bar of hydrogen overpressure can reduce significantly transport pipe toughness and accelerate fatigue crack growth. This indicates that the general properties of steel in air do not correlate with its properties in a hydrogen environment.
- However, this does not imply that hydrogen pipelines cannot be used. Instead, it highlights the need to consider and control specific parameters during the manufacturing, construction and operation of hydrogen pipelines in the steel industry.
- The study demonstrated that natural gas pipelines designed for an 80-bar rated pressure could be repurposed for hydrogen transport at a reduced operating pressure of 50 bar. This will lead to a reduction in fatigue life that requires lifetime prediction methods by the establishment of a new model based on the HEENT model for repurposed hydrogen pipelines (i.e. lifetime assessment procedure).

Infrastructure resiliency

- Emerging geopolitical conditions and security practices indicate that Finland should carefully consider the export routes.
- An underwater offshore pipeline to Estonia or Germany, as planned in the Backbone plan, cannot be fully protected from intentional interference especially in international waters. Alternative or complementary evaluated routing could involve transit connection options through other territories instead of the planned international waters in the Baltics.
- The study recommends considering decentralized infrastructure options for domestic hydrogen production, delivery and utilization.
- Energy security in the hydrogen context will require coordination between various actors, including critical infrastructure owners, private security actors, and states.
- The integration of cybersecurity measures into the hydrogen value chain is crucial as the incidents have consistently risen since 2010 and the energy sector has become more digitized.

Emission saving potential

- The results indicate that PtX value chains can provide extensive emission savings, with green hydrogen (H_2) resulting in the least climate impacts compared to other forms ("colours") of hydrogen.
- From the climate perspective, hydrogen should be used in applications where possibilities to avoid fossil emissions are the largest. Most renewable-based PtX solutions can achieve up to 90% emission savings compared to their fossil-based counterparts.
- Carbon capture and utilization (CCU) applications do not provide as extensive emission savings as green steel, e-ammonia, or green hydrogen. The green steel value chain was identified as providing the most emission savings.

3 Research results

3.1 HYGCEL research goals

The goal of the research was to identify new PtX value chains based on Finland's renewable energy resources, and to provide guidance for building an optimal and efficient energy infrastructure that aligns with energy transition goals.

HYGCEL research was arranged into six work packages covering three perspectives: *markets and regulation*, *techno-economy*, and *sustainability and safety*. The following summary contains main results from individual work packages and tasks. The results were reported in academic publications during the project.

3.2 Work package descriptions

HYGCEL research was arranged into six work packages (figure 4) covering three perspectives: markets and regulation, techno-economy, and sustainability and safety.

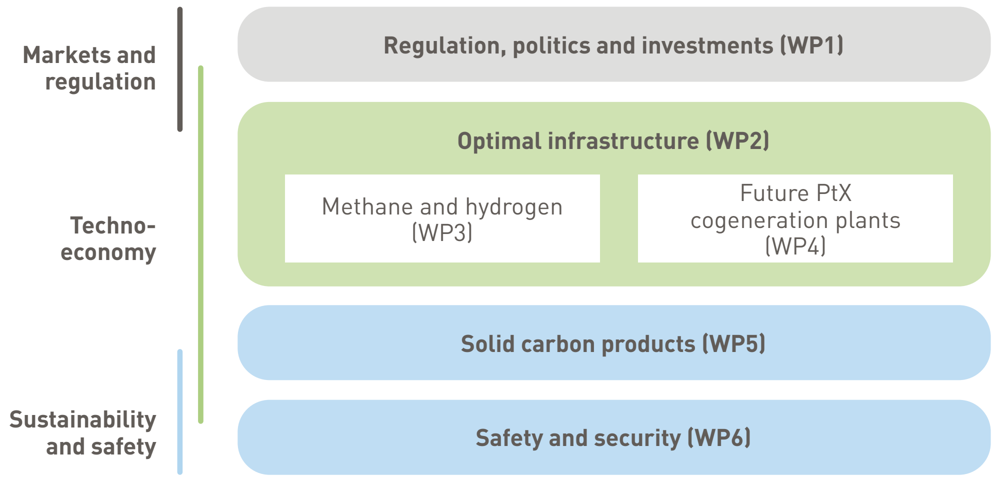

Figure 4. HYGCEL work packages.

WP 1 – Regulation, politics and investments

Motivation: A constantly growing number of countries have adopted hydrogen strategies and are in the process of designing regulatory frameworks aligned with their policy choices to support the penetration of various forms of hydrogen and hydrogen-based products. Raw material availability (electricity, hydrogen, and carbon dioxide) creates new location-based competitive advantages in production.

The task 1 focused on understanding the legislative frameworks for hydrogen uptake in leading countries and the regulatory choices made to support these policies. The primary goal was to identify the type of regulatory framework that can ensure national interests in Power-to-X (PtX) technologies, considering the regulatory choices in leading countries and the impact of international law, particularly international trade law, on hydrogen trade.

The task 2 explored the national visions for hydrogen development in key countries, the driving national interests, and the implications for Finnish business actors. The primary goals of the task were to understand the types of national visions for hydrogen development, the extent to which these visions can be realized, and how emerging hydrogen geopolitics will shape the choices of Finnish business actors.

The task 3a studied the level of awareness and acceptance among citizens regarding hydrogen projects and products, as well as the attitudes and willingness of investors to invest in hydrogen projects. The primary goals were to understand the determinants of awareness and acceptance among citizens and to analyze investors' attitudes and the financing of hydrogen projects.

The task 3b developed a capital investment model for analyzing investments in novel hydrogen-based Power-to-X (PtX) value chains and studied investment opportunities for PtX products in Finland. The research aimed to address two main questions: the creation of a capital investment model and the application of this model to a case study involving e-methanol production.

WP 2 – Optimal infrastructure

Motivation: Variable renewable electricity is the main primary energy source in the production of carbon-neutral products. It is available on a large scale and is almost unlimited. In addition, other feed materials, such as CO_2 and N_2, are also needed to manufacture carbon-neutral end products, such as methanol and ammonia. However, there will be regional differences in the availability of renewable electricity resources. Therefore, there is a need to analyze the generation potential and the competitiveness of producing different types of carbon-neutral end products in different geographical locations.

The task 2.1 focused on analyzing Finland's renewable electricity and CO_2 sources within the strategic context of energy infrastructure planning. The primary goal was to identify Power-to-X (PtX) related regional opportunities and challenges by evaluating location-specific metrics such as electricity generation potential, district heat demand, industrial CO_2 emissions, and available land space.

The task 2.2 explored the infrastructure and cost structures required for the optimization of Power-to-X (PtX) product value chains, focusing on e-hydrogen, e-ammonia, and e-methanol. The primary goal was to identify the necessary infrastructures and datasets for optimizing the PtX product value chain, analyze the required infrastructures for delivering PtX products to target sites, and investigate the development of infrastructure requirements over time. Additionally, the study aimed to obtain optimized cost structures for PtX products at generic onshore sites globally and analyze the key structure elements of the global value chain for PtX products.

The task 2.3 aimed to develop tools and methodologies for optimal operation of energy systems and sector-coupling in Finland. The primary goal was to showcase a holistic scenario building and analysis of energy systems infrastructures, including electricity, heat, hydrogen, and CO_2 grids and storages. The future energy system of Finland was modeled using the Backbone modeling environment based on the General Algebraic Modelling System (GAMS).

WP 3 – Methane and hydrogen

Motivation: The overall goal of the WP was to study how methane-based infrastructure, especially the gas network, could be used in the hydrogen-based energy system. Another goal was to study the role of biogas and biogenic/biological PtG gases and how they will utilize the network in the future.

The task 3.1 investigated the role of existing methane-based (natural gas) infrastructure in a hydrogen-based energy system. The primary goal was to understand the potential of existing pipeline infrastructure for transporting hydrogen and other gases and to evaluate the costs, energy consumption, and greenhouse gas emissions associated with different hydrogen transportation options in Finland.

The task 3.2 investigated the critical material aspects of hydrogen-based infrastructure, including pipelines, storage facilities, and network components. The primary goal was to understand the effects of hydrogen on materials used in existing methane-based (natural gas) infrastructure and to evaluate the feasibility of repurposing these infrastructures for hydrogen transport.

The task 3.3 investigated the potential of biomethanation in Finland, focusing on converting carbon dioxide (CO_2) from biogas into methane. The primary goals were to evaluate the potential increase in methane production at biogas plants by 2030, assess the environmental performance of using hydrogen (H_2) in biomethanation processes, and understand the effects of variations in gaseous feedstock availability and composition on the biomethanation process.

WP 4 – Future PtX cogeneration plants

Motivation: The goal of the work package was to model a single PTX plant at different system levels (electrolysis, CO_2 capture models, synthesis processes, heat and process integration, water treatment) and to integrate it into the surrounding operational environment.

The task 4.1 focused on developing dynamic process models in Aspen Dynamics to handle variations in electrolytic hydrogen input for green methanol and catalytic methanation processes. The primary goal was to design and implement process models that can operate effectively under variable feed conditions, which is essential for integrating renewable power sources with synthesis processes.

The task 4.2 studied the design and operation of Power-to-X (PtX) systems at the plant level, emphasizing flexibility, system integration, and optimization of unit operations and capacities. The primary goal was to study how PtX systems can be designed and operated to handle the intermittent nature of renewable energy sources, like wind and solar power, ensuring efficient and cost-effective production of hydrogen and e-methanol.

The task 4.3 focused on applying artificial intelligence (AI) methods to enhance Power-to-X (PtX) applications, specifically in renewable energy storage, hydrogen production, and methanol synthesis processes. The primary goal was to design a comprehensive AI-based infrastructure that utilizes advanced technologies, such as the Internet of Things (IoT), big data analytics, edge computing, and machine learning, to optimize PtX operations.

WP 5 – CO_2 solid carbon products

Motivation: This work package studied electrochemical reduction of CO_2 with molten salt electrolysis to solid carbon products, e.g. nanotubes.

The task 5.1 explored the potential of utilizing CO_2 to produce valuable carbon products through molten salt electrolysis. The primary goal was to evaluate the feasibility and market potential of solid carbon products, particularly nanostructures, produced by this method.

The task 5.2 focused on the conversion of CO_2 to elemental carbon via molten carbonate electrolysis, a process within the broader context of carbon capture and utilization (CCU). The primary goal was to optimize the process conditions to minimize energy consumption while ensuring high-quality carbon products.

The task 5.3 focused on the conversion of CO_2 to elemental carbon via molten carbonate electrolysis, aiming to upscale the process to an industrial level. The primary goal was to develop new reactor designs that enable the transition from small-scale to industrial-scale processes, including the impact of industrial power supplies on specific energy consumption and product quality.

WP 6 – Opportunities and risks

The tasks 6.1 and 6.2 explored the environmental and economic feasibility of Power-to-X (PtX) value chains, focusing on the potential to reduce greenhouse gas (GHG) emissions, cost-effectiveness, and the regulatory and financial risks threatening business. The primary goal was to assess whether PtX product chains reduce GHG emissions compared to conventional fossil-based products, evaluate the cost-effectiveness of reducing GHG emissions through PtX solutions, and identify the regulatory and financial risks that could impact business.

The task 6.3 addressed the operational risks and cybersecurity vulnerabilities associated with the hydrogen production and distribution value chain. The primary goals were to identify the primary operational risks in transitioning from small-scale to large-scale hydrogen production and distribution, and to analyze cybersecurity vulnerabilities in hydrogen infrastructure, particularly in regions with advanced smart grid systems, like Finland.

3.3 Task results

Task results are based on work reported in task reports in Attachments 1–18 and on project's website: www.lut.fi/en/hygcel/results/final-results.

Task 1.1 - Regulation of raw materials and end products

The results indicate that while the regulatory frameworks in the EU, US, and Australia are similar, there are significant differences driven by policy goals, market approaches, and the division of competences between federal and state levels. The EU framework is detailed and may risk overregulation, creating uncertainty for investors. It focuses on electrolyzer-based production, which benefits Finland but may slow the creation of a hydrogen market in the EU. Public subsidies in all three regions focus on green or clean hydrogen, with the US approach (at least until 12/2024) being more emissions-focused rather than renewable quality-focused. The EU framework's requirements are challenging for third countries to implement, slowing international trade. Different certification rules in various regions mean products must be certified for each import market.

For Finland, the regulatory frameworks are crucial for making final investment decisions in hydrogen facilities. The EU's leadership in regulatory development provides opportunities for public subsidies for hydrogen production, transport, and end-use. The Finnish industry benefits from the EU's focus on green hydrogen and electrolyzer technology, given Finland's strong conditions for producing green hydrogen and e-methanol. National state aid decisions for hydrogen production should be expedited to strengthen Finland's competitive position. The EU's detailed regulatory framework and subsidy mechanisms position it as a global leader in hydrogen regulation, influencing international standards and trade practices.

Task authors: Kim Talus, Sirja-Leena Penttinen, Moritz Wustenberg.

Task 1.2 - Geopolitical scenarios and investor opportunities

The results indicate that hydrogen fuel markets are likely to emerge in a fragmented manner due to highly different visions for the role of hydrogen, and consequently, different standards for renewable or clean hydrogen adopted in studied countries. Transport costs are expected to be higher than initially thought, and access to the High Seas may become limited due to geopolitical risks, reinforcing the trend towards more regional markets. Key countries pursue similar strong RDI support and demand creation policies, with China leading in mass development of electrolyzer production and Japan focusing on substantial cost reductions of highly efficient electrolyzers. Japan's hydrogen strategy has shifted to focus on electrolyzer technology, hydrogen applications in heavy transport, residential heating, and co-generation (of energy) of ammonia and coal. However, some of Japan's revised priorities appear misaligned with global energy transitions. Russia is unlikely to play a significant role in hydrogen value-added sectors globally, despite early phase projects with Norwegian and Japanese partners. Energy security in the hydrogen context will require coordination between various actors, including critical infrastructure owners, private security actors, and states.

For Finland, the emerging geopolitical conditions and security practices indicate that a direct hydrogen pipeline to Germany or Estonia may not be the most economically advantageous or easily secured option. Instead, higher value-added products such as e-ammonia and alternative trade routes via Sweden and Norway should be actively pursued. Decentralized infrastructure options should also be considered for domestic hydrogen production, delivery, and utilization systems, especially in areas without local access to biomass. These decentralized solutions may turn into business opportunities as resilient energy concepts, devices, and services are also needed in many other countries. The main markets for Finnish actors will likely be in central Europe and the UK, with the EU markets being the widest if the EU adopts stricter strategic autonomy policies. However, state aid in Finland for hydrogen development may not be on the same level as it is in some potential competitor countries, which may delay Finland's start in the hydrogen economy.

Task authors: Pami Aalto, Sarah Kilpeläinen, Anna Claydon, Minna Hanhijärvi.

Task 1.3a - Hydrogen investment acceptance

The results indicate that citizen acceptance of hydrogen projects is generally high, particularly for local establishments that are seen to positively influence living and well-being in the area. Acceptance is closely linked to information and knowledge, with better-informed citizens showing higher acceptance levels. The study found that innovative attitudes and interest in new energy solutions also facilitate acceptance. On the investor side, the sentiment analysis revealed a moderately positive overall investor sentiment, with Finland having a slight leading edge compared to the USA and Australia. However, investors still face high uncertainties, and various types of public sector and regulatory support are needed to grow the market. The interviews made for Finnish hydrogen projects highlighted the need for a wide range of funding sources, including grants, subsidies, and equity investors. Key promoting factors include cooperation schemes and long-term contracts for cheap energy supply and final product demand. However, barriers such as the capacity of electrolyzer production, unclear and unpredictable regulation, permitting processes, and a shortage of skilled experts were identified.

In Finland, the high level of citizen acceptance can be leveraged by actively spreading knowledge about hydrogen's potential in the energy transition towards green energy solutions. Finland's slight leading edge in investor sentiment is promising, but the high uncertainties and the need for public sector and regulatory support must be addressed to foster market growth. The findings suggest that both investor and citizen acceptance are crucial for advancing hydrogen projects. The study underscores the importance of addressing regulatory and market uncertainties to unlock the potential of hydrogen investments and strengthen the Finnish economy.

Task authors: Kaisu Puumalainen, Sanna Heinänen, Mariana Lyra.

Task 1.3b - Value chain economics of chosen products

The research involved creating an investment model using a design science research process. The model was applied to a case study focusing on e-methanol production, comparing two scenarios: one utilizing point source CO_2 and the other using atmospheric CO_2. The study analyzed different investment approaches, including one-time investments and phased investments, under various electricity price scenarios. The impact of subsidization on investment feasibility was also examined.

The findings indicate that e-methanol production close to point source CO_2 is economically more feasible than the utilization of atmospheric CO_2. For point source CO_2, one-time investment generates greater cash flows while being more capital intensive and involving higher risks when compared to the alternative approach, investing in phases. Feasibility differences between the value chain roles emerged, H_2 production being the least viable part of the chain across the scenarios. This is noteworthy as all PtX value chains will involve this role. Thus making hydrogen production attractive is important for the successful development of the hydrogen economy.

Another important factor seems to be subsidization that plays a significant role for investment feasibility, especially in H_2 production. Discount rates naturally also influence the results.

The research provides valuable insights for stakeholders in Finland regarding the economic viability of PtX investments under different conditions. The findings can guide decision-making processes for investments in hydrogen-based technologies and e-methanol production.

Task authors: Antti Ylä-Kujala, Timo Kärri, Antero Tervonen, Maija Luukka.

WP 2 – Optimal infrastructure

Task 2.1 - Energy resources and their efficiencies

The analysis revealed that the theoretical maximum wind power potential is between 700 and 2500 TWh annually, with around 70% clustered in Northern Ostrobothnia and Lapland. The theoretical maximum solar PV potential was evaluated to be 186 TWh for rooftops, peat areas, and meadows, increasing to about 1300 TWh when including all agricultural fields. Although solar PV sites are scattered, a significant portion of the potential is located along the coastal areas in Southern and Southwest Finland.

The results indicate that Finland has the potential to generate more energy than it currently utilizes, providing a substantial opportunity to convert and export surplus electricity and PtX products. The future energy system will be sector-coupled, with electricity serving as a primary and flexible feedstock that can be converted into other energy carriers and products, such as methanol, a versatile industrial feedstock and fuel, which can be synthesized from hydrogen and CO_2. In this, the hydrogen production will also play a crucial role in coupling electricity and heat sectors. The study highlights the need for effective transport solutions to fully utilize renewable electricity, hydrogen and bio-CO_2 resources, as some regions have significant renewable wind generation potential but lack CO_2 sources, and vice versa.

Finland has a significant potential to produce renewable electricity, with estimates suggesting it could generate over 10% of the EU's renewable electricity. Thus, Finland has the potential to play a larger role in the European economy by leveraging its renewable electricity potential.

However, deliberate actions are necessary to balance economic interests with considerations of biodiversity, landscape, and social equity, as some renewable electricity potential is in sensitive nature areas. Additionally, a major part of the bio-CO_2 resources are in areas at risk of lagging behind in renewable energy production, such as Eastern Finland, providing unique opportunities for these regions. Effective transport solutions and strategic planning of energy systems are crucial to fully harness Finland's renewable energy potential and achieve carbon-neutrality objectives.

Task authors: Jukka Lassila, Hannu Karjunen, Markus Salmelin, Otto-Eeti Räisänen.

Task 2.2 - Optimal national and international infrastructures

The main activities of the study included assessing the feasibility of e-hydrogen imports to Germany and Finland from regions with low-cost renewable electricity, such as Chile and Morocco, and comparing these imports to domestic supply. The study also analyzed the cost of imported e-ammonia and e-methanol to Germany, Finland, and Spain from Morocco and Chile, and evaluated the impact of transportation costs on final import costs. The research extended to case studies of Greenland and Egypt to understand the energy system implications of e-fuel exports.

The results indicate that e-hydrogen is economically unattractive for long-distance transportation due to high additional costs, making local production more viable. Main findings indicate that e-hydrogen should be transported only for short distances of not more than a few hundreds of kilometres.

e-Ammonia and e-methanol, however, can be economically feasible for transport, with shipping being more advantageous than pipelines for long distances.

The relative transportation costs of electricity, hydrogen, and CO_2 were compared to determine the optimal location for methanol synthesis in Finland, assuming new investments due to the full utilization of existing capacities. The results showed that transporting CO_2 to an electricity production site for e-methanol production resulted in the lowest product costs for all scenarios and years studied. The product costs for the other transportation cases, i.e. either electricity or hydrogen transported to a CO_2 source, were relatively similar: e-methanol product price with electricity or hydrogen transported was 3–13% more expensive in 2030 and was increasing to 5–15% in 2050 as the share of energy costs declined and the share of transportation infrastructure costs got more pronounced. Despite lower costs for CO_2 transportation, the slightly higher costs for power lines may be justified due to their greater flexibility and more diverse use cases.

The study found that Greenland and Egypt (the studied case regions) have the potential to become significant exporters of e-fuels and e-chemicals, benefiting from their abundant renewable resources. Greenland's transition to a renewable energy system could enhance energy security and provide additional export revenues, while Egypt could technically provide a significant portion of Europe's demand for e-fuels and e-chemicals, improving the perfomance of its domestic energy system.

The findings highlight the importance of considering infrastructure challenges and transportation costs in the planning and development of PtX product value chains. Effective planning of infrastructure and strategic investments are crucial for Finland to leverage its renewable energy potential and achieve energy sovereignty.

Additionally, the study underscores the need for Finland to balance economic interests with considerations of biodiversity, landscape, safety, and social equity and acceptance, particularly in regions with sensitive nature areas.

Task authors: Christian Breyer, Tansu Galimova.

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Task 2.3 - Scenarios for feasible infrastructures in Finland

The main activities in the study involved scenario analyzes to understand how different cases affect the national energy system structure and operation. The scenarios included Business as Usual (BAU), Self Sufficiency (SS), and Maximal Utilization (MU) for the years 2035 and 2050.

The analyzes focused on analysing energy balances in different regions, and the requirements for electricity and hydrogen transmission between regions. The analyses revealed that the energy imbalances between regions must be balanced by transferring energy between surplus and deficit areas.

The study highlighted the need to strengthen grids, either electric or gas grids, depending on the locations of hydrogen production units relative to electricity production units. If hydrogen production units are co-located with renewable electricity production, energy must be transmitted as hydrogen via gas grids, and conversely, if hydrogen production units are near end-use areas, energy must be transmitted as electricity via electric grids. Therefore, the strategic placement of hydrogen use significantly impacts the transmission requirements.

The study also highlighted the need for peak electricity transmission capacity, which varies depending on the scenario. This increases the importance of having mechanisms to reduce electricity transmission needs between areas to avoid costly investments.

In addition, the study emphasized the importance of flexible energy resources, such as the flexible operation of electrolyzers, energy storages (mainly hydrogen and heat), and import and export electricity transmission capacity to optimize energy production and usage in Nordic and northern European areas.

The results help Finland to evaluate the systemic requirements the PtX economy imposes on the entire energy system. Extensive investments are required to strengthen the existing energy transmission system to accommodate the increased energy transfer between distributed renewable energy production sites and end-use or final product refinery locations. Collaboration between energy producers, consumers, and delivery companies is essential to avoid unnecessary infrastructure costs and harmful market impacts. The study underscores the importance of considering all sectoral interconnections between hydrogen, heat, and CO_2 systems in the design of system structures.

Task authors: Yrjö Majanne, Venla Vilhonen, Sami Repo, Matti Vilkko.

WP 3 – Methane and hydrogen
Task 3.1 - Hydrogen in the gas transmission network

The study focused on the role of existing methane-based infrastructure in a hydrogen-based energy system. Its aim was to understand the potential of utilizing current pipeline infrastructure for the transport of hydrogen by repurposing the natural gas pipelines. The studies indicated that the suitability of every pipeline for hydrogen transport must be carefully analyzed and several issues, such as leakage, leakage detection, effects of hydrogen on pipeline assets and end users, corrosion, maintenance, and metering of gas flow, must be considered. The blending of hydrogen into a natural gas grid has been found to be harmful for some end users, and de-blending can be expensive. In addition, limited coverage and potentially unfavorable locations of existing pipelines in Finland may necessitate the construction of new hydrogen transfer pipelines. Some activity was also allocated to studies related to hydrogen gas odorization that is normally used in distribution gas pipelines. Based on a review it can be stated that the results concerning the applicable odorants conflict. Some sources claim that there are already products available on the market, and others claim that there are still some challenges to be tackled before application.

For analyzing the feasibility to utilize existing pipelines compared to other transportation options, five different hydrogen delivery pathways were reviewed. The pathway options included mill-site electrolysis (i.e., hydrogen manufacturing at the site), hydrogen pipeline transportation in new and repurposed pipelines, transportation of hydrogen in a pipeline as synthetic methane, and hydrogen delivery by shipping. A hypothetical steel mill located in Southern Finland was used as an example case. Findings indicate that mill-site electrolysis and hydrogen pipeline transportation (both new and repurposed) were the most feasible in terms of costs, energy consumption, and greenhouse gas emissions. The transportation of synthetic methane and hydrogen shipping were both found to be less feasible due to higher costs and energy consumption. However, the feasibility of each investment depends on several factors, including hydrogen volumes, transportation distances, and the location of hydrogen producers and users. It was found that detailed studies, using specific local input data, are required for individual investment decisions.

Task authors: Esa Vakkilainen, Satu Lipiäinen.

Task 3.2 - Material aspects in hydrogen and methane-infrastructure

The core activities of the study involved analyzing key properties for transport pipe material, including strength, ductility, and toughness, which are influenced by hydrogen embrittlement. The study primarily focused on the fatigue performance of materials, as fatigue crack growth rates are significantly higher in hydrogen environments than in methane environments. Linear Elastic Fracture Mechanics (LEFM) was utilized to model fatigue crack growth and to assess the feasibility of pipeline conversion, including determining appropriate inspection intervals. The results were published in several recent activities by LUT Mechanics of Materials [1–5].

The findings indicate that hydrogen exposure leads to significant material degradation, resulting in accelerated fatigue crack growth. The fatigue crack growth rate is up to 100 times faster in a hydrogen environment compared to a methane environment[4]. The study demonstrated that natural gas pipelines designed for an 80-bar rated pressure could be repurposed for hydrogen transport at a reduced operating pressure of 50 bar. Even 1 bar of hydrogen overpressure can reduce significantly toughness and accelerate fatigue crack growth, meaning that the general results of the steel properties in the air are not related to the material properties in the hydrogen environment. This does not mean that hydrogen pipelines can't be used. Instead, the required parameters need to be considered and controlled during the manufacturing of hydrogen pipelines in the steel industries and the construction of pipelines (e.g. evaluation of material grade assessment based on the newer generation of steel pipelines and local grades, Material Fabrication Method Assessment, and construction on site, as well as protection and lifetime assessment procedures). Some parts of these studies are still ongoing in collaboration between LUT Mechanics of Materials and steel industry companies, such as SSAB Europe and others (e.g. FOSSA II, Grant ID 5462/31/2023, WP2, Business Finland Project). Other relevant studies are being conducted, and additional studies should be planned to consider the required parameters that should be controlled during the manufacturing of hydrogen pipelines in the steel industry and the construction of pipelines, as well as to eventually test the pipelines in a hydrogen environment based on both the existing and emerging standards.

The analysis highlighted that the initial crack size, determined by manufacturing quality, and the critical crack size, governed by yield strength and fracture toughness, are key factors in assessing pipeline fatigue life. However, the complexity of damage remaining from natural gas service can affect the lifetime of the pipeline which will be the subject of future studies. Furthermore, the proposed reduced operating pressure of 50 bar will lead to a reduction in fatigue life that requires the establishment of a new model based on the HEENT model for repurposed hydrogen pipelines (i.e. lifetime assessment procedure).

In Finland, the findings suggest that existing natural gas pipelines should be adapted with caution, and the accelerated hydrogen-assisted crack can lead to premature fracture and toughness loss in normal hydrogen pressures. A thorough case-by-case assessment and integration of the recently developed model (e.g. the HEENT)[6] for monitoring hydrogen-assisted fatigue are crucial to ensure long-term safety and reliability.

Task authors: Kalle Lipiäinen, Timo Björk, Masoud Moshtaghi.

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Task 3.3 - Industrial applicability of biogenic PtG

The main activities of the study included evaluating the biomethanation potential in Finland from the perspective of available CO_2 in biogas and bioethanol plants. The environmental impacts of using H_2 in in-situ (inside the biogas reactor) and ex-situ (outside the biogas reactor) biomethanation processes were assessed using life cycle assessment (LCA) and compared to a more traditional CO_2 separation (i.e., removing of CO_2 from a raw biogas stream) using a membrane separation technology.

The results indicate that methane production at biogas plants in Finland could increase from approximately 130 Mm^3/a (1.3 TWh/a) in 2020 to around 540 Mm^3/a (5.4 TWh/a) by 2030, considering new biogas plants and the potential use of biomethanation technology. Biomethanation could account for about 30% of the methane produced. The LCA results showed that upgrading biogas by membrane separation achieves a 59% emission reduction, while ex-situ and in-situ biomethanation achieve reductions between 49% and 62%, depending on the electricity source for H_2 production. The study also found that in-situ biomethanation is more sensitive to standby periods in feeding compared to ex-situ biomethanation. The main impurities in CO_2-rich feedstocks that may negatively affect the biomethanation process include nitrogen and sulfur oxides, hydrogen sulfide, and heavy metals.

For Finland, there is still potential to enhance methane production. Evaluating the environmental performance using LCA can guide the development of biomethanation value chains towards more sustainable practices. Enhancing the utilization of waste streams is also important from the nutrient recycling point-of-view as e.g., anaerobic digestion produces nutrient-rich sludge as a side stream.

Task authors: Marika Kokko, Husain Patel, Jouni Havukainen.

WP 4 – Future PtX cogeneration plants

Task 4.1 – Dynamic modelling of synthesis processes

The main activities involved creating a dynamic simulation model for methanol production. The modeling was divided into two parts: crude methanol (a mixture of methanol and water) production and methanol purification (see the task report for the more detailed technical description of the modeling). This approach ensures that only the crude methanol production process needs dynamic modeling. The model was used to test different scenarios of power variation, focusing on the minimum load and ramping rates for the process.

The results indicate that the minimum load of the model is around 20%, with maximum allowable ramping rates of 3.25% per minute for ramp-down and 2.10% per minute for ramp-up between full and minimum load. The main limitation for the minimum load point is the operational lower limit of the compressors. The constructed control structure demonstrated that the process could effectively handle continuous variations in electrolytic hydrogen input.

In Finland, the development of dynamic process models for methanol production under variable feed conditions supports the integration of renewable energy sources into industrial processes.

This advancement can enhance the flexibility and efficiency of synthesis plants, allowing them to operate under fluctuating power conditions. Thus, the study provides valuable insights for improving process design and control structures. Additionally, the results can help evaluate the need and size of intermediate hydrogen storage to minimize overall production and storage costs.

Task authors: Hung Nguyen, Arto Laari.

Task 4.2 – Plant-level design and flexibility

The results of the study indicate that flexibility in PtX processes brings significant benefits, allowing for the production of green products while managing fluctuations in renewable energy production and prices. Hydrogen storage was identified as a key factor for flexibility, with both small, dedicated storages and large-scale shared storages being viable options. The study found that the design of hydrogen storage is highly case-specific, influenced by factors such as pressure levels and production-consumption profiles. The optimal operation and capacities of other processes, such as electrolysis, synthesis, and CO_2 capture, were also found to be case-specific, depending on input parameters and future cost assumptions. The research highlighted the importance of integrating processes and utilizing waste energy recovery to improve efficiency and reduce costs.

The findings provide practical examples for Finland of how PtX processes and plants can be designed and operated to maximize flexibility and efficiency. The study underscores the importance of optimizing hydrogen storage to consider whether storages should be built at local or national scales.

Task authors: Eero Inkeri, Hossein Enayatizadeh, Tero Tynjälä, Jaakko Hyypiä, Sampo Vilve.

Task 4.3 – Advanced data-driven methods in PtX operations

The results of the study indicate that IoT technology enables the collection, transmission, and processing of vast amounts of data from various points in the PtX production chain, including renewable energy production, electrolysis, and chemical synthesis. Big data analytics helps extract valuable insights from the data, optimizing resource allocation, improving efficiency, and reducing downtime. Machine learning plays a crucial role in predictive analytics, allowing PtX systems to forecast outcomes based on historical data and optimize operations.

The study developed a theoretical architecture integrating IoT, big data, and machine learning technologies, demonstrating how these technologies can enhance the efficiency and flexibility of PtX operations.

Implementing advanced data-driven technologies in PtX cogeneration plants can lead to digitalization of processes from data collection to predictive analytics. The developed IoT platform selection framework ensures that industries can choose the most suitable IoT platform based on their operational needs, facilitating the integration of renewable energy sources and supporting the hydrogen economy. By leveraging these innovative technologies, Finland can strengthen its position as a leader in sustainable energy systems.

Task authors: Mehar Ullah, Daniel Gutierrez Rojas, Pedro Nardelli

WP 5 – CO_2 solid carbon products

Task 5.1 - Solid carbon products and markets
Task 5.2 - Energy efficient CO_2 electrolysis
Task 5.3 - Industrial scale CO_2 electrolysis

The main activities of T5.1 included a literature review of existing solid carbon products, such as carbon fibers, carbon nanotubes, and carbon nano-onions. The results indicate that graphite is the largest carbon product market, with carbon nanofibers currently dominating the nanostructures market and expected to grow significantly. The production cost of carbon nanotubes was found to be less than 2 €/kg, making it a feasible option for further development. The study also revealed that the markets for the most expensive carbon (valuable) products are limited. The produced carbon nano-onions had a relatively low specific surface area, limiting their application in superconductors or filters but showing potential as raw materials for electrodes in batteries and electrolysis.

The results of T5.2 revealed that the choice of electrode materials significantly impacts the morphology and purity of the produced carbon. Nickel cathodes tended to produce spherical nano-onions, while steel-based cathodes resulted in tubular structures due to the presence of iron acting as a nucleation seed. The study also found that both electrolyte composition and electrolysis temperature affect the carbon morphology, with the effect of the electrolyte being more pronounced at lower temperatures. The Li_2CO_3-$CaCO_3$ electrolyte showed more promising results in terms of product quality compared to the Li_2CO_3-$BaCO_3$ electrolyte.

The results of T5.3 revealed that gas bubble size significantly impacts the current density distribution and the two-phase flow dynamics, affecting the uniformity of carbon deposition on the cathode surface. The study found that the electric field distribution is stronger at the corners of the cathode, leading to larger carbon deposits in those regions. The presence of metallic impurities, as identified in previous experimental work, also affects the carbon morphology. The CFD simulations provided valuable insights into the high-temperature process, which is challenging to measure directly. Additionally, the study showed that current ripples do not significantly affect product quality but do increase power consumption. The growing market for solid carbon products presents an opportunity for Finland.

Task authors: Tero Joronen, Jyrki Mäkelä, Miika Sorvali, Vesa Ruuskanen, Tuomas Koiranen, Emma Laasonen, Anafi Aini, Jero Ahola.

WP 6 – Opportunities and risks

Task 6.1 - Possibilities and risks arising from climate issues

Task 6.2 - Regulatory and financial risks threatening business

The results of the studies indicate that PtX value chains can provide extensive emission savings, with green hydrogen (H_2) having the lowest climate impact compared to blue, turquoise, and grey hydrogen. Carbon capture and utilization (CCU) applications do not provide as extensive emission savings as green steel, e-ammonia, or green hydrogen. The green steel value chain was identified as providing the biggest emission savings. Most renewable-based PtX solutions can achieve up to 90% emission savings compared to their fossil-based counterparts. For Finland, exporting low-carbon products can enable other regions to meet their climate targets, providing a "positive handprint" by offering low-carbon alternatives.

The studies also highlighted that H_2 production is the key factor determining the risks and costs in PtX value chains due to high capital expenditure (CAPEX) and operational expenditure (OPEX) costs. To reduce H_2 production costs, the price of electricity needs to be feasible, the weighted average cost of capital should be low, and investment subsidies may be necessary.

The studies underscore the importance of strategic investment timing in relation to emission savings: phasing investments can reduce economic risks but may postpone some emission reductions compared to heavy one-time investments. Additionally, the study emphasizes the need for public support and regulatory changes to make PtX value chains competitive against fossil-based alternatives.

All countries implementing PtX should focus on PtX value chains that achieve the highest emission reductions and provide the highest economic added value. Public support, low-cost capital, cost reduction development, and regulatory changes are needed to start the transition, as most PtX value chains cannot currently compete with fossil-based ones. The study underscores the importance of early decision-making in order to maximize the benefits from the PtX economy in achieving climate goals.

Task authors: Jani Sillman, Husain Patel, Rami Alfasfos, Jouni Havukainen, Risto Soukka.

Task 6.3 - Operational risks and cybersecurity

The results of the study indicate that most hydrogen-related incidents occur during the storage and distribution phases of the hydrogen value chain. Components, such as valves, fittings, and other connection points, are particularly vulnerable due to hydrogen's physical properties, such as high diffusivity and low molecular weight, which make it prone to leaks and failures.

Human error is a significant factor, accounting for 87% of the incidents analyzed, often linked to insufficient training, inadequate safety procedures, and poor operational oversight. The study emphasizes the need for enhanced safety training, improved maintenance protocols, and better design and materials for critical components to mitigate these risks.

The transition from small-scale to large-scale hydrogen usage amplifies the potential for accidents, highlighting the need for thorough safety assessments and management strategies. The study also identified gaps in current safety legislation and regulatory frameworks for hydrogen, suggesting to tailor more specific and stringent regulations to meet the unique challenges posed by hydrogen.

Regarding cybersecurity, the study highlights the increasing threat of cyberattacks on the energy sector, with a consistent rise in incidents since 2010. Political and espionage motives are predominant, with major energy companies being primary targets. The integration of cybersecurity measures into the hydrogen value chain is crucial as the energy sector becomes more digitized, particularly with the adoption of smart grids and IoT technologies. The study recommends well-designed safety procedures, increased awareness and education among workers, and effective communication among stakeholders to mitigate these risks.

For Finland, the findings emphasize the critical need for integrating robust safety and cybersecurity measures as the hydrogen economy scales up. Enhanced safety protocols, comprehensive training programs, and strengthened cybersecurity frameworks are essential to gain public trust and secure investment. Ensuring that these measures are in place will be crucial for the successful development and expansion of hydrogen facilities, supporting Finland's long-term environmental and economic goals.

Task authors: Rami Alfasfos, Jani Sillman, Esa Vakkilainen, Risto Soukka.

H2YGCEL

Appendices: Task reports

WP1 TASK 1.1

Regulation of raw materials and end products

ABSTRACT

Task 1.1 was motivated by the need to understand how countries leading the hydrogen uptake have designed their legislative frameworks and what regulatory choices they have made in support of the implementation of these policies. It focused on the question of what type of regulatory framework can ensure that national interests (both in terms of public and private actors) in P2X can be realized when considering the regulatory choices in leading countries in this area and how international law, and international trade law in particular, impacts the trade in hydrogen and related products.

These questions were studied through comparing the regulatory frameworks in the EU, the US and Australia. In this comparative approach, EU was used as the base-case and the US and Australian frameworks were compared to the EU framework. The findings confirm that the regulatory frameworks in these areas are similar but have certain significant differences. Some of these differences are driven by the policy goals (importer/exporter) of PtX products, i.e. hydrogen and its derivatives. Other differences are connected to the approach to markets (public vs private sector having the leading role, public sector leading the market formation in the EU and market forces having a more profound role in the US), available resources and the constitutional division of competences between the Federal and State levels. Results indicate clearly that the EU framework is leading the developments in this area globally.

In relation to EU regulatory framework, we also found that that the EU framework is extremely detailed, and the risk of overregulation is apparent. Similarly, we found that the future changes in the regulatory framework (especially through multiple delegated acts foreseen by the current regulations) create uncertainty for the investors, slowing the pace of investments in PtX projects.

MOTIVATION

The investments to clean hydrogen and its derivatives hold great promises in terms of achieving carbon neutrality on a global scale, but also in strengthening the Finnish economy. However, many final investment decisions are being held back by regulatory and market uncertainties. It is important to identify the main drivers and barriers from the investors' perspective. Furthermore, the lack of international standardization and differing regulatory structures hamper the international trade in PtX products. The regulatory framework for hydrogen is indicated in Figure 1.

Figure 1. The regulatory framework for hydrogen.

RESULTS

In all three case regions the first policy question was whether the focus should be on green hydrogen, or whether other forms of hydrogen should be included in the regulatory framework, subsidy schemes in particular. This policy level discussion was also connected with the available resources. In Australia and the EU, the decision was to focus on green hydrogen. The US approach was to a certain extent different, and the focus was on emissions reductions, rather than on renewable quality. In all three regions, all kinds of hydrogen can be produced and sold, but the public subsidy is focused on green or clean hydrogen.

The details of the regulatory frameworks in these three systems are connected to the vertical division of competences between federal and state levels. While there are strong similarities in the EU and the US systems, with strong EU level or Federal role, Australian approach is more focused on the State level regulation. However, also Australia has strong Federal level public subsidy schemes in place.

Another driver of the differing regulatory frameworks in the three systems, was the general approach to markets. The EU approach to energy markets has traditionally been public sector driven, and this is visible in the approach to hydrogen and PtX markets and their regulation. This entails that the EU level regulation is driving market development and uptake of hydrogen. Contrary to this, the US approach has traditionally been more market driven. Although this is also visible in the regulatory frameworks for hydrogen and PtX products, the Inflation Reduction Act (IRA) created a change in this respect. IRA creates a public sector subsidy mechanism that is geared to kick-start a hydrogen economy within the US. The Australian system is somewhere between the EU and the US, with focus on State level decision-making but significant role is given to the Federal level through the green hydrogen subsidy mechanisms.

The EU framework, in particular, is currently focused on electrolyser-based production and departs from the more traditional technology neutral approach. It leaves little scope for technical innovation in this area. This is beneficial for Finland but may slow down the creation of a liquid hydrogen market in the EU.

In terms of international trade, the EU framework for hydrogen and its derivatives apply fully to production of these products in third countries. However, as the EU regulatory framework is created by the EU and for the EU, some of the EU requirements for green hydrogen are difficult to implement and comply with in third countries. Such example is the rules around bidding zones, which are based on EU electricity market design. Also, a number of required important international agreements and international certification mechanisms are still missing and this is likely to slow down international trade in hydrogen. Different regions have different rules and for a potential importer, this means that the product has to be separately certified for all intended import markets. There are also international trade rules under the

WTO framework that applies to the future hydrogen trade and create certain constraints on national policy approaches, an example of this being the carbon border adjustment mechanism in the EU. Similarly, the national or EU level certification schemes for green hydrogen need to be designed in a way that does not impose unfair or restrictive requirements on imports, as this could lead to violations of WTO trade laws.

The Finnish industry is likely to benefit from the slower emergence of international trade in hydrogen and its derivatives. Finland aims to become a supplier of hydrogen within the EU and due to slow start in international trade, it faces less competition from third countries. Similarly, the focus on green hydrogen and electrolyser technology within the EU framework benefits the Finnish industry, as the conditions to produce green hydrogen and e-methanol in Finland are comparably strong, in particular because of the low energy costs. In order to further strengthen the competitive position of the Finnish industries, decisions on national State aid for hydrogen production and hydrogen value-chains should be taken without delay.

APPLICATIONS/IMPACT

The planned hydrogen facilities are mainly still waiting for investment decisions to proceed for building the facilities. The regulatory frameworks are in the makings and EU has been a global leader in this respect. The rules on the production of green hydrogen are in place, although there is some uncertainly regarding their future development. The subsidy mechanisms at EU level, but also national level, are focused on green hydrogen and provide opportunities for public subsidies for production, transport and end-use of hydrogen. There are still limited opportunities for subsidies in Finland, but Finnish companies can apply for EU level funding. Both EU and national funding for hydrogen economy needs to be significantly increased.

MAIN CONTACT

Kim Talus, UEF Law School, kim.talus@uef.fi

AUTHORS

Kim Talus, Sirja-Leena Penttinen, Moritz Wustenberg

WP1 TASK 1.2

Geopolitical scenarios and investor opportunities

ABSTRACT

Task 1.2 had three main research questions: (1) What types of national visions for hydrogen development exist in key countries of hydrogen geopolitics, and what types of national interests drive these visions? (2) To what extent can these national interests and visions be realized? (3) How will the emerging hydrogen geopolitics shape the choices of Finnish business actors? Regarding question (1), case studies were conducted on the national hydrogen visions in the USA, Australia, China, India, Japan and Russia, and the underpinning national interests. Regarding question (2), the structuration model of energy policy formation (e.g. Aalto et al. 2021) was adapted to the needs of hydrogen analysis, to study how various structural qualities enable and constrain visions and policies pursued. To answer question (3), more abstract country actor types were constructed: fossil fuel producers having to adapt to the demand for renewable and/or 'clean' hydrogen fuels (USA, Russia, Australia, Gulf Cooperation Council Member States); likely major exporters (Australia; possibly India); likely major importers (Japan, EU); and largely self-sufficient countries not expected to greatly shape global hydrogen fuel trade, but which could offer technologies (USA, China) (see Figure 1.2.1). The patterns of energy security and diplomacy were then analyzed for this actor constellation.

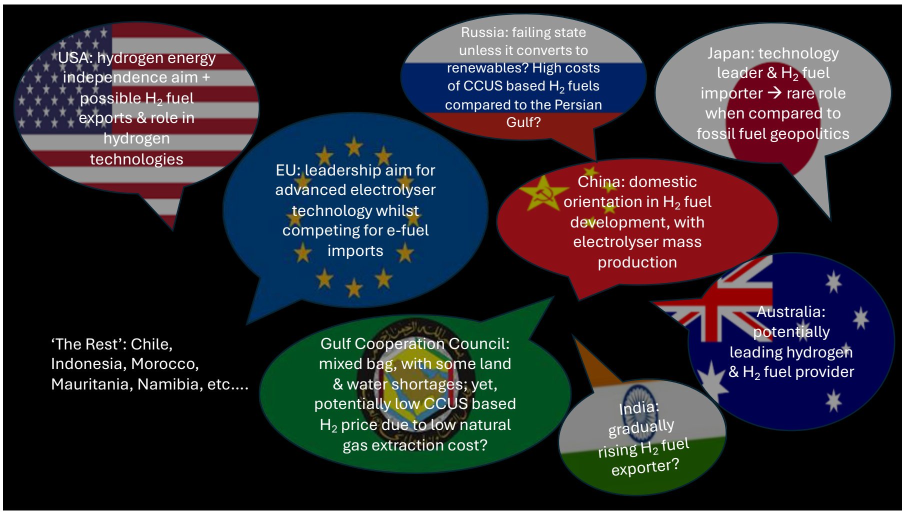


Figure 1.2.1 Some key actors in hydrogen geopolitics

MOTIVATION

Industrial development including hydrogen sectors increasingly takes place in a context wherein liberal trade and economy, and least-cost options including highly optimized supply chains are no longer the global rule. Instead, we find return to (green/clean) developmentalism, that is massive state aid in key countries, leading to state capitalism in some of them; along with friend-shoring and foreign investment screening, plus intensifying trade wars and competition among the USA, China, EU and Russia, as well the emergence of a wider BRICS, along with grey zone activities in NATO members states and military warfare in their neighbourhood. In this geopolitical setting, RDI and prospective trade in hydrogen value added sectors become infiltrated with political risks (i.e., regulatory risk) and geopolitical risks (targeting of vulnerabilities of states, and public and private companies including critical infrastructure owners, operators and users). Understanding the national interests of key countries, how these interests affect their industrial and commercial sectors, and the associated geopolitical risk is crucial for long-term RDI and infrastructure investments.

RESULTS

The results are disseminated via MBA type 5ECTS online course 'Geopolitics of hydrogen' offered via FiTech; briefs circulated via e.g. HYGCEL; all results are also compiled into a 65,000-80,000 collective monograph contracted with Palgrave, to be published in spring 2025.

The results indicate that:

- hydrogen fuel markets are likely to emerge first in a relatively fragmented form, given the different standards for renewable or 'clean' hydrogen adopted in key countries
- since transport costs are set to be higher than initially thought – as also suggested by other HYGCEL WPs – and access to High Seas may become limited due to terrorism, wars and threats by rogue states, the markets may remain quite regional
- key countries pursue largely similar, strong RDI support and demand creation policies (e.g. the EU, India, Japan, the USA) (for examples, see tables 1.2.1 – 1.2.2)

Command-and-control	Example	Notes
Performance standards	RFNBO (= renewable liquid and gaseous fuels of non-biological origin)	Criterion: 3.4kg of CO_2e/kg H_2 (volumetric); or 28.2g CO_2e/MJ (energy)
Targets		
EU gas and hydrogen package (2023/2024)	42.5% of H_2 renewable by 2030) = 4Mt; 60% 2035	Missing target for 2040; by 2050, hydrogen is to make up 13-20% of the EU energy mix (presumably 100% RFNBO)
ReFuelEU Aviation (Fit for 55 package)	1.2% of aviation fuel 'synthetic' RFNBO by 2030; rising to 35% by 2050	The 1.2% can include also CCUS based fuels fulfilling the RFNBO criteria
FuelEUMaritime (Fit for 55 package)	1% transport fuels renewable H_2 by 2030 (RFNBO) = 360.000t	Efforts to steer the 1% towards the aviation and maritime sectors
Blending obligation (Hydrogen and Gas package (2023/24)	Natural gas pipeline operators to accept 2% H_2 1.10.2025→ 75% tariff discount for low-carbon gas, 100% discount for renewable H_2	Initially, a 5% target proposed by the European Commission, watered down by Member States
Incentives		
Hydrogen Bank	720Me in subsidies in the first round (CfD type) for 1.58Mt production in 10 years, 7 projects (one of these to Finland); second round 1.2Me	Member States' own incentives for projects not receiving EU funding, e.g. DE 350M€; EST 39Me
RDI support	Clean Hydrogen Partnership: 190M€ (2024); ICPEI 6.9bln €; + Horixon Europe, RRF, etc.	Member States subsidise their own projects not qualifying for ICPEI, 10M€+ in BR, NET, DE, DK

Table 1.2.1 EU policy instruments for hydrogen development (examples)

Command-and-control	Examples	Notes
Performance standard	Green Hydrogen Standard for India (2023)	Criterion for RES based, incl. biomass; < 2.0 kgCO_2e/kg of H_2 (12months average); methodology TBA
Target	'Self-reliant India' scheme (2020)	Energy independence by 2047
Incentives		
Production subsidy	USD 25mln →5 Mt of 'renewable' hydrogen by 2030 (with 125GW RES capacity additions)	May reach 10 Mt/yr incl. exports
Competitive bidding scheme, 2.2bln USD	Subsidy for electrolyser development	Part of SIGHT programme
Competitive bidding scheme, 2.2bln USD	Subsidy for RES based H_2 production	Part of SIGHT; USD 0.64/kg) for 1st year, USD 0.51/k) for 2nd year; USD 0.38/Kg) for 3rd year
Waiver	Electricity transmission charge exemption	Until 2030/2036
Management instruments	Manufacturing zones for green H_2	Spatial planning policy
	H2 safety certification programme	
	H2 fuel quality control system	

Sources: e.g. IEA (2023); Pal et al. (2024); Government of India (2023)

Table 1.2.2 India's policy instruments for hydrogen development (examples)

- China appears to lead the mass development of electrolyser production, but mostly in less high-tech segments, whereas the RDI focus is on very substantial cost reductions of highly efficient electrolyzers in Japan (1/6 of current price);

- Japan has considerably revised its wide-reaching, pioneering 'Hydrogen society' strategy, after first intending hydrogen consumption in nearly all sectors, to focus on electrolyser technology; hydrogen applications in (heavy) transport; residential heating; and co-generation of ammonia with coal. However, some of these revised priorities appear ill-focused in global comparison. This can be explained by how Japan's energy sector has a long-term path-dependency on nuclear energy priority, and on (fossil) fuels use in heating and power generation. Because of these path-dependencies, Japan is opting for solutions out of sync with global energy transitions (coal-based ammonia), and for some highly inefficient solutions (imported gaseous H_2 fuels in heating vs. heat pumps). However, the Japanese industry's long-term competitive edge in efficiency improvements for its part is functional and path-creating for developing electrolysers and heavy transport applications (Figure 1.2.2);

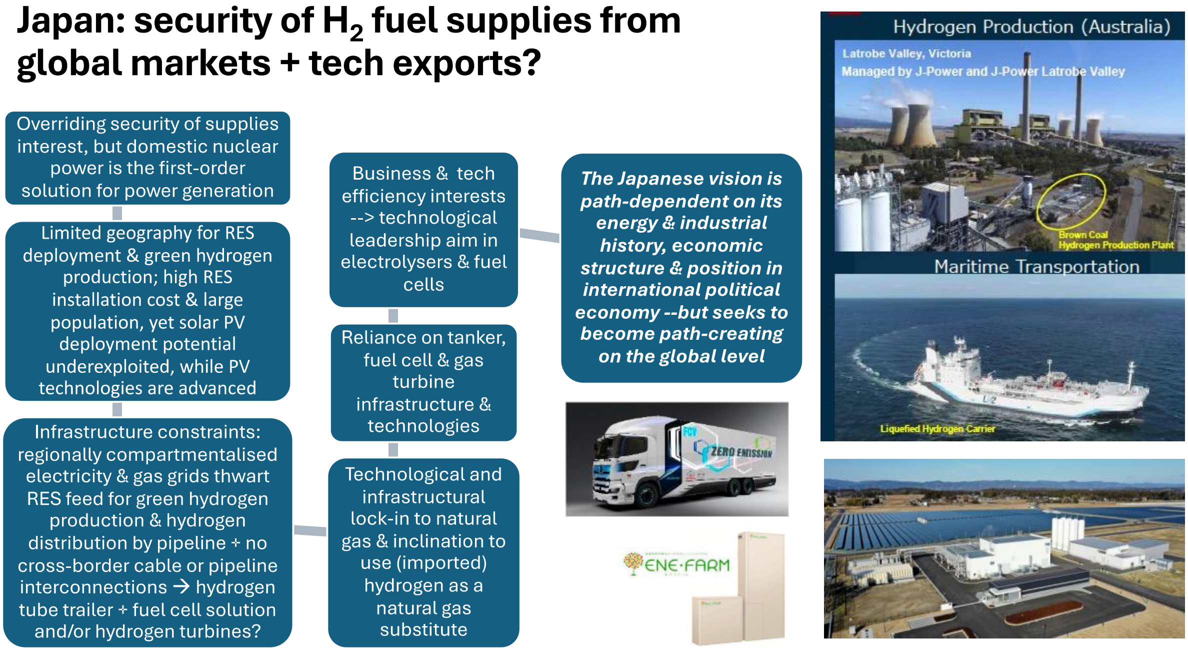


Figure 1.2.2 Some elements of Japan's hydrogen strategy

- out of major fossil fuel producers, Russia is unlikely to play much of a role in hydrogen value added sectors globally despite early phase projects e.g. with Norwegian and Japanese partners prior to 2022; however, Japan needs Russia as a geopolitical counterweight to China and North Korea, and may seek to store CO_2 in Russia's Sakhalin Island in the future;

- energy security in the hydrogen context will have a networked nature, requiring coordination between critical infrastructure owners and operators, private security actors and states, since no one actor is in full command of security practices such as technical resilience (critical infrastructure operators); risk management (e.g. insurance/owners), safety (companies for practice, authorities for requirements), local level resilience (municipalities), surveillance & intelligence (private and public); security governance (policing), and military protection of assets;

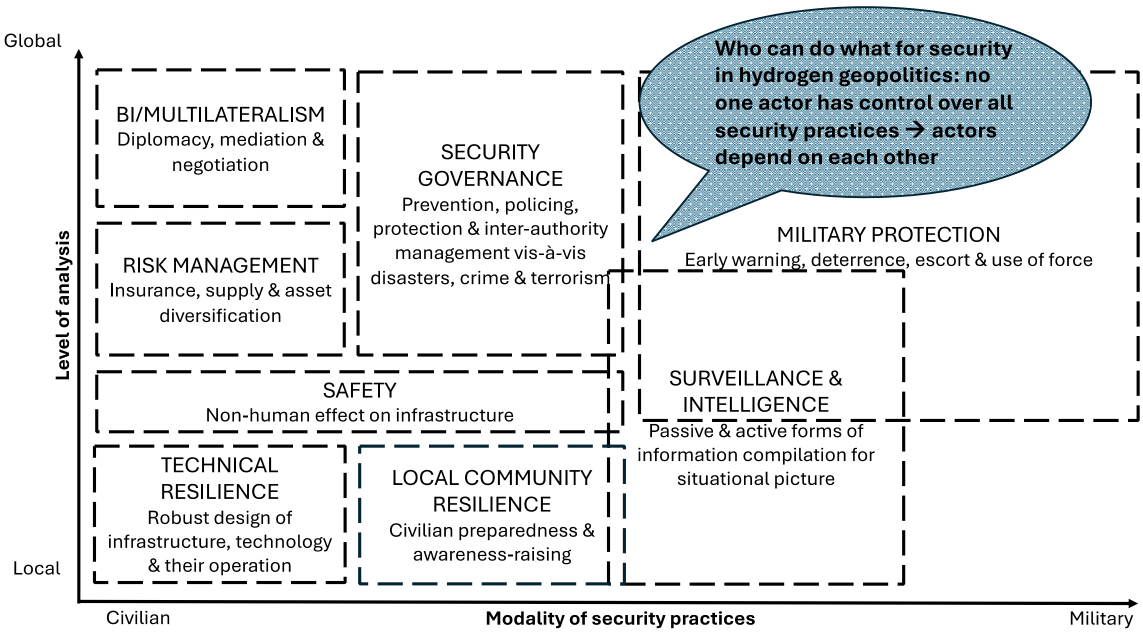


Figure 1.2.3 Security practices actors can use in hydrogen geopolitics

- regarding these security practices, the Finnish and EU focus so far in hydrogen infrastructure development leans heavily on technical resilience, safety and risk management practices. These will be insufficient on their own in the geopolitical conditions that have emerged since 2022. Notably, bilateralism or multilateralism cannot likely solve the problem due to the EU, Russia and NATO lacking diplomatic channels in the medium to long-term. Security governance for its part is as a rule functional when the damage has already been done, e.g. sabotage of infrastructure. Surveillance and intelligence can give early warning and act as deterrent against cyber threats (operation systems) and kinetic threats (rocket; missile; drone, etc.), whereas military protection is expensive and can ultimately be only partial. Planners of extensive, cross-national and/or undersea pipelines must take a notice of the vulnerabilities of such infrastructure and of required security practices.

- many H_2 fuel producer countries relying on maritime supplies via the High Seas, most prominently Persian Gulf exporters, will become vulnerable in case US-dependent military protection of the High Seas weakens (further), which may be an eventuality; EU & China will have a hard time replacing the USA in this function
- at the same time, most diplomatic activity to back up emerging hydrogen-based fuel trade is bilateral, whilst the capacity of major powers to agree on multilaterally may remain seriously compromised for several years, suggesting that global standards supporting the trade may develop slowly
- in this emerging setting, the main markets for Finnish actors will likely be in central Europe (e.g. Germany, Benelux) and in the UK, in the form of e-methanol/e-ammonia
- the EU markets would be widest for Finnish hydrogen-based fuels were the EU to adopt stricter strategic autonomy policies; however, several EU Member States are already developing hydrogen fuel trade with the EU's regional neighbours
- It is notable that state aid in Finland for 'hydrogen push' is not on the same level as that of some potent competitors, and this may delay Finland's start

APPLICATIONS/IMPACT

In the emerging geopolitical conditions – considering the security practices available for Finnish actors nationally and in the EU and NATO context – our conclusion regarding Finnish H_2 fuel exports is that a direct hydrogen pipeline from Finland to Germany or Estonia can be not only economically suboptimal as suggested by other HYGCEL work. It can also be difficult, or rather, impossible to secure in the current grey zone situation, let alone in a war situation for which Finland must also prepare. Hence not only higher value-added products such as e-ammonia but also alternative trade routes via Sweden and Norway should be actively pursued, including routing through Sweden, Norway and the Norwegian Sea, or Norway and the Barents Sea. Decentralized infrastructure options should also be considered as part of the domestic Finnish hydrogen production, delivery and utilization systems despite these lacking economies of scale benefits. Such systems may be especially relevant in areas with no local or nearby access to biomass. Prospectively, decentralized solutions may turn into business opportunities as resilient energy concepts, devices and services are needed also in many other countries than Finland.

MAIN CONTACT

Pami Aalto, Faculty of Management and Business/Politics, Tampere university;
pami.aalto@tuni.fi

AUTHORS

Pami Aalto, Sarah Kilpeläinen, Anna Claydon, Minna Hanhijärvi

WP1 TASK 1.3a

Hydrogen investment acceptance

ABSTRACT

Task 1.3a had two main research questions: (1) What is the level of awareness and acceptance among citizens (as consumers and community member nearby facilities) regarding hydrogen projects and products? What are key determinants of awareness and acceptance? (2) What are the investors' attitudes and willingness to invest in hydrogen projects, and how are the projects financed? The first question was analyzed by means of a survey targeted at citizens in Lappeenranta, and the second by analysis of investors' online discussions in USA, Australia and Finland, complemented by interviews in seven Finnish hydrogen projects. The findings indicate a moderately positive overall investor sentiment, where Finland seems to have a small leading edge compared to USA and Australia, but from the investor point of view the uncertainties are still very high and many types of public sector and regulatory support is needed to get the market growing. Concerning the citizen acceptance of hydrogen, it is on average very high. Most willing people are to accept local establishment, and they are seen to influence the living and well-being of the area.

MOTIVATION

The investments to clean hydrogen and its derivatives hold great promises in terms of achieving carbon neutrality on a global scale, but also in strengthening the Finnish economy. However, many final investment decisions are being held back by regulatory and market uncertainties. It is important to identify the main drivers and barriers from the investors' perspective. Furthermore, understanding the level and drivers of citizens' acceptance can indirectly contribute to solving the regulatory and demand visibility challenges.

RESULTS

At the individual level acceptance is closely attached to information and knowledge. The acceptance can be seen as a process moving from the generic level of accepting changes that are expected in energy transition and leading to various innovation. In the present study this referred to acceptance on hydrogen economy that covers an economic system in which fossil-based energy or raw materials are switched to hydrogen that is produced with clean or low-carbon energy and used as an energy storage or raw material. The generic acceptance requires knowledge of sustainable energy solutions and personal way of life supports sustainable goals. Moving the level of acceptance towards mode detailed and focused target like concrete establishments in the close living environment, the acceptance is facilitated by innovative attitudes and interest towards new energy solutions. In addition, the better citizen's objective knowledge of hydrogen and its characteristics, the higher the acceptance of new facilities being build. Figure 1 illustrates citizen acceptance of hydrogen at different levels (scale 1-5, 5 indicates high acceptance).

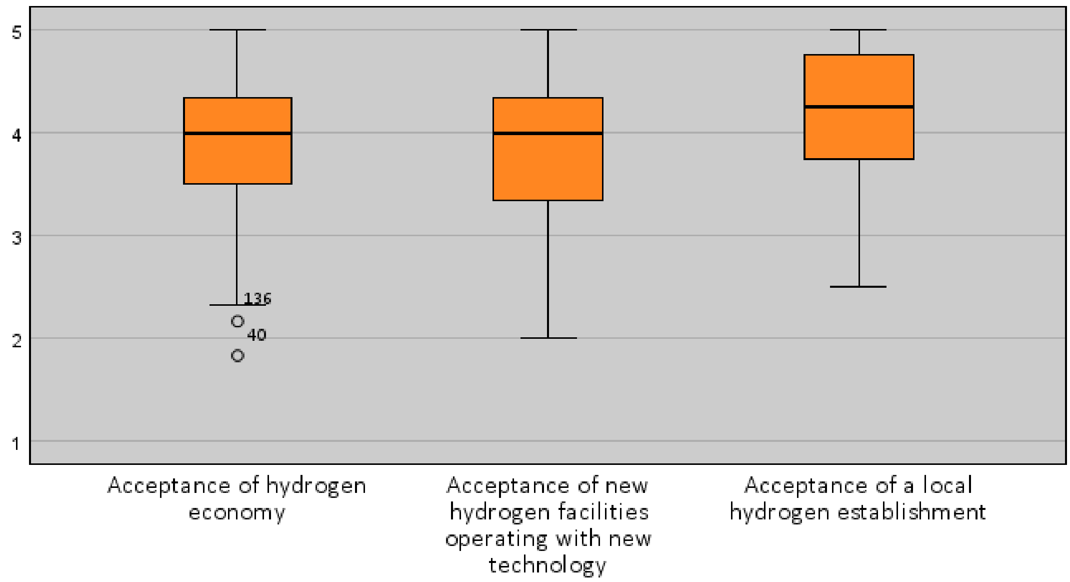


Figure 1. The citizen acceptance of hydrogen in generic and more specific levels.

In terms of investors' attitudes, the aspect-based sentiment analysis of retail investors' comments in thirteen online discussion forums during Jan 2019 – Mar 2023 revealed that the discussion is way more active in Finland than in USA or Australia. The share of positive sentiment was about 30% in all countries, but negative sentiment was more prevalent in USA and Australia (20-24%) than in Finland (7%). The themes of the investors' discussions were categorized in nine aspect groups with general aspects, transport and finance being the most common themes (Figure 2). Safety was not much discussed, but the sentiment was more negative than for other aspect groups (Figure 3). Discussion about investments was most active in Finland in the year 2020, whereas USA and Australia peaked in 2021. Despite the amount of discussion decreased, there was no downward trend in the share of positive sentiment.

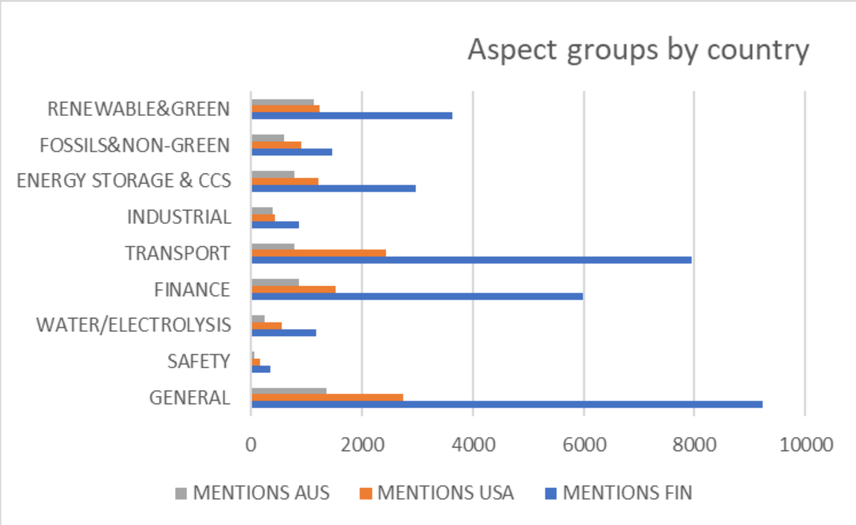


Figure 2. Activity of investor discussion by theme and country.

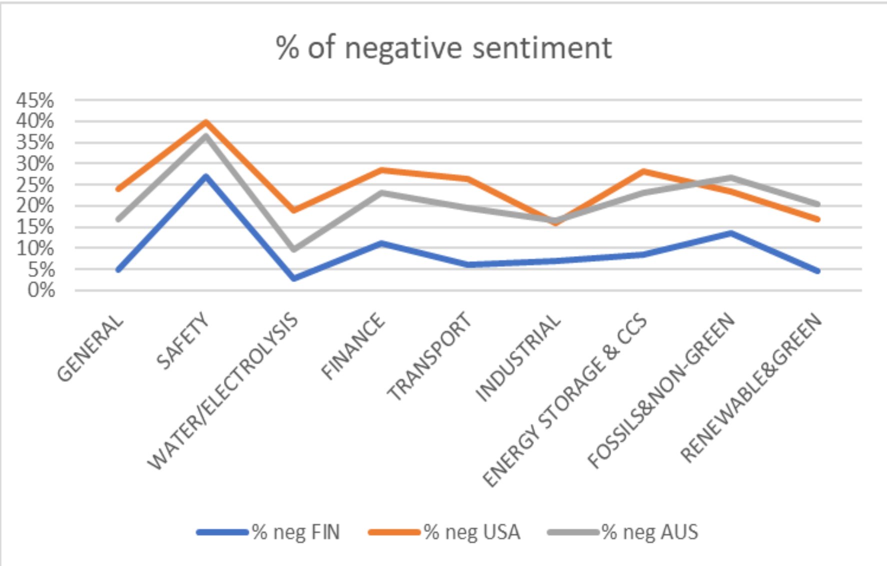


Figure 3. Share of negative sentiment by theme and country.

The interviews with seven hydrogen projects at different stages of maturity in Finland revealed that the vast scale of required investments necessitates a wide range of funding sources including grants, subsidies, and various types of equity investors. Co-operation schemes and long contracts for cheap energy supply and final product demand are seen as key promoting factors but numerous barriers are perceived, e.g. in the capacity of electrolyzer production, unclear and unpredictable regulation, permitting processes, and shortage of skilled experts.

APPLICATIONS/IMPACT

The planned hydrogen facilities are mainly still waiting for investment decisions to proceed for building the facilities. Both investors and citizens acceptance are needed for things to happen. Citizen acceptance can be promoted by actively spreading the knowledge related to hydrogen's possibilities in energy transition towards green energy solution. Finland seems to have a small leading edge in investor sentiment compared to USA and Australia, but from the investor point of view the uncertainties are still very high and many types of public sector and regulatory support is needed to get the market growing.

MAIN CONTACT

Kaisu Puumalainen, LUT Business School, kaisu.puumalainen@lut.fi

AUTHORS

Kaisu Puumalainen, Sanna Heinänen, Mariana Lyra

WP1 TASK 1.3b

Investment modeling of PtX value chains

ABSTRACT

Task 1.3b had two main research questions: (Q1) What kind of capital investment model can be established for analyzing investments in novel hydrogen-based PtX value chains? (Q2) How investment opportunities for PtX products can be studied in the Finnish context by applying modeling and case study approaches? The first research question (Q1) was covered by creating an investment model of PtX value chains using design science research process. The second research question (Q2) was addressed with an e-methanol value chain case study. A multi-role investment model was achieved and applied to the case study. The findings indicate that e-methanol production close to point source CO_2 is economically more feasible than the utilization of atmospheric CO_2. For point source CO_2, one-time investment generates greater cashflows while being more capital intensive, and involving higher risks, as compared to the alternative approach, investing in phases. Feasibility differences between the value chain roles emerged, H_2 production being the least viable part of the chain across the scenarios. Another important factor seems to be subsidization that plays a significant role for investment feasibility, especially in H_2 production. Discount rates naturally also influence the results.

MOTIVATION

PtX value chain investment modeling is essential for optimizing the transition to sustainable energy systems. By forecasting costs, returns, and potential risks, these models enable stakeholders in different value chain roles to make informed decisions about capital investments in technologies that convert renewable energy into valuable products, such as hydrogen, synthetic fuels, and chemicals. This kind of modeling approach not only enhances understanding of economic viability, but also accelerates the adoption of green technologies, reduces carbon emissions, and supports global efforts to combat climate change.

RESULTS

The value chain case study compared investments in e-methanol and related hydrogen production close to point source CO_2 (Case1) and using atmospheric CO_2 (Case2). Case 1 illustrates that the two scenarios, **one-time investment** and **investing in phases**, perform very differently (see **Figure 1** and **Table 1**). Net cashflow (NCF) for one-time investment ranges between -340 M€ ($Case1_{on}$-10) and 463 M€ ($Case1_{oll}$-10), while investing in phases sees less variation in NCF ranging from -168 M€ ($Case1_{pn}$-10) to 199 M€ ($Case1_{pll}$-10). The cashflow generating potential of one-time investment is evidently greater than that of investing in phases, especially in case of the lowest electricity price that approaches an average price of 27 €/MWh. Plotting NCF over time enables different analyses, such as how each value chain role fares in comparison to others, what is the total investment expenditure, and how much subsidization of H_2 production influences the results.

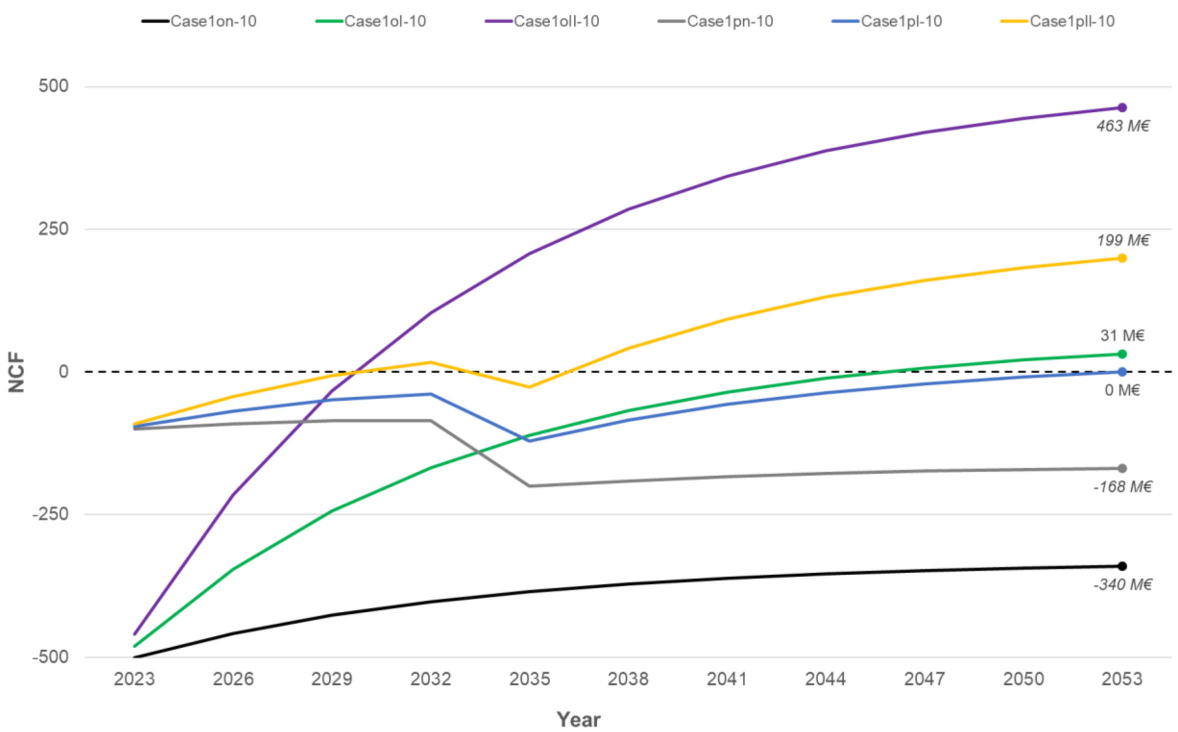


Figure 1. One-time investment vs. investing in phases

$Case1_{on}$: one-time investment, normal electricity price (black)
$Case1_{ol}$: one-time investment, low electricity price (green)
$Case1_{oll}$: one-time investment, lowlow electricity price (purple)
$Case1_{pn}$: investing in phases, normal electricity price (grey)
$Case1_{pl}$: investing in phases, low electricity price (blue)
$Case1_{pll}$: investing in phases, lowlow electricity price (gold)

Sub-indexes are as follows:
o - one time investment
p - investment in phases
n – normal electricity price scenario (wind 45 €/MWh, solar PV 55 €/MWh)
l – low electricity price scenario (wind 35 €/MWh, solar PV 45 €/MWh)
ll - very low (low low) electricity price scenario (wind 25 €/MWh, solar PV 35 €/MWh)

The number after the dash indicates the discount rate applied in the scenario.

Table 1. A summary of results for the different scenarios

NCF	$Case1_{on\text{-}10}$		$Case1_{ol\text{-}10}$		$Case1_{oll\text{-}10}$		$Case1_{pn\text{-}10}$		$Case1_{pl\text{-}10}$		$Case1_{pll\text{-}10}$	
CO_2 provider	76	M€	81	M€	88	M€	33	M€	34	M€	37	M€
H_2 provider	-856	M€	-514	M€	-128	M€	-392	M€	-233	M€	-55	M€
e-methanol producer	440	M€	464	M€	503	M€	191	M€	200	M€	217	M€
Value Chain with Subsidy	**-340**	**M€**	**31**	**M€**	**463**	**M€**	**-168**	**M€**	**0**	**M€**	**199**	**M€**
Tot. Investment	518	M€	518	M€	518	M€	245	M€	245	M€	245	M€
Profit. Index	**-66 %**		**6 %**		**89 %**		**-69 %**		**0 %**		**81 %**	
No Subsidy	**-631**	**M€**	**-258**	**M€**	**173**	**M€**	**-289**	**M€**	**-120**	**M€**	**82**	**M€**
Tot. Investment	808	M€	808	M€	808	M€	368	M€	368	M€	368	M€
Profit. Index	**-78 %**		**-32 %**		**21 %**		**-79 %**		**-33 %**		**22 %**	

Note: profitability index = NCF / total investment, subsidy = 60% of technical investment (H2 production)

Although one-time investment performs better in absolute terms (i.e., in NCF), it also carries a heavier CAPEX burden compared to investing in phases (518 M€ vs. 245 M€), which translates to similar profitability indexes across the different scenarios. The higher uncertainty inflicted by heavy CAPEX should be factored in investment decision making, thus making investing in phases an attractive alternative considering the state of the PtX market.

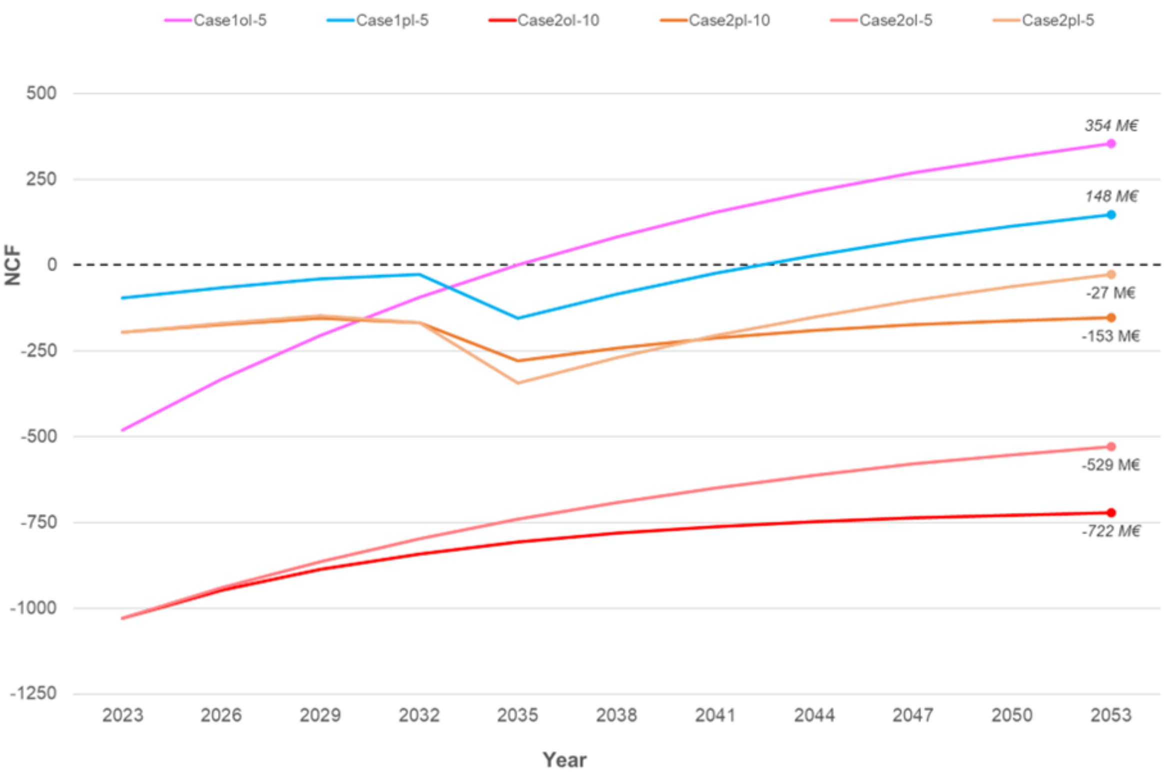
Investment subsidy for the technical investment in H_2 production impacts NCF significantly, moving the point of profitability towards lower prices of electricity. **Subsidization is hence another factor** that may impact the soundness of PtX investments.

NCF of H_2 production is critically dependent on the price of electricity consumed in the electrolysis. When the price of H_2 is set at 1200 €/t, **the H_2 production is never feasible**. $Case1_{pll}$-10 can reach NCF of only -55 M€ at the lowest electricity price. This is noteworthy as all PtX value chains will involve this role and thus making hydrogen production attractive is important for the successful development of the hydrogen economy. Lastly, it should be noted that the transportation and storage expenditure in relation to the overall electricity expenditure is minimal. These costs ranged from 0.97% to 1.16% depending on the scenario.

When comparing Case2 (atmospheric CO_2) against Case1 (point source CO_2), one-time investment as well as investing in phases **demonstrate rather poor economic performance** (see **Figure 2** and **Table 2**). When CO_2 is captured from the atmosphere, NCF of $Case2_{ol}$-10 is very low at -722 M€ and remains quite low at -153 M€ for $Case2_{pl}$-10. Even at a 5% weighted average cost of capital (WACC), the atmospheric CO_2 route is not economically feasible, although Case2$_{pl}$-5 comes relatively close at -27 M€ NCF. At 5% WACC, atmospheric CO_2 cannot match point source CO_2 at the initial 10% capital cost either. As can be seen, **the cost of capital has a considerable influence** on the economic feasibility of PtX investments.

The investment **utilizing atmospheric CO_2 is significantly more CAPEX intensive** than investment close to point source CO_2, which is seen in both one-time investment (1029 M€ vs. 518 M€) and investing in phases (691 M€ vs. 245 M€). Heavy CAPEX of atmospheric CO_2 results in negative NCFs and poor profitability indexes. Removing the subsidy from H_2 production makes the situation worse as even the best performing scenario, Case2$_{pl}$-5, declines from -27 M€ to -182 M€. We can conclude that investment utilizing atmospheric CO_2 is nowhere near economically feasible when the value chain is not subsidized.

Figure 2. Comparison of alternative CO2 sources: point source vs. atmospheric



Case2$_{ol}$: one-time investment, low electricity price (red)
Case2$_{pl}$: investing in phases, low electricity price (orange)
Case1$_{ol}$: one-time investment, low electricity price (magenta)
Case1$_{pl}$: investing in phases, low electricity price (blue)

Sub-indexes are as follows:
o - one time investment
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l – low electricity price scenario (wind 35 €/MWh, solar PV 45 €/MWh)
ll - very low (low low) electricity price scenario (wind 25 €/MWh, solar PV 35 €/MWh)

The number after the dash indicates the discount rate applied in the scenario.

Table 2. A summary of results for the different scenarios

NCF	Case1$_{ol-5}$	Case2$_{ol-10}$	Case2$_{ol-5}$	Case1$_{pl-5}$	Case2$_{pl-10}$	Case2$_{pl-5}$
CO_2 provider	172 M€	-749 M€	-842 M€	89 M€	-147 M€	-142 M€
H_2 provider	-683 M€	-554 M€	-747 M€	-400 M€	-246 M€	-423 M€
e-methanol producer	865 M€	581 M€	1060 M€	459 M€	240 M€	538 M€
Value Chain with Subsidy	**354 M€**	**-722 M€**	**-529 M€**	**148 M€**	**-153 M€**	**-27 M€**
Tot. Investment	518 M€	1029 M€	1029 M€	245 M€	691 M€	691 M€
Profit. Index	**68 %**	**-70 %**	**-51 %**	**60 %**	**-22 %**	**-4 %**
No Subsidy	**64 M€**	**-1010 M€**	**-817 M€**	**-8 M€**	**-272 M€**	**-182 M€**
Tot. Investment	808 M€	1317 M€	1317 M€	368 M€	910 M€	910 M€
Profit. Index	**8 %**	**-77 %**	**-62 %**	**-2 %**	**-30 %**	**-20 %**

Note: profitability index = NCF / total investment, subsidy = 60% of technical investment (H_2 production)

APPLICATIONS/IMPACT

PtX production plants are waiting for investment decisions due to economic and other types of uncertainties. Investment modeling of PtX value chains produces economic insights into elements of investment decision making. The findings highlight investment viability under different conditions, such as varying electricity price and investment subsidization, for one-time investment versus investing in phases using point source and atmospheric CO_2 in e-methanol production. The modeling approach provides guidance for stakeholders in different value chain roles in making informed investment decisions.

MAIN CONTACT

Antti Ylä-Kujala, Industrial Engineering and Management, antti.yla-kujala@lut.fi

AUTHORS

Antti Ylä-Kujala, Timo Kärri, Antero Tervonen, Maija Luukka

WP2 TASK 1

Energy resources and their efficiencies

ABSTRACT

The activities of task 2.1 involved the detailed analysis of Finland's renewable electricity and CO_2 sources in the strategic context of energy infrastructure planning. The task identified PtX-related regional opportunities and challenges by comparing and evaluating location-specific metrics like electricity usage, district heat demand, industrial CO_2 emissions, and available land space. Geographic information system (GIS) tools were used to identify the exact location and the production potential of renewable electricity. Furthermore, the identified wind and solar potentials were compared against current and expected future electricity demand and compared with the location of large-scale CO_2 point sources, and district heat demand. The analysis suggests that Finland has the potential to produce even above 10% of EU's renewable electricity due to significant wind and solar potential. Our land-use based estimate for theoretical maximum wind power potential reached 1600 TWh (sensitivity analysis ranged between 700 – 2500 TWh), of which around 70% was clustered in North Ostrobothnia and Lapland. Theoretical maximum solar PV potential was evaluated to be 186 TWh for all rooftops, peat areas and meadows, increasing to about 1300 TWh when all agricultural fields are included. Although the solar PV sites are scattered into small segments, a significant portion of the potential is located along the coastal area in Southern and South-Western Finland. These estimates provide a basic understanding about energy transport needs between the areas of Finland, providing a solid foundation for Finland's further energy infrastructure planning.

MOTIVATION

A renewable electricity-based energy system will require diverse infrastructural elements, and the renewable power production and power grids will be the key enables of that. The new electricity infrastructure will need to be capable of connecting renewable power resources, alleviating the national bottlenecks, and ensuring transmission to neighboring countries. Molecule-based energy transmission will be necessary to deliver fuel and feedstock in hard-to-abate sectors such as steel manufacturing and heavy-duty transportations. Achieving carbon-neutrality objectives on time requires foresight in investment timing and efficient allocation of funds to the areas where the transmission needs are the greatest. Just and rational decision-making depends on an accurate understanding of resource locations, technical realities, and the socio-economic impacts of various energy solution pathways. This work enables data-driven strategic energy system planning in Finland.

RESULTS

Regional renewable power production potentials were evaluated on the basis of land availability. The land availability in turn, is highly dependent on the underlying assumptions regarding setback distances and various types of limiting criteria. This type of bottom-up approach allows a detailed analysis of the placement of individual wind turbines, providing baseline information for energy system studies, and for the power grid development, in particular. The detailed study that was made resulted a total production potential for wind power from around 700 TWh to an impressive 2500 TWh of annual production. Solar PV production potential could similarly reach 1300 TWh, although the majority of this potential lies on agricultural land which is currently in active use. Therefore, these figures represent the highest theoretical potential from a land-use perspective, and it can be assumed that the realistic production capability will be less than that. Combined production potentials for solar and PV are illustrated in **Figure 1**.

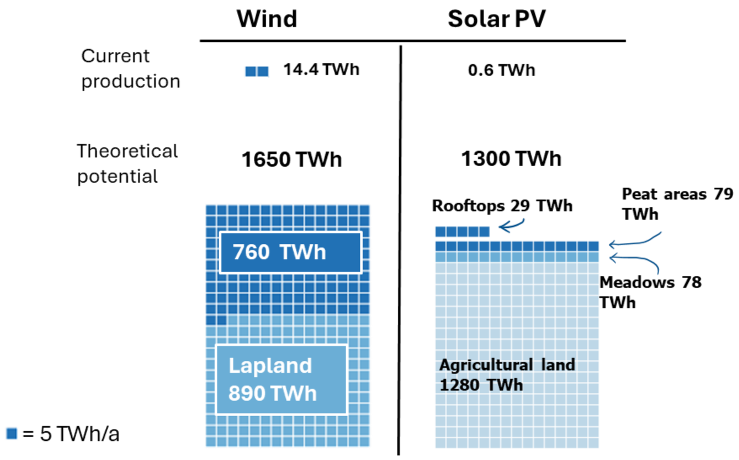


Figure 1. Finland's annual wind and solar PV production potential as obtained from the land-availability analysis.

In a future energy system, electricity will serve as a primary and flexible feedstock that can be converted into other energy carriers and products. The future energy system will be sector coupled and significant development steps have already been in that. In the future, production of hydrogen will couple electricity and heat sectors, and hydrogen production and use will further extend these coupling opportunities to other industrial sectors. One practical example of this extension is methanol, a versatile industrial feedstock and fuel that may be synthetized from H2 and CO2.

Figure 2 presents a regional overview of these opportunities. The figure points out renewable wind potential alongside current electricity demand in the area. Additionally, it shows the amount of electricity that is required to convert the available CO2 from large industrial point sources into methanol. In addition, the amount of heat produced in electrolyses and in syntheses is approximated. Full utilization of bio-based CO2 sources (into methanol) would require twice the amount of electricity currently used in Finland. Coupling the electrolyser waste heat to district heat network might be a challenge, as the availability of renewable power generation sites and hydrogen production will not take place in the regions having the largest district heat demand.

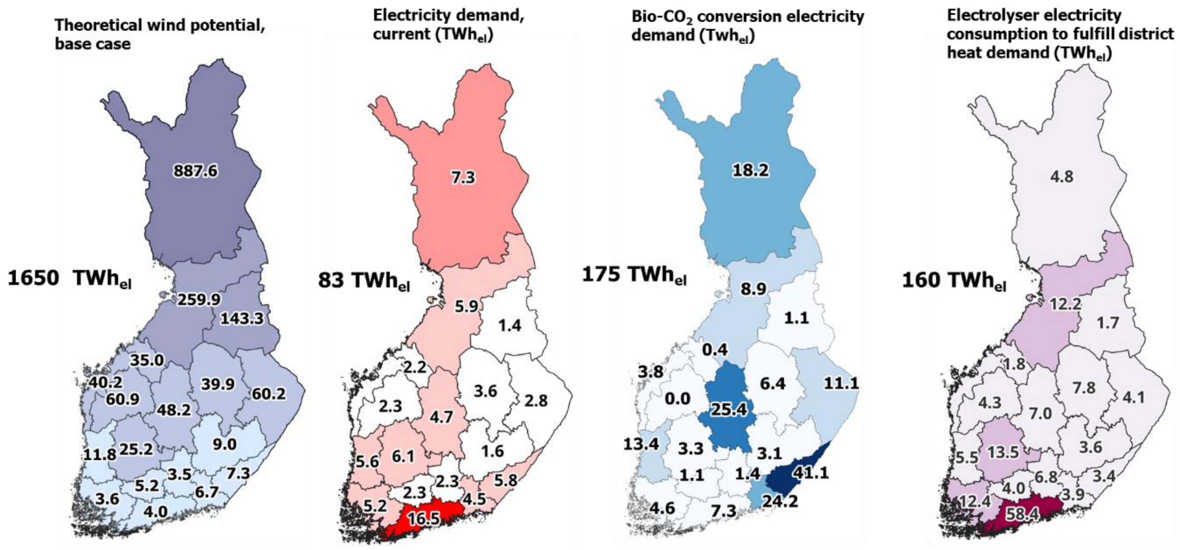


Figure 2. Regional overview of renewable wind production potential, current electricity demand, methanol, and heat potentials.

Hydrogen and CO_2 capture activities are likely to locate in special industrial sites, similar to the Porthos CCUS hub in Rotterdam. Implementing the first electrolyser plants alongside suitable CO_2 sources is relatively straightforward due to small volumes involved. However, as production volumes increase and the most accessible sources have been utilized, transport distances will increase as resources will need to be gathered from a larger area.

Figure 3 illustrates the situation where each wind site is integrated to the closest point source of CO_2. The figure shows that, some regions have a significant renewable wind generation potential but no CO_2 source, and vice versa. Transportation of CO_2 has been implemented on an industrial scale for decades. The study highlights the fact that CO2 will be a potential raw material to get transported alongside electricity and hydrogen pipeline transmission. Each of the stream will have their own characteristic transportation challenges and costs. So far it seems that no single transport solution can be said to be better the other.

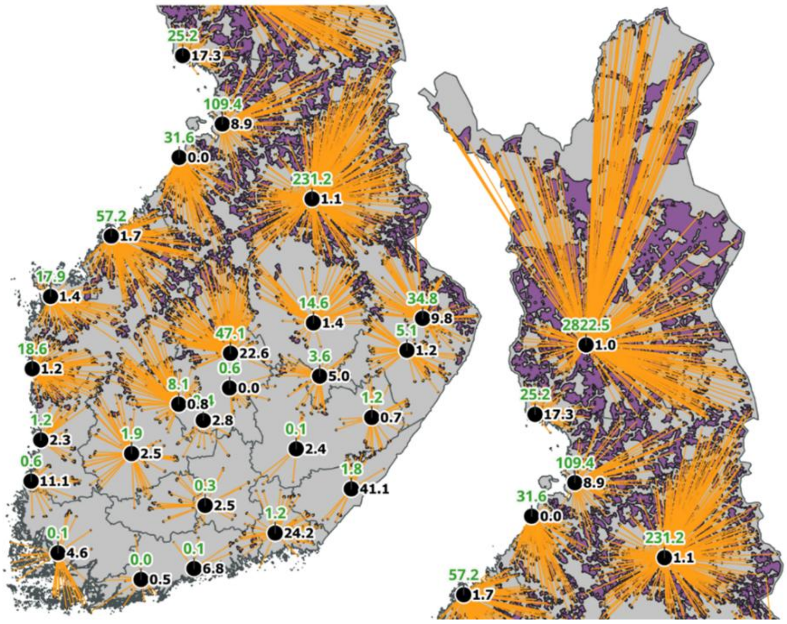


Figure 3. Demonstration of integration of wind sites with nearest CO2 sources.

APPLICATIONS/IMPACT

The land-use analysis indicates that Finland has the potential to generate more energy than it currently utilizes, providing a huge potential to convert and export the surplus electricity and PtX products. Renewable hydrogen (H_2) and bio-CO_2 hubs can be established into several locations, but effective transport solutions will be needed to fully utilize these resources. If implemented, Finland would have a significantly larger role as part of European economy. Some of Finland's renewable electricity potential locates in sensitive nature areas, meaning that deliberate actions are necessary to balance the economic interests with considerations of biodiversity, landscape, and social equity. Additionally, it can be noted that a major part of the bio-CO_2 resources locates in areas that are facing risks of lagging behind the development and these resources provide unique opportunities for them.

MAIN CONTACT

Hannu Karjunen, LUT School of Energy Systems, hannu.karjunen@lut.fi

AUTHORS

Jukka Lassila, Hannu Karjunen, Markus Salmelin, Otto-Eeti Räisänen

WP2 TASK 2

Optimal national and international infrastructures

ABSTRACT

Task 2.2 had three main research questions: RQ1 (infrastructure): Identify the to be considered infrastructures and required datasets for power-to-X (PtX) product value chain optimisation. Analyse the required infrastructures to deliver the onsite PtX products to any other target site. Investigate the development of the infrastructure requirements over time. RQ2 (cost structures): Obtain the optimised cost structures of PtX products at any generic onshore site globally. Analyse the key structure elements of the global value chain for PtX products and the associated infrastructures. RQ3 (energy system integration): Identify the PtX product costs influenced in sector coupled energy systems versus de-coupled greenfield developments. The focus of RQ1 and RQ2 has been laid on e-hydrogen, e-ammonia, and e-methanol to capture pure hydrogen, carbon-free e-fuels and e-hydrocarbons for a broad variety of infrastructure analyses. RQ3 has been conducted on the case of Greenland (wind-based exporter) and Egypt (solar-based exporter), while respective research for Finland has not been allocated to this task. Main findings indicate that e-hydrogen shall be transported only for short distances of not more than a few hundreds of kilometres. e-Ammonia and e-methanol are best transported via ships beyond a few hundreds of kilometres. Excellent wind and solar resources emerge as the basis for e-fuels and e-chemicals exports, while in the short-term excellent wind sites are more attractive, then substituted by excellent solar sites. For production of e-methanol within Finland CO_2 pipelines are the lowest cost transport option and the power grids being the second, while power grids may be the more valuable infrastructure. Several new research questions have been identified for follow-up research. In total, eight scientific articles have been prepared as part of this task.

MOTIVATION

PtX products represent a large fraction of final energy and non-energy use demand and require considerable infrastructure which partly has to be newly built. As the energy transition is ongoing and infrastructure projects require years to be realised an as early as possible investigation of the needs and challenges ahead is essential for proper planning and stakeholder discourse. Finland may be in the role of remaining an energy importer, with good chances to emerge at least a high degree of energy sovereignty with respective self-supply, and even PX export opportunities will arise. That requires the investigation of these fundamental archetypes.

RESULTS

Findings for infrastructure fundamentals for e-hydrogen, e-ammonia, e-methanol

Widely available and low-cost solar photovoltaics and wind power can enable production of renewable electricity-based **hydrogen** at many locations throughout the world. Hydrogen is expected to emerge as an important energy carrier constituting some of the final energy demand; however, its most important role will be as feedstock for further processing to e-fuels, e-chemicals, and e-steel. Apart from meeting their own hydrogen demand, countries may have opportunities to export hydrogen to countries with area limitations or higher production costs. It was assessed the feasibility of e-hydrogen imports to Germany and Finland from two case regions with a high availability of low-cost renewable electricity, Chile and Morocco, in comparison to domestic supply. Special attention was paid to the transport infrastructure, which has a crucial impact on the economic viability of imports via two routes, shipping and pipelines.

This study has found that despite lower e-hydrogen production costs in Morocco and Chile compared to Germany and Finland, additional transportation costs make imports of e-hydrogen economically unattractive (see Figure 1). In early 2020s, imported fuel costs are 39–79% and 34–100% higher than e-hydrogen produced in Germany and Finland, respectively. In 2050, imported e-hydrogen is projected to be 39–70% more expensive than locally produced e-hydrogen in Germany and 43–54% in the case of Finland. e-Hydrogen may become a fuel that is mostly produced domestically and may be feasible for imports only in specific locations. Local e-hydrogen production may also lower dependence on imports, enhance energy security, and add jobs.

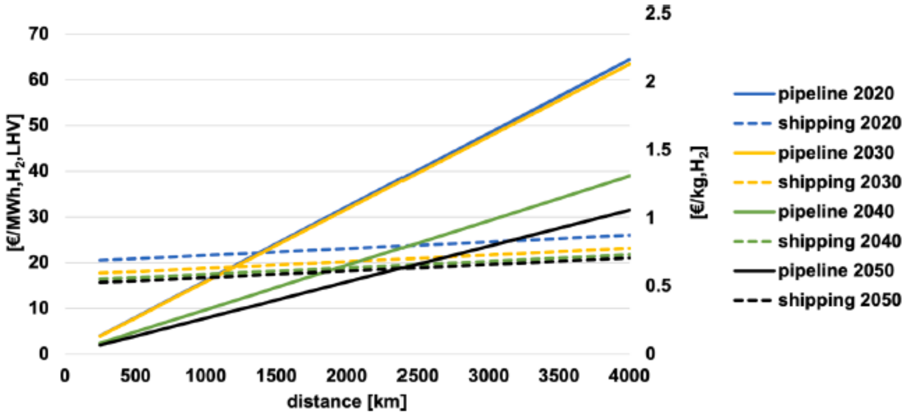
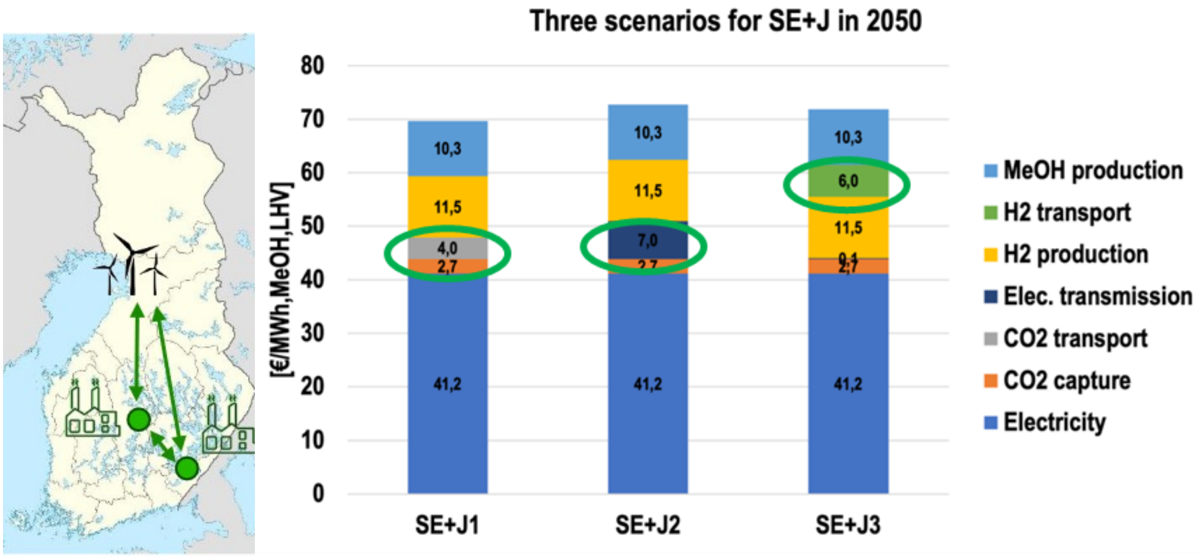


Figure 1. Cost comparison of two hydrogen transportation options via pipeline and shipping in 2030, 2040, and 2050 for distances up to 4000 km.

Ammonia is a key chemical for the agriculture and chemical industries, and a potential future marine fuel. Potential growth in ammonia demand further highlights the importance of ammonia production defossilisation to comply with climate goals. Widely available renewable resources and declining costs of solar photovoltaics and wind power enable the production of green e-ammonia at many locations and potential exports to countries with less optimal resources and other restrictions. It was compared the cost of imported e-ammonia to Germany, Finland, and Spain from regions with excellent renewable resources, Morocco and Chile, to the cost of local production, and to quantify potential economic savings due to trading. Transportation costs are calculated with techno-economic parameters reported in detail in the scientific publications (see e.g., Galimova et al., 2023a) to assess their impact on final import costs, and to allow comparison of shipping costs to pipeline transmission costs over various distances. Pipeline imports from Morocco were found to be significantly higher in cost compared to imports by sea from Chile and Morocco or local production. Imports from Chile were found to be economically feasible for Germany and Finland, with import costs 10–33% lower than domestic e-ammonia production in 2030–2050. Imports to Spain may be attractive in 2030s, but, after 2040, local solar resources enable local e-ammonia production costs at the same or lower cost as imported e-ammonia. Ammonia trading in the future may depend on access to the sea. Other factors such as creation of jobs, additional revenues, and energy security concerns may also impact e-ammonia trade.

Methanol, a key chemical industry feedstock, is expected to have an important role in high value chemicals production and as a clean maritime fuel. Renewable electricity-based methanol or e-methanol may be crucial for defossilisation of hard-to-abate sectors and to address climate change. It was examined the cost competitiveness of e-methanol production in solar-rich regions of Morocco and Chile compared to representative European countries of Germany, Finland, and Spain. Domestic European production costs were assessed against those from potentially exporting regions. Detailed analysis of pipeline and shipping costs was conducted to evaluate their impact on final import costs. Results indicate that Germany may benefit from imports from Morocco and Chile with 4–14% and 15–22% lower in cost in 2050, respectively. Finland can achieve cost reductions of up to 26% in 2030 and up to 37% in 2050 with imports. Spain, with its abundant solar resources, may not benefit from pipeline imports from Morocco, but can achieve 5–15% savings in 2030–2050 if e-methanol is imported by sea from Chile or Morocco. Shipping is found to be more advantageous for e-methanol trading than pipeline. Other factors such as energy security, tax revenues, and job creation should also be considered by potential importers.

Renewable electricity-based **methanol** is increasingly important for reducing the emissions of hard-to-abate sectors such as the chemical industry and long-range shipping. The main challenge with sustainable methanol, however, is the **supply of sustainable CO_2**. While point source CO_2 is cost-effective, it is not widely available. Availability of CO_2 raises the question of the optimal e-methanol production locations in case CO_2 point source and the best low-cost renewable electricity sites are located far apart. It was compared the relative transportation costs of electricity, hydrogen, and CO_2 to determine the **best methanol synthesis location** for the case of Finland, all based on new investments due to utilised existing capacities (see the Figure 2). The results show that transporting CO_2 to an electricity generation site for methanol synthesis is the lowest cost option for all years and scenarios. The cost difference across scenarios is initially limited, with methanol produced with electricity or hydrogen transported to a CO_2 source being 3-13% more expensive in 2030, but the difference rises to 5-15% in 2050, as the share of energy cost declines while the transportation infrastructure cost share gets more pronounced. Despite lower costs for CO_2 transportation, the slightly higher costs for power lines may be justified due to the higher flexibility and more diverse use cases. In addition to costs, other factors must be considered as well, such as safety, societal acceptance, long-term fuel demand, availability of input materials, and the risk of stranded assets. Moreover, municipalities that expedite regulatory approval could benefit from investments, additional revenues, and job creation.



A) B)

Figure 2. A) Location of resources and transportation options B) Breakdown of projected e-methanol cost in 2050 in Finland. The transport cost share is displayed within a green circle. Abbreviations: SE – Southeast Finland, J – Jyväskylä; indicating different investigated cases.

Findings for energy system implications of e-fuels exports: Cases Greenland and Egypt

Climate change-driven temperature rise in the Arctic has been shown to increase faster than on global average, heavily affecting **Greenland**'s environment. Rich wind resources complementary with solar resources may enable a transition to a sustainable and self-sufficient energy system. Greenland's transition from a fossil fuels-based system to a 100% renewable energy system between 2019 and 2050 and its position as a potential e-fuels and e-chemicals production hub for Europe, Japan, and South Korea, has been investigated. Importing regions, such as Europe and East Asia, can benefit from some of the lowest-cost energy carriers in the world in 2030, and these energy carriers will continue to have a low-cost level in 2050. It was estimated that the production and export of e-fuels and e-chemicals would require up to 300,000 workers for construction and operations. Renewable energy enables a full defossilisation of Greenland's energy system, enhances energy security, and provides opportunities for additional export revenues.

Transitioning to renewable energy to mitigate climate change requires solutions for hard-to-abate energy sectors. It was investigated the techno-economic impacts of offering e-fuels and e-chemicals exports on an exporting country's energy system as it transitions to renewable energy by 2050. **Egypt** is used as a representative case study for sunbelt countries with adequate land area. Four scenarios with different system configurations have been investigated using the LUT Energy System Transition Model and compared to a reference domestic renewable energy system. The results show that Egypt can technically provide 10% of Europe's demand for e-fuels and e-chemicals starting from 2025 within land use constraints. The provision of e-fuels and e-chemicals exports enhances the domestic energy system performance by reducing the levelised costs of important feedstocks, carbon dioxide and hydrogen, as well as other domestic cost metrics and system losses. These findings are extendable and relevant to similar sunbelt countries. They are also relevant to European countries looking to fulfil their climate targets while diversify their energy imports sources.

APPLICATIONS/IMPACT

The findings clearly indicate that infrastructure challenges have to be considered right in time. Hydrogen transportation via pipelines up to a few hundreds of kilometres is well doable, while longer distances lead to quite high costs and also hydrogen shipping lacks economic attractiveness. Ammonia and methanol transportation up to a few hundreds of kilometres is attractive with pipelines and thousands of kilometres via ships induces comparably low cost.

In conclusion, hydrogen shall be exported in form of its products. In case of differing locations for electricity and CO_2 for e-hydrocarbons a differentiated assessment is required as total costs are close, with CO_2 transportation the least cost whereas electricity transmission may be more flexible. Exports of e-fuels and e-chemicals most likely starts in regions of excellent wind resources and in 2030s sites with excellent solar resources may gain ground in exports. Domestic energy systems benefit in lower overall energy system costs from e-fuels and e-chemicals export due to scaling, flexibility, and good system integration options.

MAIN CONTACT

Christian Breyer, LUT School of Energy Systems, Christian.breyer@lut.fi

AUTHORS

Christian Breyer, Tansu Galimova

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WP2 Task 2.3

Scenarios for feasible infrastructures in Finland

ABSTRACT

The objective of the task 2.3 was to showcase a holistic scenario building and analysis of energy systems infrastructures in Finland. The aim was to develop tools and methodologies for a universal case for optimal operation of energy systems and sector-coupling. The future energy system of Finland consisting of electricity, heat, hydrogen, and CO_2 grids and storages was modelled in Backbone modelling environment based on GAMS (General Algebraic Modelling System) modelling engine.

Scenario analyses showed how these different cases affect the national energy system structure and operation including system flexibility needs, energy balances in different regions of the country, and needs of electricity and hydrogen transmission between different regions. Analyses showed the need to strengthen the power grids, either electric or gas grids, depending on the locations of hydrogen production units compared with electricity production units. Also the vital need of flexible energy resources, i.e. flexible operation of electrolyzers to follow variable renewable electricity production, energy storages (mainly hydrogen and heat) to buffer energy for end-use, import and export electricity transmission capacity to smooth and optimize energy production and usage on Nordic and northern Europe area, renewable electricity production curtailment in extreme excess situations to optimize required transmission and storage capacities, and the integration of electrolyzer waste heat to district heating systems to enhance the overall efficiency, were shown.

MOTIVATION

The value chain of a Power to X (PtX) economy is a system of systems consisting of several links from renewable electricity production and markets to hydrogen production, various PtX synthesis units, storage and end use. This system of systems includes sectoral interconnections between different systems such as district heating, biogenic CO_2 capture, and energy transmission and storing in different forms. One key issue is how the operation of variable renewable electricity powered electricity production can be matched with hydrogen end use in different industrial processes operated typically at constant production conditions. A systemic approach is needed to analyze what kind of structures, components and properties are needed to make the whole value chain operable. Systemic analysis is based on dynamic modelling and simulation of the system at electricity market time resolution. It is used to define needed generation, transmission, demand response and storage capacities and their locations to make the whole system techno-economically feasible.

RESULTS

The first result of this task is the energy system model framework (Backbone) applied to scenario analyses. Three different scenarios for years 2035 and 2050 were modelled and analyzed, Business as Usual (BAU), Self Sufficiency (SS), and Maximal Utilization (MU). BAU scenario was based on moderate increase in investments on green energy, in SS scenario all national energy consumption was supplied by national green energy investments, and in MU scenario national renewable electricity potentials were highly utilized to produce energy also for high volume export business.

The Backbone model divides Finland in nine regions and includes a huge amount of information about the components, structures, and sectoral interconnections, how the national energy system is built up and running. The second result is the scenario analyses illustrating how much electricity and hydrogen production capacities are needed for supplying needs for BAU, SS and MU scenarios, and how these different configurations influence on the operation of the whole energy system.

Electricity and hydrogen transmission requirements depend on the location of production and use of hydrogen. The main cases are that the hydrogen production units are co-located near renewable electricity production, or the production units are located near end use and end product production areas based on hydrogen. The existing industrial sites are mainly in southern part of Finland. In the first option a large share of energy must be transmitted as hydrogen via gas grid and in the second option as electricity via electric grid. Figure 1 shows electric and hydrogen energy imbalances (annual production vs. consumption) in nine regions of energy system model. The simulated cases are BAU and SS for 2035. In both scenarios the installed wind power capacity was 35 GW located mainly in coastal areas and northern part of Finland, and solar PV capacity in BAU 8 GW and in SS 35 GW was distributed to southern part of Finland. Case SS is simulated with two different locations of electrolyzers, co-located with renewable electricity production and co-located with hydrogen end use.

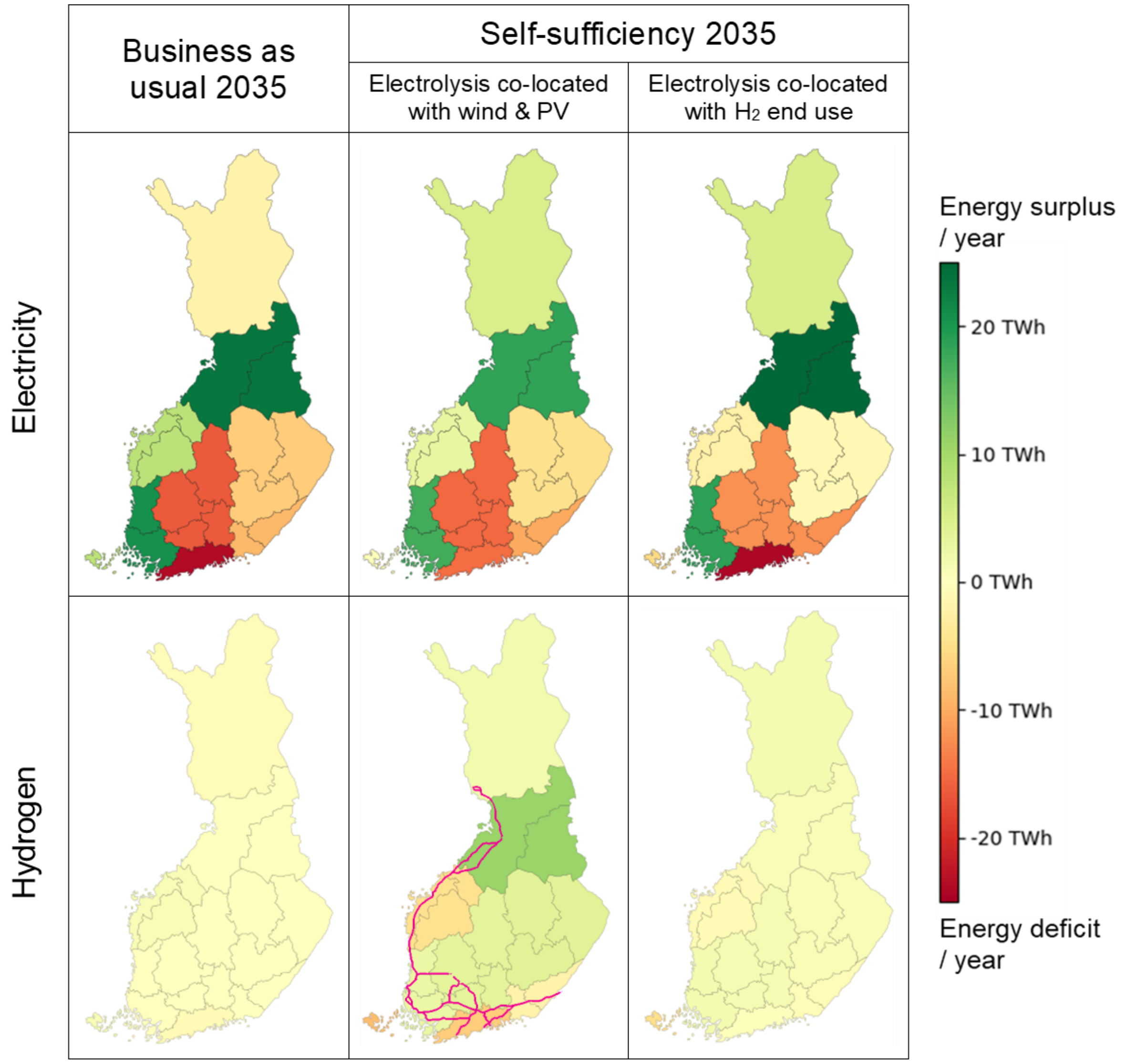

Figure 1. Electric and hydrogen energy imbalances of 2035 scenarios in Business as Usual and Self-Sufficiency cases for year 2035. Self-Sufficiency scenario is analysed with two different locations of electrolyzer plants, near electricity production and near end-use.

Energy imbalances between regions must be balanced by energy transfer between surplus and deficit areas. Figure 2 shows the duration of the curves of electric power transmission for the biggest importer and exporter regions. The peak electricity transmission capacity increases remarkably compared to the existing available capacity and varies quite a lot depending on the scenario. The existing transmission capacity is about 4000 MW between northern and southern Finland but note also that the Figure 2 is not representing the total power flow between north and south. Especially in SS scenario B, where electrolyzers are co-located with existing industrial sites increases the need for electricity transmission capacity. In SS scenario A, part of energy from excess to deficit areas is transferred in the form of hydrogen, which naturally decreases the need for electricity transmission capacity. Without energy storage and renewable electricity curtailment, the need for the peak electricity transmission capacity would be higher.

The duration curve of SS scenario B is also steeper than other two scenarios, which means that it utilizes the electricity transmission capacity less efficiently, which leads to situation where the electricity grid investments are required to payback with higher electricity transfer usage per unit cost. Therefore, the mechanisms to reduce the electricity transmission need would be very welcome to avoid investments for transmission capacity used very seldomly. Other option is to utilize the internal congestion management of Finland price area to avoid internal bottleneck, but the operation cost of redispatch or counter trading might increase to very high level. In the future, the option to divide Finland to two price areas might be necessary, if the investments for electricity transmission capacity are not progressing as fast as the investments for renewable electricity and electrolyzes. This is likely to happen, because the project timeline from the decision to build to the deployment of the investment is several years longer for electricity grid compared to renewable energy or a hydrogen production plant. Two or more price areas within Finland would remarkably impact for electricity cost of consumers in deficit areas (increasing) and producers in excess areas (decreasing), which would impact negatively for many electrification investments already made and those to come.

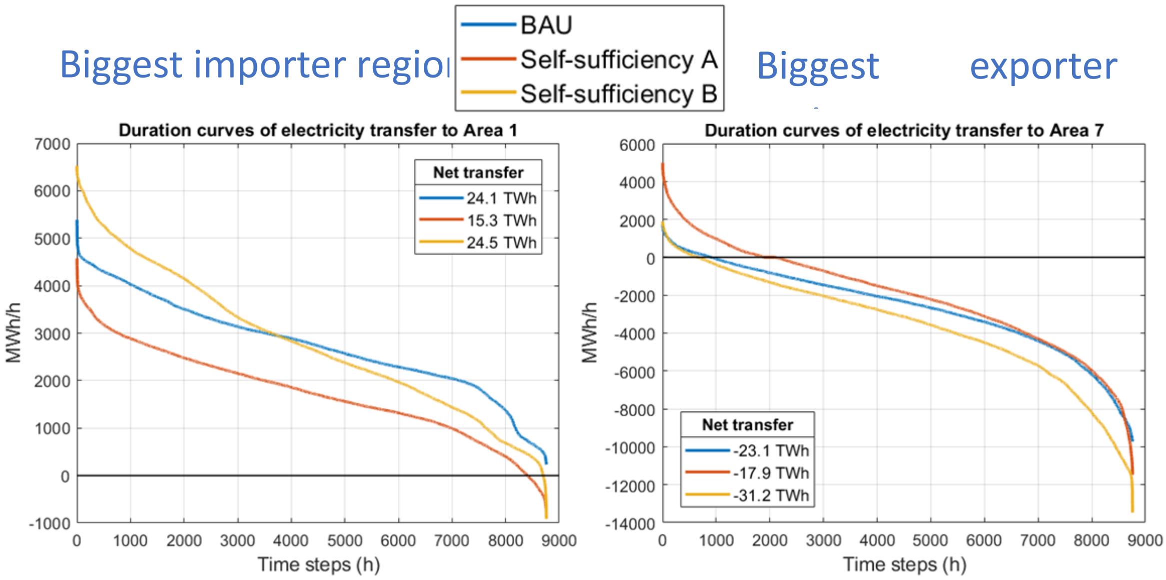

Figure 2. Simulation results showing a) the variation of the feed streams and reaction products, b) power of the compressors, c) heat duties of heat exchangers, d) compressor discharge temperatures.

The third category of results is presented in the Table 1. The electricity generation and consumption would increase from existing about 80 TWh level to remarkably higher levels and the primary energy sources in these scenarios have been wind and solar power. The balance of power system has achieved by curtailing about 2 TWh of variable renewable energy (VRE), by utilizing import and export capacities extensively (roughly 10 % of electricity is balanced in larger area than in Finland), and by utilizing electrolyzers flexible way and storing hydrogen to buffer storages. The approximation of the required hydrogen storage capacity needed to run the energy system consisting of variable hydrogen production and constant load operation of the hydrogen end use was estimated to be 2,5 TWh in BAU scenario and 8 TWh in SS scenarios. These are rough estimates but illustrate the huge need of storage capacity needed to balance the system, and the size depends on how flexible the electricity production and the demand side will be in the future.

Table 1. Characteristics values of BAU and SS scenarios.

	BAU2035	SS2035A	SS2035B
Electricity generation (TWh)	173,9	189,3	189,3
Electricity consumption (TWh)	172,2	191,2	190,9
Electricity generation, wind (TWh)	101,2	90,8	90,8
Electricity generation, PV (TWh)	7,7	33,4	33,4
Curtailed VRE generation (TWh)	1,8	2,23	2,24
Imported electricity (TWh)	16,4	19,3	19,5
Exported electricity (TWh)	15,4	14,9	14,8
Peak electricity load (GW)	29,9	36,8	36,9
Electricity to H2 production (TWh)	47,4	68,0	67,7
Maximum H2 storage capacity used (TWh)	2,5	8,1	7,9

APPLICATIONS/IMPACT

The results of the task help to evaluate the systemic requirements of the PtX economy to the whole energy system. With planned capacities of future hydrogen production and end use facilities, extensive investments are required to strengthen the existing energy transmission system. Increased amounts of energy must be transferred between distributed renewable energy production sites and end-use or final product refinery locations. Although a single hydrogen production plant can be connected to any part of the system, but the total impact of all electrification projects around Finland will create a tremendous impact for the whole energy system infrastructure and market in the long run. Therefore, the collaboration of energy producers, consumers and delivery companies are required to avoid unnecessary infrastructure costs and harmful market impacts. Sectoral interconnections between hydrogen, heat and CO_2 systems must also be considered in the design of the system structures and optimal locations. Model based systemic approach helps also in the evaluation and design of these capabilities. Also, in the early phase of the investment it is important to recognise that, since we are dealing with a system of systems, early decisions lead to a selected paths and the path dependency has to be considered in decision making.

MAIN CONTACT

Sami Repo, Tampere University, sami.repo@tuni.fi

AUTHORS

Yrjö Majanne, Venla Vilhonen, Sami Repo, Matti Vilkko

WP3 TASK 1

Hydrogen in the gas transmission network

ABSTRACT

The main research question of the Task 3.1 was: What is the role of existing methane-based (natural gas) infrastructure in the hydrogen-based energy system? The main target was to improve understanding on potential of existing pipeline infrastructure in transporting gases. The potential was analysed by studying the status of gas networks in various countries and reviewing hydrogen pipeline projects in Europe, and calculating the costs, energy consumption, and greenhouse gas emissions in different hydrogen transportation options in Finland. Furthermore, potential of existing infrastructure in transporting renewable methane (biomethane, synthetic methane) was roughly estimated. The findings indicate that methane pipelines may play a notable role in transportation of hydrogen in Europe but due to a limited coverage and possibly unfavourable location of an existing pipeline in relation to the expected locations of hydrogen production and use, building of new pipelines is needed in Finland. Pipeline transportation of hydrogen and transportation of electricity seem to be the most feasible transportation options. However, a detailed study is needed for each investment because several factors such as hydrogen volumes, transportation distances, the location of hydrogen user and producer, and available infrastructure affect the feasibility.

MOTIVATION

Existing natural gas infrastructure is seen as one means to transport hydrogen and other gases. That is studied by the gas industry in Europe and worldwide, but so far, the research from the Finnish perspective has been missing. Transportation of hydrogen and/or other resources between production and consumption sites is a significant challenge in scaling up renewable hydrogen -based solutions. Thus, it is important to improve understanding on the role of existing infrastructure on the future hydrogen-based energy system and to study other possible transportation options.

RESULTS

The potential to utilize existing infrastructure was evaluated reviewing hydrogen pipeline projects in Europe considering repurposing of natural gas pipelines to transport hydrogen, building of new hydrogen pipelines, and blending of hydrogen to a natural gas pipeline. The blending has been seen as an interesting option for transportation of hydrogen because it could allow the utilization of existing infrastructure with minor modifications and therefore cut costs and building times. Many European countries have tested injecting up to 20% of hydrogen into a natural gas pipeline. A couple of projects has repurposed a natural gas pipeline to 100% hydrogen. For example, Gasunie converted a 40 bar and 12 km natural gas pipeline to hydrogen in 2018 in the Netherlands. The pipeline has been operating since then.

Existing pipelines can also be used for transporting 100% hydrogen, and for that many countries have initiated projects for repurposing existing infrastructure to hydrogen. The repurposing can reduce costs and building times. However, the studies indicate that the suitability of every pipeline for hydrogen must be analyzed and several issues such as a leakage, leakage detection, effects of hydrogen on pipeline assets and end users, corrosion, maintenance, and metering of gas flow must be considered.

One of the studied aspects was to evaluate how the transportation of hydrogen using the existing infrastructure would affect the natural gas users in Finland. Currently, natural gas is mainly used by industry (Figure 1). However, the blending of hydrogen to a natural gas grid has been found to be harmful for some end users, and deblending can be expensive. Both blending of hydrogen with methane and transportation it as a mixture in natural gas pipelines and transportation of 100% hydrogen in natural gas pipelines would require significant modifications to current structures and end user applications, and extra activities. Moreover, as the most potential areas for renewable electricity and subsequently hydrogen production are in the west coast of Finland and the pipeline is in the east and south, there is a mismatch related to pipeline location. Thus, it can be claimed the existing infrastructure in Finland does not have as much potential as infrastructure in many other areas.

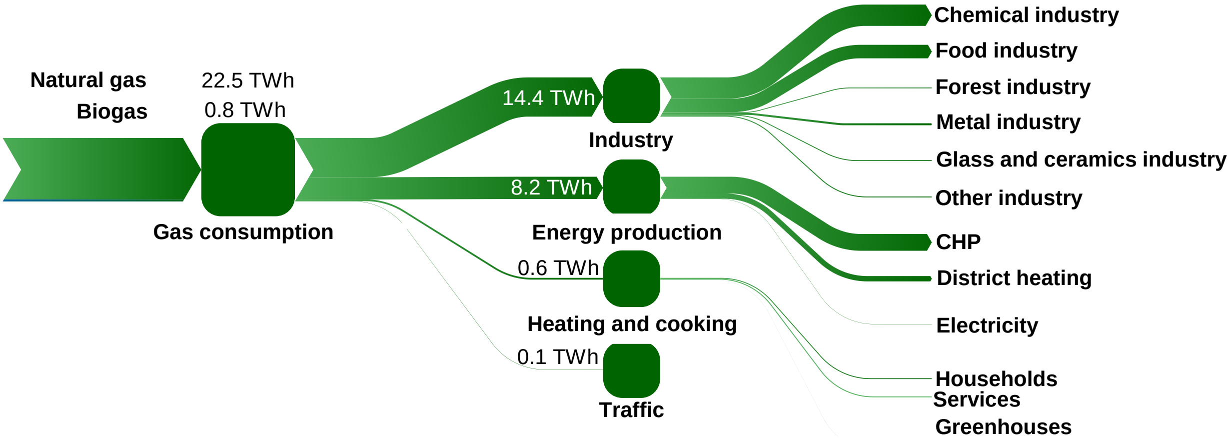

Figure 1. Natural gas consumption in Finland in 2021. Data from the Finnish Gas Association.

Minor share of the activities was allocated to studies related to hydrogen gas odorization. Odorization is normally used in distribution gas pipelines. Based on a review it can be stated that the results concerning the applicable odorants conflict. Some sources claim that there are already products available in the market, and others claim that there are still some challenges to be tackled before application. The identified challenges include a high volatility of hydrogen resulting that the hydrogen escapes before the odorant, and that the end use applications such as fuel cells might be sensitive to the odorizing gas.

For analysing the feasibility to utilize existing pipeline compared to other transportation options, five different hydrogen delivery pathways were reviewed. The pathway options included mill-site electrolysis (i.e., hydrogen manufacturing at the site), hydrogen pipeline transportation in new and repurposed pipelines, transportation of hydrogen in a pipeline as synthetic methane, and hydrogen delivery by shipping. Costs, energy consumption, and greenhouse gas emissions were estimated using a steel mill consuming 144 kt/a of hydrogen.

Mill-site electrolysis and both hydrogen pipeline transportation alternatives (i.e., new and repurposed pipelines) were found to be most feasible in terms of costs, energy consumption, and greenhouse gas emissions. Hydrogen cost varied slightly within these three options, and another two options (the transportation of synthetic methane in a natural gas pipeline and the shipping of hydrogen) led to notably higher costs (Figure 2a). Energy consumption was also the highest in the synthetic methane and shipping cases due to additional conversion processes (Figure 2b).

Greenhouse gas emissions of studied cases varied between 7.7 and 13.7 $kg_{CO2\text{-}eq}/kg_{H2}$ in the base case that assumed utilization of wind (40%) and solar (10%) electricity and grid electricity (50%). Synthetic methane route can provide a notable carbon sink if a pyrolysis process is used for converting methane to hydrogen. That opportunity is interesting especially if biogenic CO_2 is used to produce methane. However, the route is expensive and consume a lot of energy.

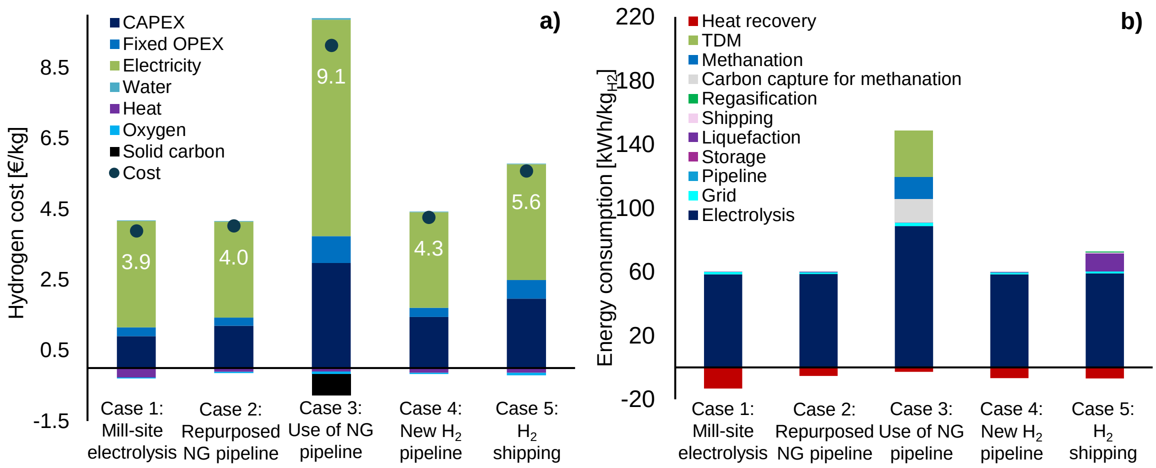

Figure 2. Production costs (a) and energy consumption (b) of hydrogen in studied supply routes.

Many of the used variables contain uncertainties. Sensitivity for some of the variations are presented in Figure 3a. In addition to these, results are sensitive to case-specific properties such as hydrogen volumes, transportation distances, the location of hydrogen user and producer, and available infrastructure. The price of electricity was found to affect the most on the hydrogen cost (Figure 3b). Each transportation case must be separately looked at before investment decisions.

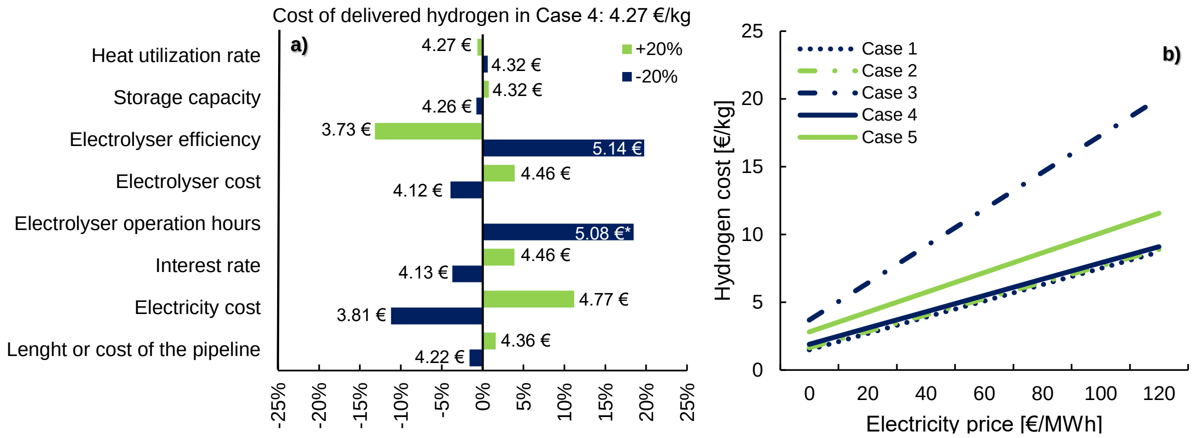

Figure 3. Effect of different variables using Case 4 as an example (a) and the effect of electricity prices on the hydrogen production costs (b).

APPLICATIONS/IMPACT

Utilization of existing natural gas network is possible but difficult, but also new infra will be needed to connect the renewable electricity production sites and CO_2 point sources to produce P2X products at industrial sites. Existing methane infrastructure could be utilized in transporting both biomethane and synthetic methane, but the volume of these gases will remain minor at least in the near future in comparison to the consumption of natural gas in recent years.

In the transportation of hydrogen, transportation as electricity (and conversion of that to hydrogen at the mill site) seemed to be among the most feasible ways. For large-scale transportation needs, hydrogen pipeline is a promising option. However, the feasibility of transportation options between electricity production, biogenic carbon source, and final user depends on several factors such as location, availability infrastructure, and volumes. Detail study needs to be done for each investment.

MAIN CONTACT

Esa Vakkilainen, LUT School of Energy Systems, esa.vakkilainen@lut.fi

AUTHORS

Esa Vakkilainen, Satu Lipiäinen

WP3 TASK 3.2

Material aspects in hydrogen and methane infrastructure

ABSTRACT

This task seeks to identify the critical material aspects of hydrogen-based infrastructure, including pipelines, storage facilities (such as underground storage), and network components. It also examines the essential material considerations necessary for converting methane-based infrastructure, namely natural gas systems, to hydrogen. Key aspects studied include the impact of hydrogen on materials. Critical material properties analysed include strength, ductility, and toughness, which are susceptible to potential hydrogen-induced embrittlement. Fatigue performance was deemed crucial in the conversion of natural gas pipelines. The fatigue crack growth rate is up to 100 times faster in a hydrogen environment compared to a methane environment. Linear Elastic Fracture Mechanics (LEFM) has proven effective as a tool for assessing the feasibility of conversion and for evaluating inspection intervals in relation to fatigue-related issues.

MOTIVATION

Use of existing natural gas (methane) infrastructure is considered to be one enabler of the hydrogen economy as is provides a potential opportunity for economical transportation of hydrogen especially in the early phase of the development with lower transport capacity needs. However, natural gas pipelines feature significantly thinner walls than dedicated hydrogen pipelines due to different characteristics of these gases and their influence on metallic materials properties. Therefore, the natural gas pipelines should only be utilized after careful case by case implementation of best practices and modifications suggested in various studies. Also, real-time monitoring tools for pipelines should be developed and implemented to ensure the safe use and efficient inspection of pipelines with pipeline inspection gauges (PIGs).

RESULTS

Linear elastic fracture mechanics (LEFM) provides a connection between existing structures and numerical methods and was therefore used to model fatigue crack growth. An example of this kind of modelling technique is illustrated in Figure 1 with typical equations needed for fatigue life assessment. This kind of monitoring during the service is needed to verify the safety of non-standardized structures.

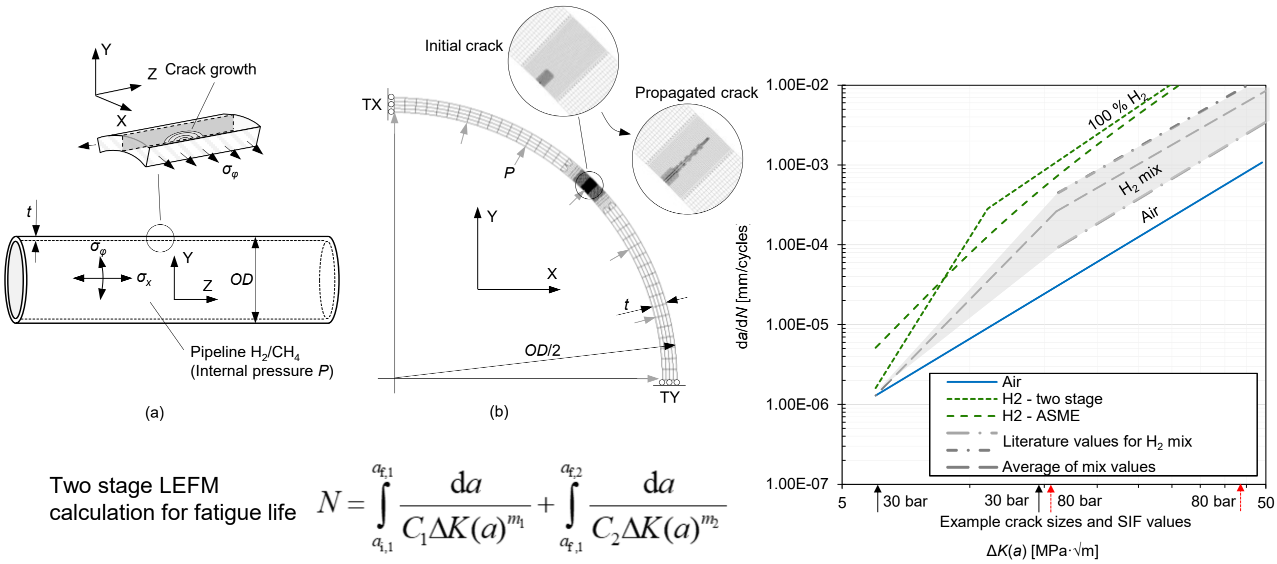

Figure 1. Stress intensity analysis of fatigue crack in the pipeline.

The result of the analysis is demonstrated in Figure 2. Reasonable fatigue life, measured as maximum operational pressure cycles, are shown as a grey shading from 5000 to 20 000 pressure cycles. Initial crack depth of 2 mm (inspectable crack size) and 1 mm (manufacturing condition, not inspectable) are used as a basis for analysis and the reasonable converted pressure for hydrogen transport can be seen when green or blue line overlaps shaded area. The results show that natural gas pipeline with 80 bar rated pressure could operate as re-purposed hydrogen pipeline with 50 bar pressure.

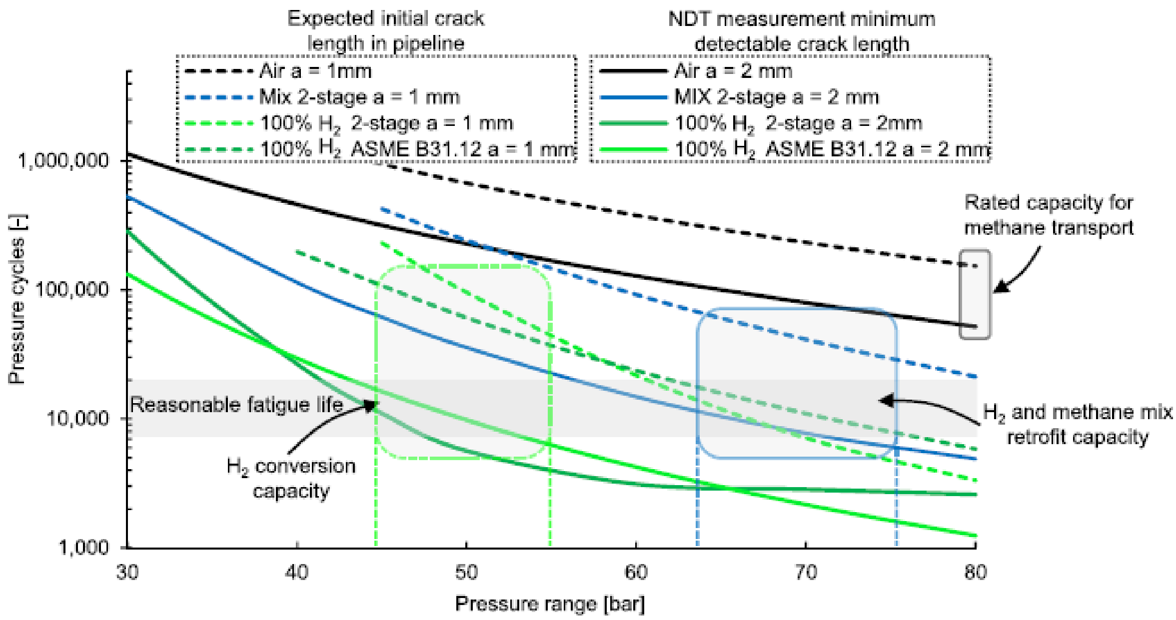

Figure 2. Fatigue life described as maximum operational cycles in respect to rated pressure and operational windows for hydrogen and methane transport in the same pipeline.

The fatigue life of a pipeline can be divided into six phases and each phase has its main determining factor (Figure 3). The initial crack size (in phase: initial crack size in the pipeline) is determined by manufacturing quality. The smallest inspectable crack size is around 2 mm in the depth direction. The final crack size (in phase: critical crack size) is determined by yield strength and fracture toughness.

From this inspectable crack depth, the introduced calculation procedure was used to estimate safe crack growth length before analytical method indicates that pipeline inspection was needed. Non-destructive testing (NDT) inspecting then verifies the situation and lifetime estimation can be updated.

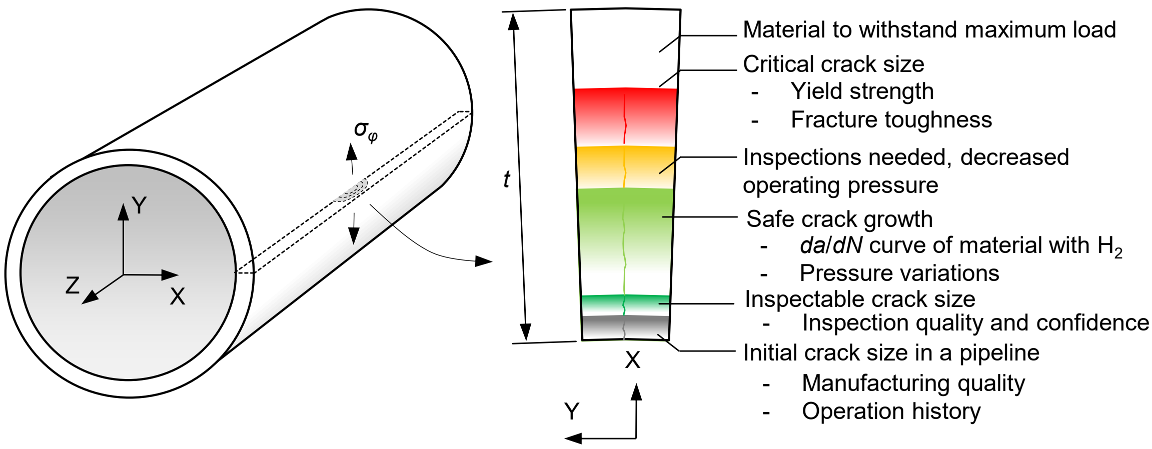

Figure 3. Characteristic fatigue crack growth rate phases and the main influencing factors of them in a hydrogen pipeline.

APPLICATIONS/IMPACT

This work identified possibility to mix methane and hydrogen in existing pipelines and conversion for hydrogen transport with numerical fatigue crack growth analysis. The used LEFM enables evaluation of conversion and estimates inspection interval and potential remaining lifetime for hydrogen transport. The study indicated that existing natural gas pipelines could be utilized for hydrogen transport when maximum operation pressure is decreased, and fatigue life monitoring is applied together with inspection plan.

MAIN CONTACT

Kalle Lipiäinen, kalle.lipiainen@lut.fi. LUT University

AUTHORS

Kalle Lipiäinen, Timo Björk, Masoud Mostaghi

WP3 TASK 3

Industrial applicability of biogenic PtG

ABSTRACT

Task 3.3 investigated the potential of biomethanation in Finland if carbon dioxide (CO_2) from biogas would be converted to methane. There is a potential to increase the methane production at biogas plants in Finland from ca. 130 Mm^3/a (1.3 TWh/a) in 2020 to ca. 540 Mm^3/a (5.4 TWh/a) in 2030, when considering both the new biogas plants and potential use of biomethanation technology. Biomethanation presents ca. 30% of methane produced. Furthermore, the environmental performance of using hydrogen (H_2) in *in-situ* and *ex-situ* biomethanation processes to enhance biogas methane content was evaluated with life cycle assessment and compared to traditional membrane separation technology. Results indicate that upgrading biogas by membrane separation achieves a 59% emission reduction, while ex-situ and in-situ biomethanation achieve reductions between 49% and 62%, depending on the electricity source for H2 production, comparing to the baseline where natural gas is used. Finally, the effects of variations in gaseous feedstock availability and composition on biomethanation process and its efficiency were reviewed. These results indicate that *in-situ* biomethanation is more sensitive to standby periods in the feeding compared to *ex-situ* biomethanation, and that the main impurities in the CO_2-rich feedstocks that may negatively affect biomethanation process include nitrogen and sulfur oxides, hydrogen sulfide, and heavy metals.

MOTIVATION

Biogenic CO_2 is produced, e.g. in pulp and paper industries, ethanol plants and biogas plants. Combining CO_2 with H_2 enables the production of methane via biomethanation that utilizes microorganisms for the conversion process. Biomethanation can be realised 1) via *in-situ* feeding of H_2 to biogas reactor processing organic waste (*in-situ* biomethanation), or 2) in external reactor converting CO_2 and H_2 into methane (*ex-situ* biomethanation). It was in the interest of this task to find out, what is the biomethanation potential in Finland, what are the environmental impacts of the technology, and what is the resilience and adaptability of the technology for the gaseous feeds that may fluctuate in availability and purity.

RESULTS

The biomethanation potential in Finland was evaluated from the perspective of available CO_2 in biogas and bioethanol plants. Information from Finnish Biocycle and Biogas Association on the biogas and methane production in 2020 and 2030 (estimations) and typical Finnish biogas processes and conversion rates were used as basis of the calculations. Compared to 2020, it is expected that biomethane production increases from ca. 130 Mm^3/a to ca. 540 Mm^3/a by 2030 due to building new biogas plants, increased biogas upgrading, and biomethanation of CO_2 in the biogas or after biogas upgrading (Figure 1).

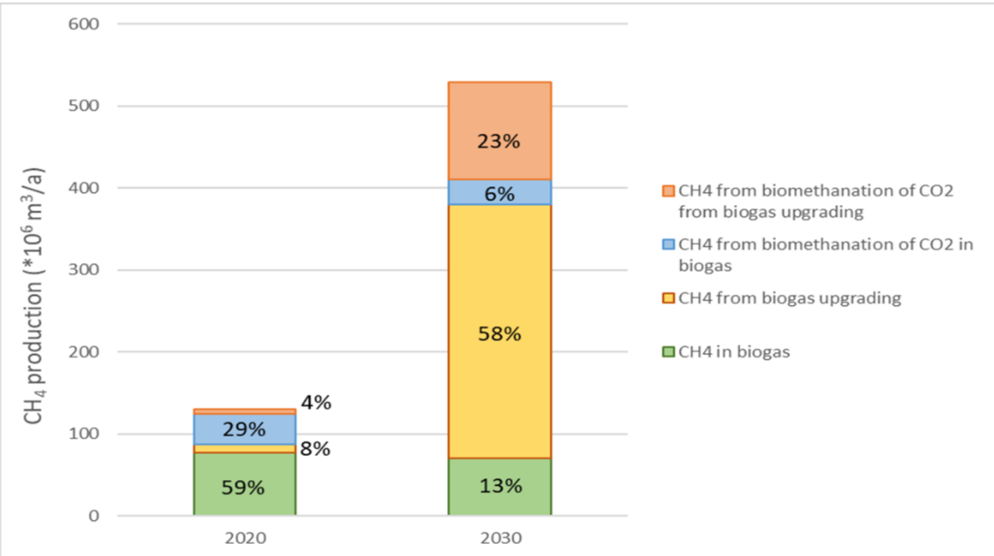

Figure 1. Methane (CH_4) production potential in 2020 and 2030 considering methane present in the biogas produced from organic feedstock in biogas plant, methane that is separated from biogas via biogas upgrading, and production of methane via biomethanation of the CO_2 present in the biogas or separated from biogas via biogas upgrading.

The environmental impacts of utilizing of H_2 either *in-situ* or *ex-situ* biomethanation process to increase the methane content of biogas were evaluated using the LCA method, and the performance was compared with traditional upgrading technologies. This was done in a case study, where a biogas process treated various organic waste streams. This results that different scenarios can significantly reduce emissions when using methane as vehicle fuel, compared to a baseline scenario (S0) (Figure 2). Specifically, membrane separation (S1) of methane form biogas achieves a 59% reduction in emissions compared to the baseline scenario (S0). *Ex-situ* biomethanation (S2) offers emission reductions ranging from 50% to 62%, depending on the electricity source used for hydrogen production. *In-situ* biomethanation (S3) provides emission reductions ranging from 49% to 61%, also depending on the electricity source for hydrogen production. The choice between using a PEM or an alkaline electrolyzer in both ex-situ (S2) and in-situ (S3) biomethanation scenarios results in negligible differences in emission reductions (approximately 0.3%).

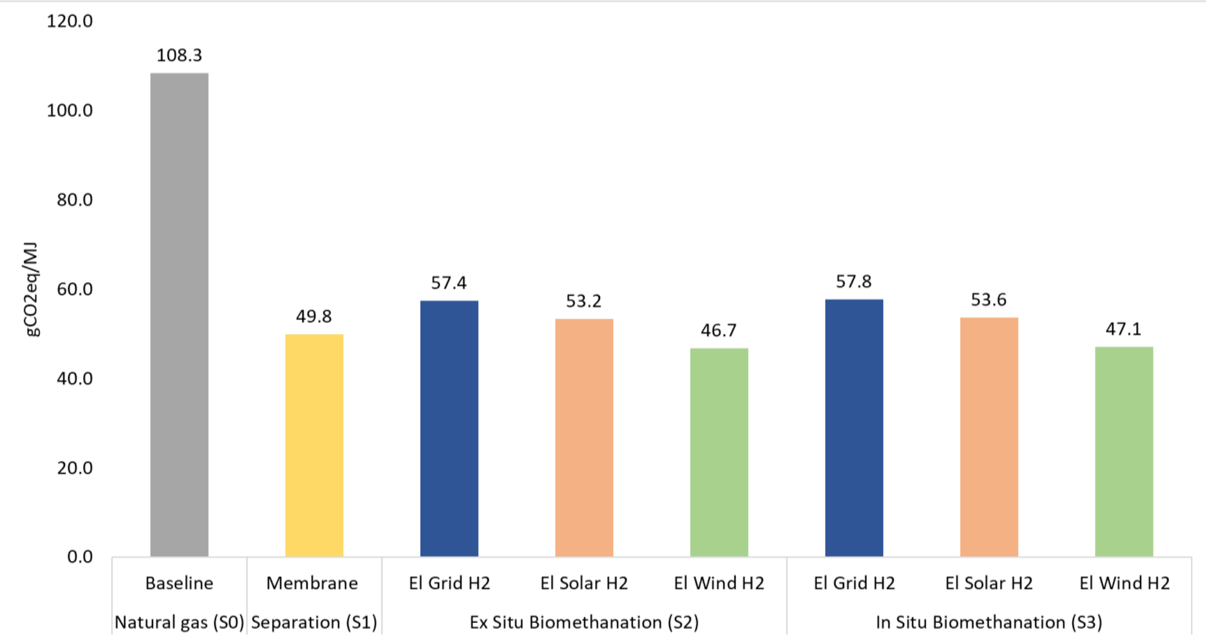

Figure 2. The life cycle impact assessment for the climate change impact category (GWP100) for Natural gas (S0), Membrane separation (S1), Ex-situ biomethanation (S2), and In-situ biomethanation of biogas (S3).

Biogenic CO_2 sources are tied to certain locations. H_2, on the other hand, can be produced at various locations via electrolysis by using renewable electricity, such as wind or solar energy, or via biomass gasification. The different technologies used to produce H_2 affect the purity of the stream. The availability of excess renewable energy varies in time, which may affect the availability of H_2 for the biomethanation process. Usually stable feeding, including gas flow rate and stoichiometric ratio of H_2 and CO_2, is essential for stable operation of a biomethanation process. Although the results on variations in feedstock availability vary based on literature, in general, short standby periods of up to six hours enable quick recovery of the process, while longer standby periods of one day or more require longer recovery time from hours to days. *Ex-situ* biomethanation is more resilient for standby periods than *in-situ* biomethanation.

Furthermore, the biogenic CO_2 sources may contain some impurities negatively affecting the microorganisms in biomethanation process, including nitrogen and sulfur oxides, hydrogen sulfide, heavy metals, and volatile organic compounds or even tar. The main impurities in the CO_2-rich feedstocks that may negatively affect biomethanation process include nitrogen and sulfur oxides, hydrogen sulfide, and heavy metals. Carbon monoxide can act as carbon source for biomethanation but in high concentrations may inhibit the microorganisms.

APPLICATIONS/IMPACT

Evaluating the environmental performance by utilizing life cycle assessment (LCA) can guide the development of biomethanation value chains to more environmentally sustainable direction. LCA enables to identify the specific life cycle phases where emissions are generated and thus highlights the key areas for improvement. This insight is crucial for implementing more sustainable methane production methods, ensuring that the adoption of biomethanation technology leads to reduced environmental impact and enhanced sustainability. Furthermore, the information of the effects of variations in the gaseous feedstock availability and composition guide in process design and in choosing right locations for the biomethanation processes in terms of the quality and availability of the CO_2-rich streams as well as H_2. Finally, the potential of converting CO_2 in biogas further to methane is high, and considering also other biogenic CO_2 sources further increases this potential, highlighting the applicability of biomethanation for methane production in the future.

MAIN CONTACT

Marika Kokko, Tampere University, marika.kokko@tuni.fi

AUTHORS

Husain Patel, LUT University, Husain.Patel@lut.fi

Jouni Havukainen, LUT University, Jouni.Havukainen@lut.fi

Marika Kokko, Tampere University, marika.kokko@tuni.fi

HYGCEL

WP4 TASK 4.1

Dynamic modelling of synthesis processes

ABSTRACT

The objective of WP 4.1 was to develop dynamic process models in Aspen Dynamics to effectively handle variations in electrolytic hydrogen input in green methanol and catalytic methanation processes. Based on prior modeling experience the modeling was divided into two parts, a crude methanol production (a mixture of methanol and water from methanol synthesis) and methanol purification. By this way, only the crude methanol process needs to be dynamically modeled. The results show that the minimum load of the model is around 20%, with maximum allowable ramping rates of 3.25%/minute for ramp-down and 2.10%/minute for ramp-up between full and minimum load. With the constructed control structure, the model demonstrates that the process can effectively handle continuous variations of electrolytic H2 input.

MOTIVATION

Renewable power is intermittent and therefore integration of synthesis processes with power and hydrogen production is not straightforward. Traditional synthesis processes are designed to operate at steady state with almost constant feed rate of raw materials. Variation of feed rate might be a cause problem in process operation. To facilitate process operation in variable conditions, processes need to be designed and operated to handle fast process variations. The motivation for this work was to develop a process model for methanol production which can operate at variable feed conditions. A new design for process syntheses and control structures needs to be invented and implemented.

RESULTS

A dynamic Aspen plus simulation model was developed for the process including the necessary control structures to facilitate methanol production with intermittent renewable power generation. The flowsheet of the process is given in Figure 1. With the constructed control structure, the model demonstrates that the process can effectively handle continuous variations of electrolytic H2 input. The dynamic model was used to test different scenarios of power variation.

It was found that for dynamic operation it is best to divide the process into two parts: 1) Production of crude methanol (mixture of methanol and water), and 2) continuous separation of methanol from water. Only the crude methanol production part needs to be modelled dynamically.

The results show (see Figure 2 for details) that the minimum load of the model is around 20%, with maximum allowable ramping rates of 3.25%/minute for ramp-down and 2.10%/minute for ramp-up between full and minimum load. The main reason for the minimum load point is the operational lower limit of the compressors.

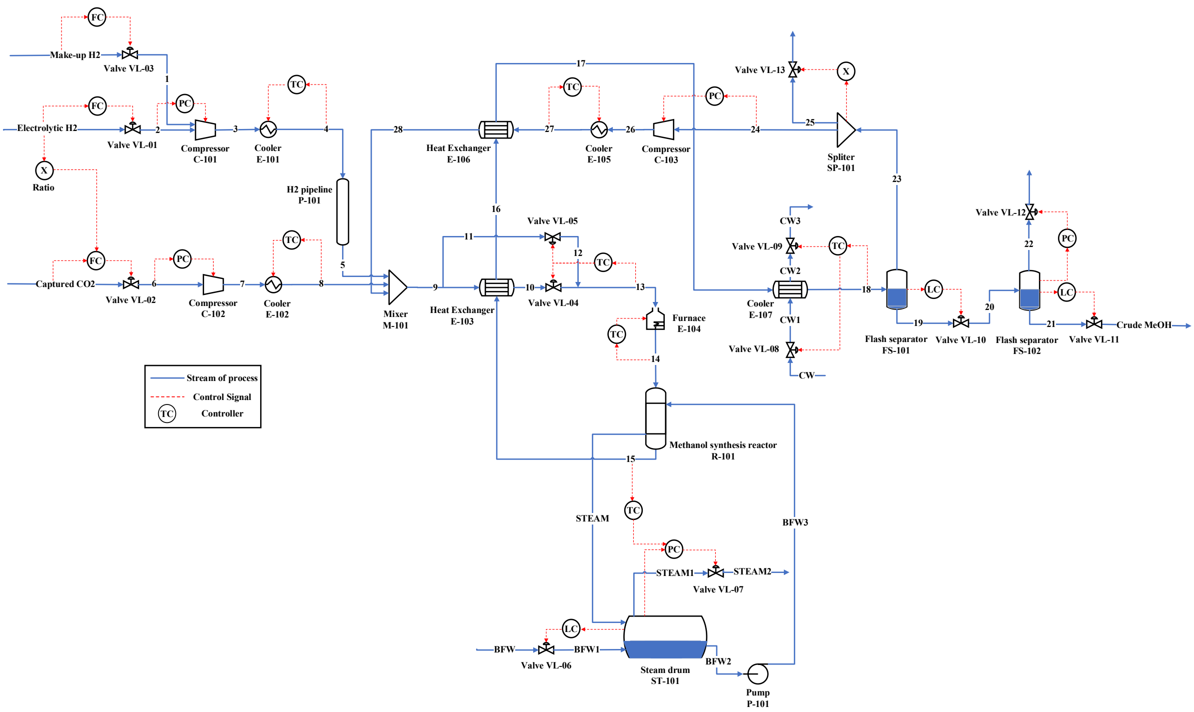

Figure 1. Flowsheet and plantwide control structure for crude methanol synthesis.

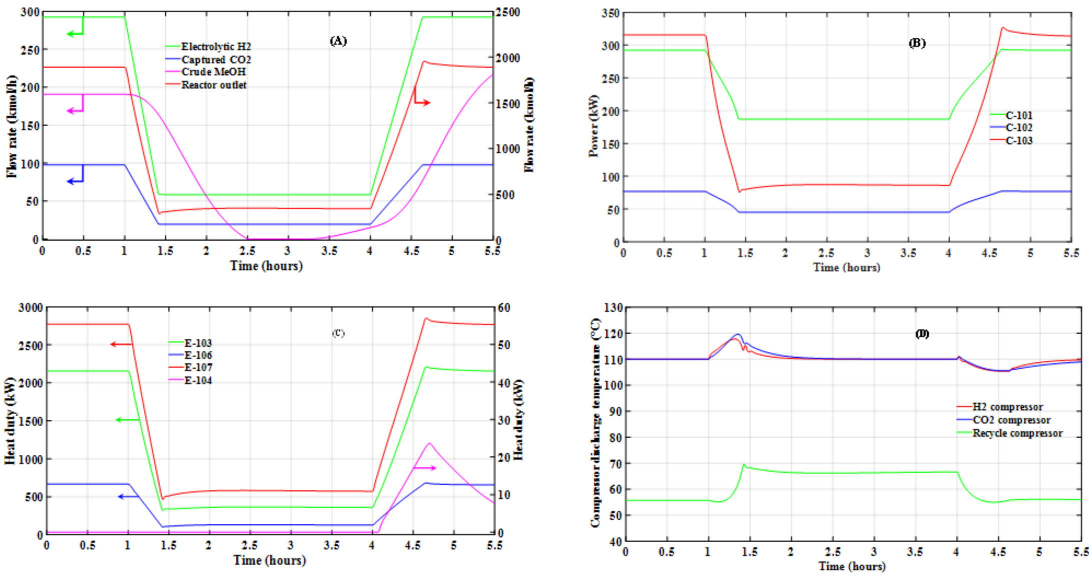

Figure 2. Simulation results showing a) the variation of the feed streams and reaction products, b) power of the compressors, c) heat duties of heat exchangers, d) compressor discharge temperatures.

APPLICATIONS/IMPACT

The results of the project allow a better design of synthesis plants that can be operated under variable feed rate. The results also show what the operational limits of the processes are and how the limits can be extended to efficiently utilize variable power in a flexible way. The results also give ideas about the still existing process bottlenecks, for example the operational limits of compressors, and how these limitations could be potentially improved. Furthermore, the results can be used to evaluate the possible need and size of intermediate hydrogen storages to minimize the overall production and storage costs.

MAIN CONTACT

Arto Laari, LUT School of Engineering Science, arto.laari@lut.fi

AUTHORS

Hung Nguyen, Arto Laari

WP4 TASK 2

Plant-level design and flexibility

ABSTRACT

Task 4.2 focused on the plant-level design and operation of different PtX systems. The interest of the research was to study flexibility and system integration, and as well as optimization of unit operations and capacities. The research was conducted by modelling single components and individual plants, using software such as Aspen Plus and Calliope. Techno-economic analysis was done for the production of hydrogen and e-methanol from electricity mixtures by wind, solar, and grid, with a mixed integer-linear programming (MILP) method. Calendar years were studied in one-hour time intervals. Process models were developed for hydrogen compressor and steel tank storage, and cryogenic capture of CO_2. Results show suggestions for H_2 compressor and tank design for different operation conditions, and the effect of storage cost to overall H_2 cost was estimated. Unit capacities and operation were optimized for hydrogen and e-methanol production, and the impact of uncertain cost parameters was estimated. Fully electrified, integrated CO_2 capture process showed cost and efficiency benefits.

MOTIVATION

New low-emission electricity production from solar and wind is the foundation for sustainable power-to-x products. This is a highly intermittent operation environment for large-scale industrial processes. Also, the cost of these green hydrogen-based products should be low enough to achieve wide usage. Many potential value chains include CO_2 capture and utilization, to re-use the CO_2 in atmosphere and to produce more valuable products like methanol. Detailed knowledge of PtX-processes and their implementation is required, to show the potential, limitations and costs. Knowledge from process modelling is applicable in techno-economic analysis of industrial cases.

RESULTS

Flexibility in processes brings additional benefits, i.e. flexibility has value. It allows production of green products from wind and solar while coping with the fluctuations in production and price, within the context of future regulation. Flexible processes can be more easily integrated with the rest of the energy system, allowing the operation according to the demands for electricity, heat, hydrogen, and other carriers, such as methanol, methane, or ammonia. Flexibility is gained from operation of storages (hydrogen, CO2, heat, end products), processes (electrolysis, synthesis, CO2 capture), and heat sources and sinks (CHP, district heat) that are integrated to the process.

Hydrogen storage has been found to be the key to flexibility in PtX-systems. Small, dedicated storages could be used at individual plants, or large-scale storages could be shared with multiple users. Storage has substantial costs, but it brings benefits during operation. Design of the storage is highly case-specific, due to for example the pressure levels and profiles of hydrogen production and consumption (Table 1).

Table 1. Hydrogen tank storage for 100 MW electrolysis (20 % of H2 is assumed to be delivered via storage).

Storage time (h/d)	Optimal pressure (bar)	Capacity (t)	LCOH (€/kgH2)
6 h	10	2.2	0.07
12 h	27	4.3	0.09
24 h	54	8.6	0.14
2 d	91	17.3	0.20
4 d	150	34.5	0.32
7 d	228	60.4	0.47
14 d	370	120.9	0.76

There are two main purposes for H_2 storage: 1) take advantage of electricity price differences and 2) allow operating the process with variable renewable electricity.***Figure 1*** Storage capacity (Figure 1) was determined by cost optimization, taking into account fluctuations in electricity prices, availability of resources (wind and solar), investment costs, and the capacity factors of units affected by storage size, such as electrolysis and synthesis. There are large differences between calendar years in the production of wind and solar and it was found that combining wind and solar together will reduce the storage demand.

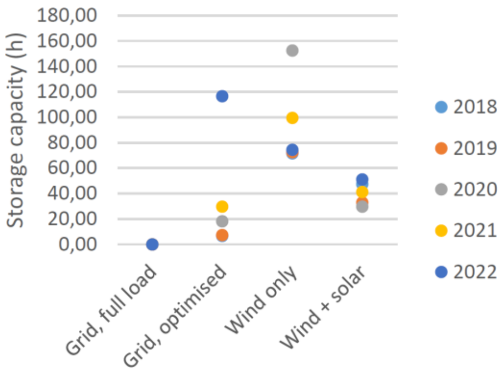

Figure 1. Optimized H2 storage capacity varies within years, wind+solar mixture reduces variation.

The optimal operation and unit capacities of the other processes (electrolysis, synthesis, CO_2 capture) were found to be **strongly case-specific** and depend on the input parameters. Especially the cost assumptions regarding future prices (equipment prices, energy prices, etc.) may affect the results significantly. Global sensitivity analysis can be used to address this, to find important parameters and interaction of them. As an example, high investment costs can cause the optimal system to be less flexible, as high full-load hours are required (Figure 2).

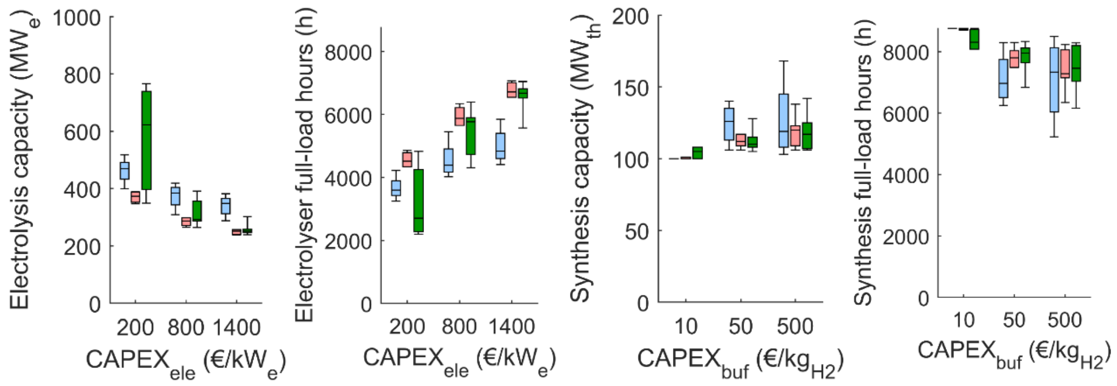

Figure 2. Effect of investment costs of electrolysis and H2 storage on capacities and full-load hours of electrolysis and synthesis. Whiskers show the minimum and maximum, the bar is for the middle 50% of the cases, and the horizontal line defines the median value among all studied cases.

Cryogenic CO_2 capture was studied as an example. This study investigated an integrated multigeneration system that produces power, cooling, and solid carbon dioxide by applying electricity-driven cryogenic carbon capture from flue gas. The integrated system comprises a gas turbine, Rankine cycle, absorption chiller, helium refrigeration cycle, and CO_2 capture process (Figure 3). Waste energy recovery is the key factor in this system. The benefits of the studied system were increased energy and exergy efficiency, low capture cost, and solid CO_2 as the product.

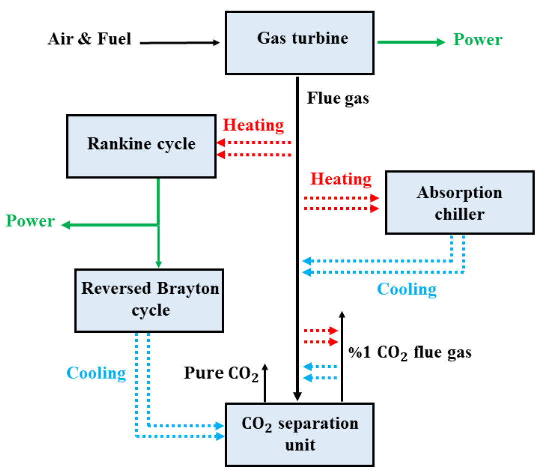

Figure 3. Schematic of the proposed integrated system.

APPLICATIONS/IMPACT

First, the results provide practical examples about how individual PtX processes and plants could be designed and operated to bring value from flexibility. The finding is relevant at the level of the individual plant and at national level and hence the question arises: is it desirable to build flexibility at the plant level or at the entire energy system level? Second, the study reveals the importance of H_2 storage optimizing. It should be considered whether storages should be built at local or at national scale, as the specific cost of large-scale cavern-type storage is much smaller compared to smaller plant-specific steel tanks or underground pipes. Third, it was found that process integration brings benefits. Local industries and communities should co-operate to find optimal PtX solutions already in the design phase.

MAIN CONTACT

Eero Inkeri, LUT School of Energy Systems, eero.inkeri@lut.fi

AUTHORS

Eero Inkeri, Hossein Enayatizadeh, Tero Tynjälä, Jaakko Hyypiä, Sampo Vilve

WP4 TASK 3

Advanced data-driven methods in Power-to-X operations

ABSTRACT

The main objective of the task was to apply artificial intelligence (AI) methods in Power-to-X (PtX) applications to enhance long-term renewable energy storage, hydrogen production, and methanol synthesis processes. The research focused on designing a comprehensive AI based infrastructure utilizing advanced technologies such as Internet of Things (IoT), big data analytics, edge computing and machine learning to optimize PtX operations. Key outcomes include an understanding of the role of AI methods in running PtX processes as a cyber-physical system, developing IoT-based architectures, selection of suitable IoT platform based on the PtX process requirements, employing machine learning models for operational parameter prediction, and integrating cybersecurity for secure hydrogen generation and storage.

MOTIVATION

Europe is leading the development of a sustainable energy system to reduce greenhouse gas emissions and achieve a green transition. Power-to-X (PtX) and cogeneration technologies are key to building a resilient, decentralized, and carbon-neutral energy network by 2050. These technologies offer huge potential for balancing electric grid loads, integrating renewable energy, and supporting the hydrogen economy. Utilizing innovative ICT tools PtX will enable more efficient energy storage and cross-sectoral integration, playing a crucial role in Europe's shift toward a reliable and cost-effective clean energy future.

RESULTS

Example of a PtX process is a synthetic CH4 (e-CH4) production system, a subset of PtX, that has a potential role e.g., as long-term energy storage. A primary process in e-CH4 systems involves converting hydrogen and carbon dioxide into methane (CH4), which can then be used as a substitute for natural gas. This methane can be stored or transported using existing natural gas infrastructure. Compared to short-term energy storage solutions such as batteries, e-methane provides long-term storage capacity and can smooth out fluctuations in energy supply caused by variable renewable energy generation.

Data driven methods in PtX

IoT technology enables the collection, transmission and processing of vast amounts of data from various points in the PtX process chain, including renewable energy generation, electrolysis, and chemical synthesis. This data is collected and analyzed to improve decision-making and grid management. IoT data is linked to several companies across industries, bringing challenges to store and analyse data, particularly in large and interconnected devices.

Big data analytics helps address the challenges posed by the massive amounts of data generated by IoT systems. By utilizing advanced analytics tools, organizations can extract valuable insights from structured, semi-structured, and unstructured data. In the context of PtX, big data analytics enables continuous improvement of plant operations by optimizing resource allocation, improving efficiency, and reducing downtime.

Machine learning plays a crucial role in predictive analytics, allowing PtX systems to improve operational efficiency by forecasting outcomes based on historical data. In the PtX context, machine learning algorithms are used to predict the best times for hydrogen production, storage, and utilization, minimizing the levelized cost of products such as methane. By training algorithms using historical data, the study showcases how machine learning models can predict future values more accurately and assist in optimizing system operations.

Figure 1 shows a theoretical architecture that integrates IoT, big data, and machine learning technologies.

HYGCEL

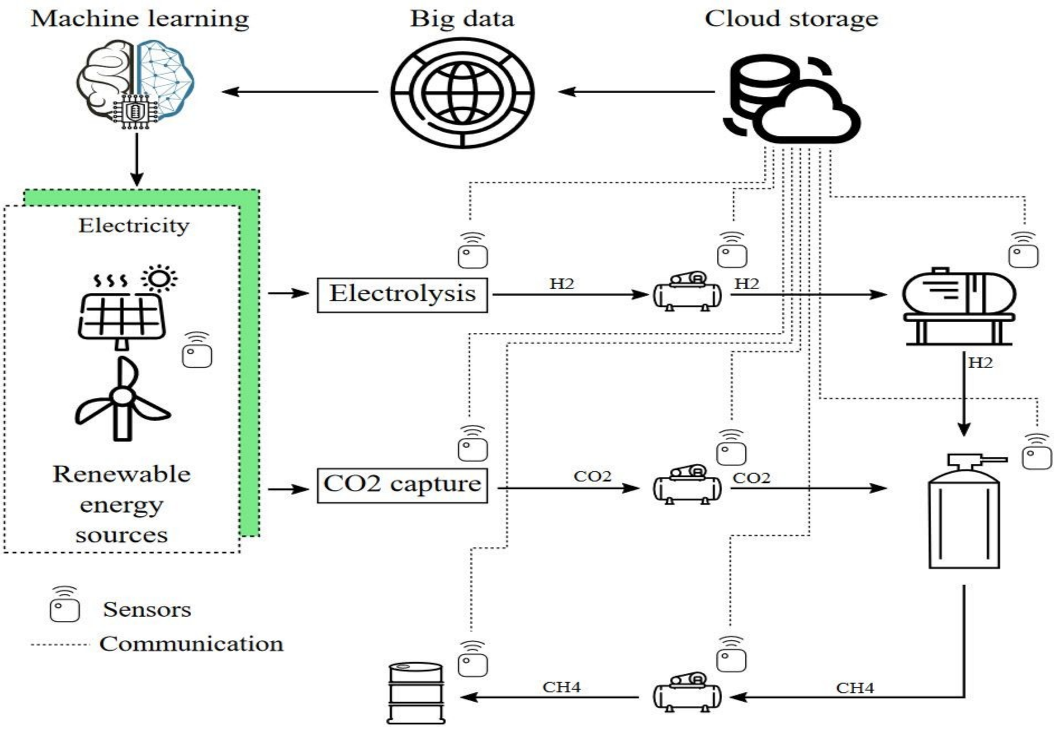

Figure 1. Main architecture designed for working of methanol synthesis.

The architecture involves four stages:

Data collection (IoT): Sensors are deployed across the PtX infrastructure to collect data related to renewable energy generation, electrolysis processes, CO_2 capture, and hydrogen/methane storage. ***Data storage****:* The collected data is stored in the cloud for subsequent processing. ***Big data processing****:* The stored data is processed using big data analytics tools to derive insights that can optimize system performance. ***Machine learning prediction****:* The processed data is used to train machine learning models that predict optimal operational parameters for the PtX system.

Based on this study, the major challenge for industries in implementing IoT and other latest technologies in Power-to-X (PtX) plant is the selection of the most appropriate Internet of Things (IoT) platform from the vast number of available options. The choice of an IoT platform is critical because it needs to be aligned with the unique requirements of PtX plants, which involve complex interactions between renewable energy sources, electrolysis, CO_2 capture, and fuel synthesis.

The research proposed a general framework as shown in figure 2 for IoT platform selection on PtX sector.

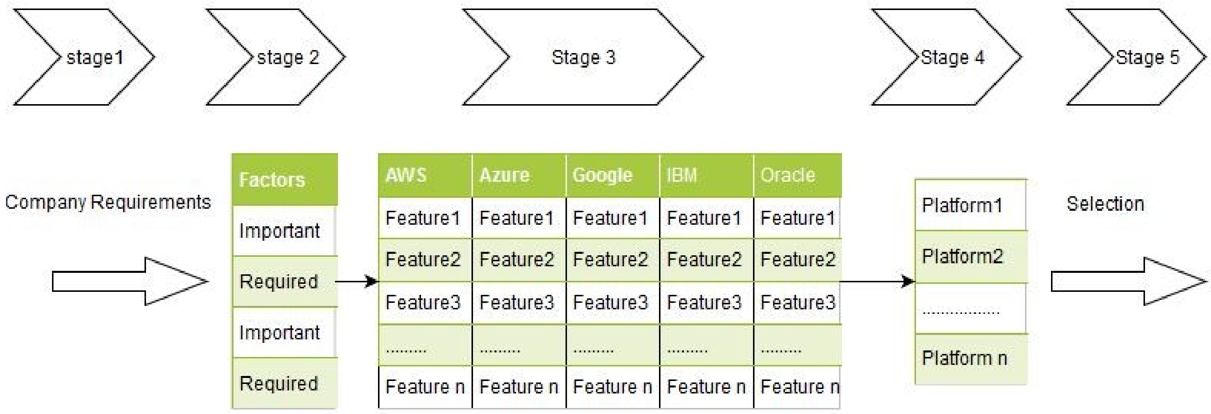

Figure 2: IoT platform selection Framework for PtX cogeneration plant

The framework provides an objective and systematic methodology to guide industries in selecting the most suitable IoT platform based on their operational needs. The use of this methodology in the framework ensures that the platform selection process is data-driven, transparent, and aligned with business goals.

The framework consists of five key stages. The *first stage* involves understanding the basics of IoT and how it supports the monitoring, data collection, and optimization of processes in the plant. The *second stage*, Identifies the plant's specific requirements, such as real-time data monitoring, energy storage management, and system automation. *Third stage* prioritizes these requirements as Required (R), Important (I), or Not Required (-) to focus on critical factors. This prioritization helps industries focus on the most critical factors when evaluating IoT platforms. In the *stage four*, the "Required" and "Important" factors are compared with the features of different IoT platforms**.** This comparison enables a more focused evaluation of which platforms can meet the essential requirements for the PtX cogeneration plant, narrowing down the options to those that are the best fit. In cases where multiple platforms satisfy all the requirements, the *final selection stage* is based on specific "Important" criteria, such as pricing, security etc.

APPLICATIONS and IMPACT

Implementing advanced data-driven technologies like IoT, big data, edge computing, and AI (machine learning) in PtX cogeneration plants offers significant benefits. First, these technologies enable the full digitalization of the plant's processes, from data collection to predictive analytics. Second, the new architecture using the latest innovations to enhance the efficient conversion of renewable energy into other forms that can be stored long-term and used when needed. The developed IoT platform selection framework ensures the selection of the IoT platform based on business needs.

MAIN CONTACT

Mehar Ullah, LUT School of Energy Systems, mehar.ullah@lut.fi

AUTHORS

Mehar Ullah, Daniel Gutierrez Rojas, Pedro Nardelli

WP5 TASK 5.1

Solid carbon products and markets

ABSTRACT

A feasible way to utilize CO2 might be to reduce (convert) it to valuable carbon products. One novel way to produce carbon products is the molten salt electrolysis. It utilizes high temperature and electricity to efficiently produce nanocarbon structures. In this part, the solid carbon product and markets were evaluated. First, a literature study of the existing solid carbon products like carbon fibers, carbon nanotubes and carbon nano-onions were studied. The graphite is largest carbon product, but for the nanostructures, carbon nanofibers are currently dominating the market and are increasingly growing. Secondly, a feasibility study of the carbon nanostructures production was conducted. The production cost of the carbon nanotubes was found to be less than 2 €/kg. By this price the production of it is feasible and the development of the technology should be continued. A carbon product from 5th Innovation Ltd was tested for being utilized as electrodes of lithium carbonated based molten salt electrolysis at Tampere University. Their biobased solid carbon was stable as cathode and may substitute typical Nickel cathode, but the oxidative conditions at anode corroded the carbon in tested 30 minutes run.

MOTIVATION

Solid carbon products can become a valuable and feasible way to utilizateCO2 in the existing market products to replace their fossil and mineral peers. Thus, it is important to study the existing markets and the prices of the products. The particular focus of the study was on the nanostructures that are produced by molten salt electrolysis as it is found to be a potential production technology [1]. Different allotropies were studied [2].

APPROACH

Pure carbon products are required in many applications e.g., as carbon black (color, reinforcing filler material). Nanotubes are potential high-value products which can be used in electrodes of batteries and fuel cells and as a semiconductor in electronic components.

Different applications set different requirements for carbon properties e.g. by means of morphology and purity. That is why also the price of carbon products varies significantly affecting the profitability of molten carbonate electrolysis-based carbon production.

The work consisted of three different tasks, and the literature review was made on existing solid carbon product market using scientific and internet sources. The first part studied the prices and markets for selected carbon allotropes [3]. The second part studied the solid carbon products of molten salt electrolysis, and a literature review and a case study of feasibility were conducted [4]. The third part was made in collaboration with 5th Innovation company to study the stability of their bio-based solid carbon as the electrodes of molten salt electrolysis [5]. In addition, during the project, the utilization of the products was evaluated in the end of the project.

RESULTS

The market development of Carbon nanotubes (CNT), Graphene, Grafite and Carbon nanofibers were studied. The market estimates are presented in Figure 1. The largest market is for graphite, and it is also estimated to grow faster than CNFs. CNFs are reaching some billion dollars market by 2030. The markets of graphene are remaining low, rising to approximately one billion dollars annually by 2030.

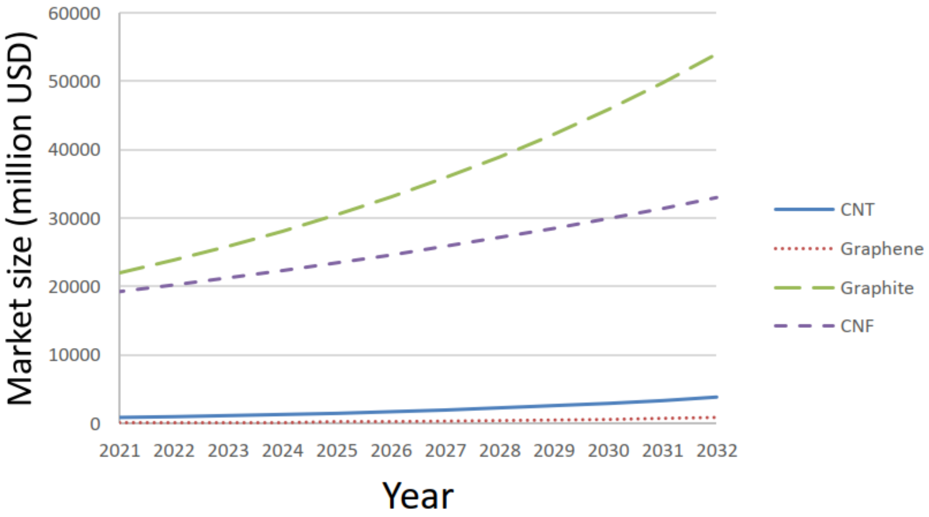

Figure 1. The estimated markets of Carbon nanotubes (CNT), Graphene, Graphite, and Carbon nanofibers. [3]

The price estimates of carbon types of graphite, Single wall carbon nanotubes (SWCNT), Double wall carbon nanotubes (DWCNT), multi wall carbon nanotubes (MWCNT), carbon nano-onions (CNO), carbon nanofibers (CNF), and graphene are presented in Table 1. The prices are significantly affected by the quality, purity, and production method of the material. Pure graphene is the most expensive, and high-quality nanostructures are of high value in addition. If pure nanostructures could be produced by molten salt electrolysis, its production would become feasible. However, the market analysis also revealed that the markets of the most expensive products is rather limited. Mass produced products are always relatively mildly priced. Based on the test runs, the obtained product of nano-onions [6] was in the optimal range for quality and prices.

Table 1. Reported prices of different carbon types [3]

Carbon type	Price per mass	Reference
Graphite	600–2,750€/t	[7, 8]
SWCNT	28–2,800€/g	[5, 11]
DWCNT	14€/g	[5, 11]
MWCNT	0.085–140€/g	[5, 11, 27]
CNO (fullerenes)	129–373€/g	[17]
CNF	2,350–8,900€/kg	[10, 11]
Graphene	70–237,000€/kg	[21 ,11]

An industrial case was studied in a techno-economic study. The applied parameters are presented in the Table 2 and 3. The results of the cost estimation for a CNT production plant having a 0.7 kg/hour production capacity were estimated. The estimated production cost was found to be 1.35 €/kg. However, this estimate is based on small scale production, and might thus be quite optimistic by nature, and therefore the error marginal of the results is large. The result can be considered only as an indicative value. The financial estimate would be fully reliable when demonstrated on a real operating plant in an industrial scale.

Table 2. The values applied in the economic analysis.

Parameter	Value	Unit
Inflation	1.5	% [24]
CO_2	80	€/t [23]
Reference year	2022	
Operational hours	8000	h/a
Discounting rate	10	%
Operational years	30	a
Electricity cost	70	€/MWh [20]
CNT price	100	€/kg [31]
CNT production rate	0.7155	kg/h [7]
Initial investment	7813.124	€ [32]

Table 3. The cost estimates of large-scale molten salt electrolysis process.

Parameter	Cost	Unit	Reference
Electricity	915.95	€/t	[7]
Labour	140.90	€/t	[7]
Capital expenses	230.75	€/t	[7]
Maintenance	61.08	€/t	[27, p.13]
Total	1348.76	€/t	

In the tests of the solid carbon electrode material produced by 5th Innovation a molten salt electrolysis process developed at Tampere University was applied as Cathode [5]. A photo of the equipment is presented in Figure 2 below.

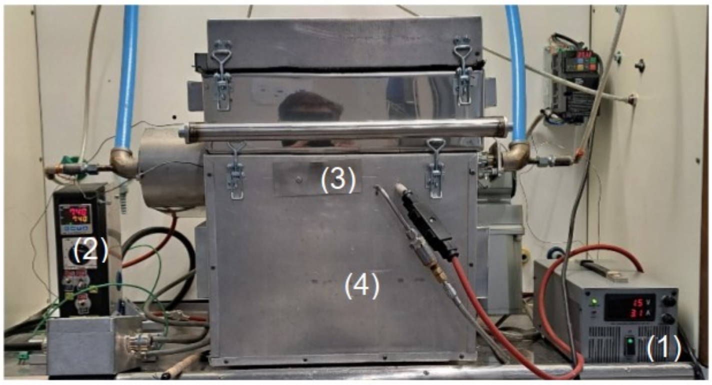

Figure 2. The molten salt electrolysis equipment (1) power source, (2) temperature controller, (3) opening for the electrode holders, and (4) the oven. [5]

In the tests, nominal result was obtained by stable electrode materials studied earlier in HYGCEL project Nickel for cathode and Tin dioxide for anode. The basic electrodes are presented in Figure 3.

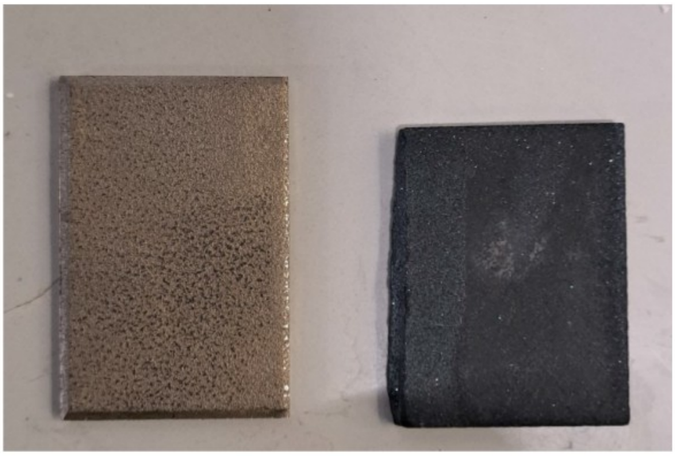

Figure 3. the electrodes applied in the nominal case, left Nickel for cathode and right Tin dioxide for anode. [5]

A stable combination for the tested carbon electrode was made for the cathode. The tested electrodes are shown in Figure 4.

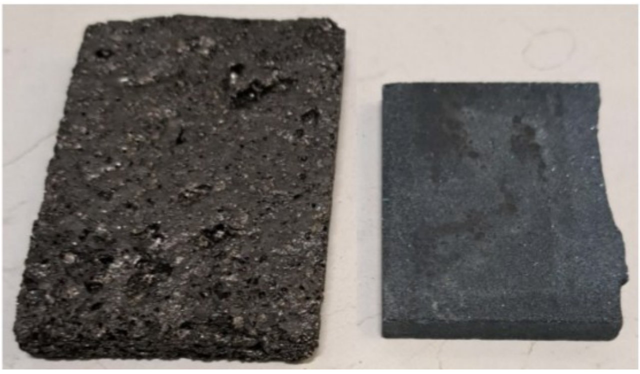

Figure 4. Successfully tested electrodes, left biobased solid carbon cathode and right the Tin dioxide anode. [5]

The carbon was produced on the surface of the cathode. The used electrodes are presented in Figure 5.

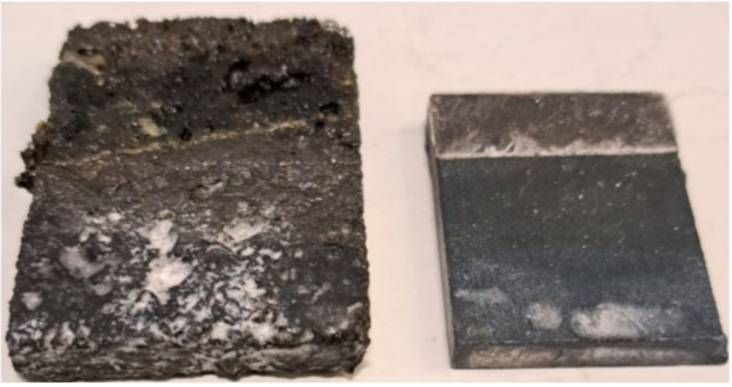

Figure 5. Used biobased cathode on left and anode on right. White contamination on the cathode is lithium salt. [5]

A standard results of carbon nano-onion was found from the washed cathode. A SEM figure is presented in Figure 6.

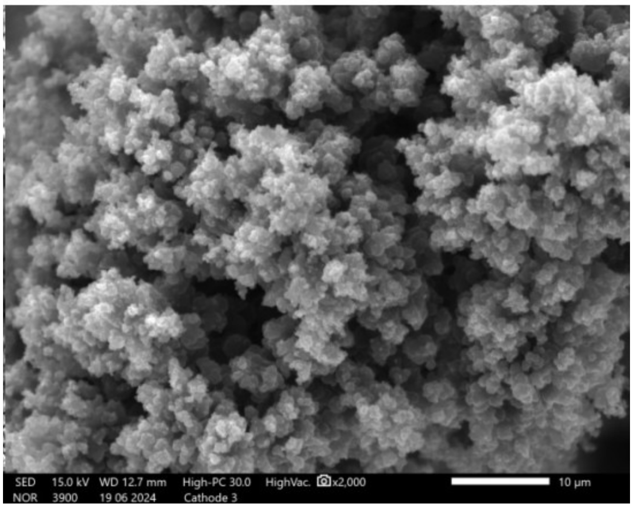

Figure 6. Homogeneous and pure nano-onion sample obtained on the bio-based carbon cathode. Photo by Jussi Laurila. [5]

In the analysis of the produced carbon nano-onions at Tampere University [6] it was analyzed that the specific surface area of the carbon is relatively low 7 m2/g. This limits the utilization of the carbon, and for example, applications of superconductors or filters are not feasible. The application as raw materials of electrodes for batteries and electrolysis are further studied in further coming projects.

APPLICATIONS/IMPACT

The solid carbon products markets are growing fast, and feasible products that are of high price are available. The production is an area of high interest.

The bio-based solid carbon of 5th Innovation is stable in molten salt electrolysis at cathode.

In the analysis of the produced carbon nano-onions at Tampere University [6] it was analyzed that the specific surface area of the carbon is relatively low 7 m2/g. This limits the utilization of the carbon. Applications of superconductors or filters are not feasible. The application as raw materials of electrodes for batteries and electrolysis are further studied in further coming projects.

MAIN CONTACT

Tero Joronen, TAU, tero.joronen@tuni.fi

AUTHORS

Tero Joronen, Jyrki Mäkelä, Miika Sorvali, TAU

Vesa Ruuskanen, Tuomas Koiranen, Emma Laasonen, Anafi Aini, Jero Ahola, LUT

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WP5 TASK 5.2

Energy efficient CO_2 electrolysis

ABSTRACT

Carbon capture and utilization (CCU) is a viable approach to convert atmospheric CO_2 into various valuable end products such as fuels, chemicals, and construction materials. In the context of CCU, this research focuses on the conversion of CO_2 to elemental carbon via molten carbonate electrolysis. The effect of electrolyte selection, electrolysis temperature, and cathode material on the specific energy consumption and carbon morphology produced was studied in this work. The focal points of the experimental work were selected based on a lack of previous studies and/or previous studies having contradictory results. Previous studies related to CO_2 conversion in molten salts indicate that the produced elemental carbon can exist in various morphologies, such as carbon nanotubes (CNTs), nanofibers (CNFs), nano-onions (CNOs), platelets, and amorphous carbon.

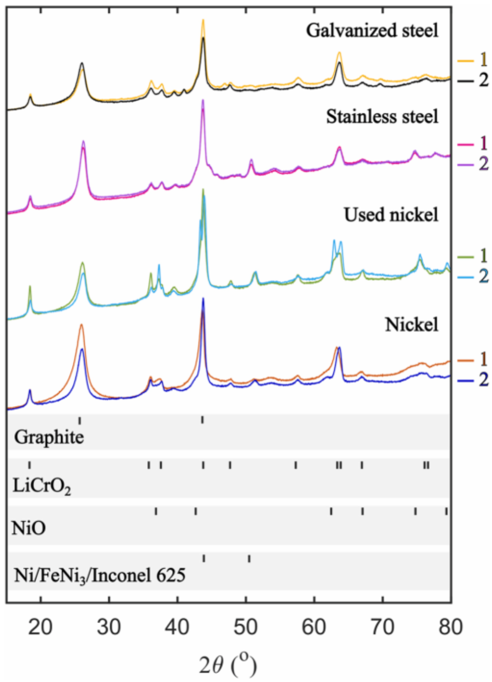
MOTIVATION

To make molten salt electrolysis competitive option for traditional fossil-based carbon production methods process energy consumption needs to be minimized while high quality of carbon product is granted. In a high temperature electrochemical process material selection and controlling electrode degradation is essential. In addition to electrolyte and electrode materials selection, process conditions optimization is a key for a competitive process.

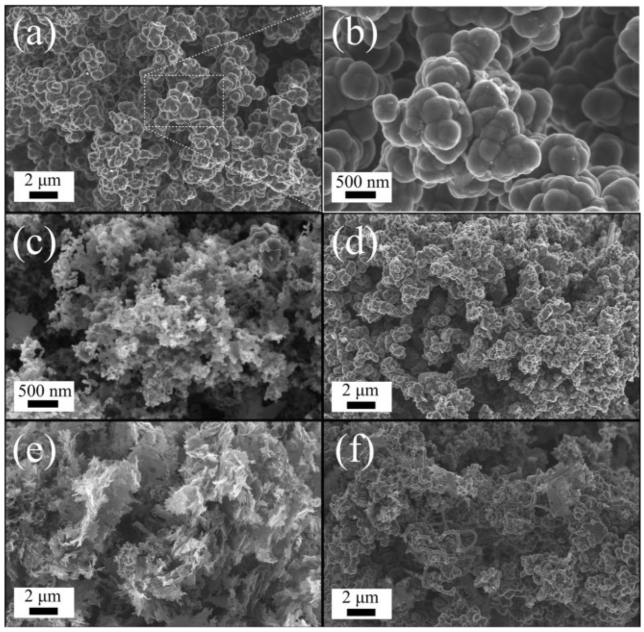
RESULTS

The experimental work was conducted with two different types of electrolyser setups: coaxial and planar. One of the key challenges encountered in the design and selection of materials for these setups is the harsh process conditions. The combination of molten salt, high temperatures, and the generation of oxygen in the process make the process conditions extremely corrosive. Corrosion is producing metallic impurities and those getting mixed with carbon is an issue of concern, as any impurities affect the product quality.

A comprehensive understanding of the produced carbon was achieved through the utilization of various analytical methods, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD). The results revealed that the different metals dissolved from the electrodes affect the carbon produced and its morphology. Different metals and different amounts of metals seem to have different types of effects. With little to no dissolved metals mixed with the product, spherical nano-onions were the dominant product. These spherical, onion-like structures were the main product when using nickel cathode. With the presence of iron, tubular structures were dominant, as the iron acted as a nucleation seed for tube growth. Tubular structures were found when steel-based cathodes, both stainless and galvanized steel, were used. Generally, it seems that impurities cause inconsistent products containing various carbon morphologies.



A)

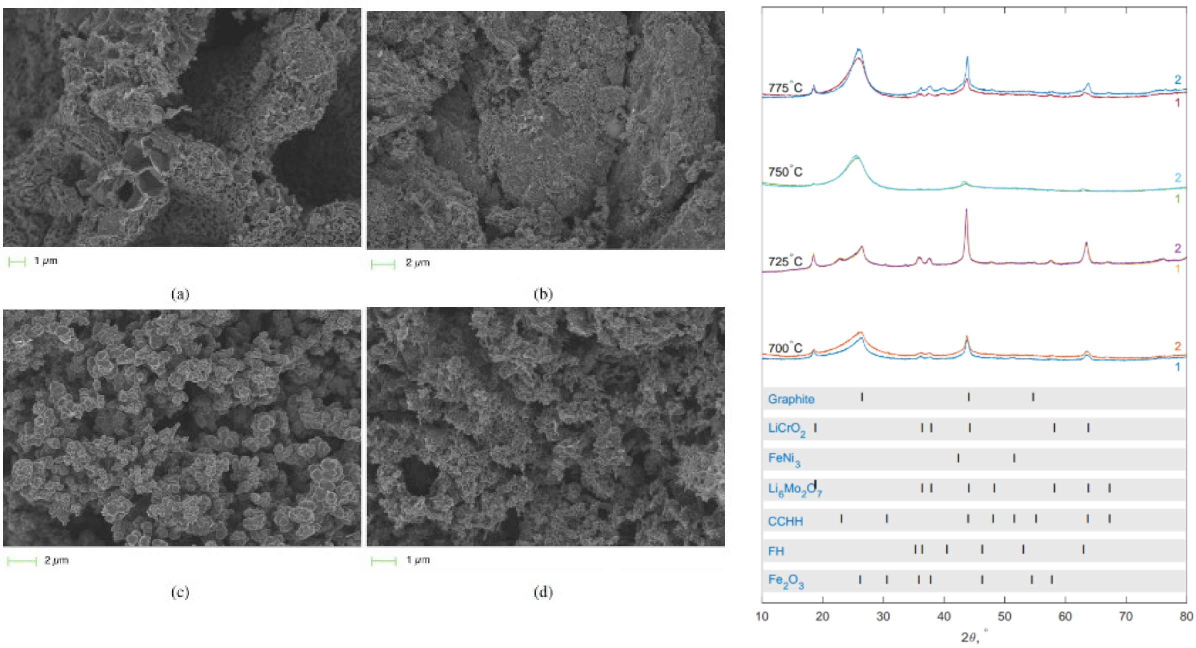


B)

Figure 1. A) XRD patterns of the carbon samples produced with different cathode materials at otherwise fixed conditions. The number of the sample is marked on the right side of the figure, and the most significant peaks for the main identified phases as a function of diffraction angle at the bottom of the figure. B): SEM images of nickel cathode samples: (a) the major morphology of the samples is nano-onions, (b) a higher magnification of nano-onions, (c) significantly smaller spherical structures, (d) more irregular shapes, (e) platy structures, and (f) tubular structures.

In addition to electrode materials, the work studied the effect of electrolyte composition and electrolysis temperature on the carbon morphology produced. Electrolytes studied were Li_2CO_3-$BaCO_3$ and Li_2CO_3-$CaCO_3$ 80:20 mol%. The results showed that both electrolyte composition and electrolysis temperature affect the carbon morphology. The effect of the electrolyte composition was more significant at lower temperatures, as the product morphology differed considerably between the electrolytes. The number of tubular structures increased along increasing temperature in both electrolytes, which indicates that the effect of the electrolyte is not as significant at higher temperatures. Based on XRD diffraction patterns, it can be concluded that not only the morphology of the carbon changes, but also the type and number of metallic impurities.

The results from Li_2CO_3-$CaCO_3$ electrolyte show more promising compared to results from Li_2CO_3-$BaCO_3$ electrolyte in terms of product quality. Regarding electrolysis power and voltage efficiency, Li_2CO_3-$CaCO_3$ proves equal or superior to other electrolytes, depending on temperature. Heat generation occurs in all the experiments, which emphasizes the importance maintaining a constant electrolysis temperature in industrial processes to manage heat generation effectively. Further upscaling process to industrial scale was studied in HYGCEL WP5 task 5.3.



A) *B)*

Figure 2. A) SEM images and B) XRD patterns of carbon produced in Li_2CO_3-$CaCO_3$ electrolyte at a) 700 C, b) 725 C, c) 750 C, and d) 775 C temperature with otherwise fixed conditions.

HYGCEL

APPLICATIONS and IMPACT

Molten carbonate electrolysis is still in the development i.e., it has not yet reached a commercial stage. The key aspect in the molten carbonate electrolysis profitability is the purity of end product in addition to the specific energy consumption of the process. Major aspects affecting the morphology and the purity are electrode materials, electrolyte composition and temperature. Corrosion heavily affects the carbon quality, and it is challenging to reach low-cost stack structure to elevate system voltage in order to limit the current requirement and power supply cost.

MAIN CONTACT

Vesa Ruuskanen, LUT, vesa.ruuskanen@lut.fi

AUTHORS

Tero Joronen, Jyrki Mäkelä, Miika Sorvali, TAU

Vesa Ruuskanen, Tuomas Koiranen, Emma Laasonen, Anafi Aini, Jero Ahola, LUT

WP5 TASK 5.3

Industrial-scale CO2 electrolysis

ABSTRACT

Carbon capture and utilization (CCU) is a viable approach to convert atmospheric CO_2 into various valuable end products such as fuels, chemicals, and construction materials. In the context of CCU, this research focuses on the conversion of CO_2 to elemental carbon via molten carbonate electrolysis. New reactor designs were studied to enable upscaling to industrial process including the effect of industrial power supplies on the specific energy consumption and product quality.

MOTIVATION

To increase the applicability of molten carbonate electrolysis new reactor designs are required. Advances and challenges related to stacking of single molten carbonate electrolysis cells into stacks in the similar manner as in case of water electrolysis needs to be studied. Further, replacing batch process with a continuous process might be a promising pathway towards industrial scale process.

RESULTS

The electrodeposition process of carbon in molten lithium carbonate electrolysis and the associated gas-liquid flow hydrodynamics characteristics were investigated using computational fluid dynamics (CFD) for the first time. The high-temperature (750 ◦C) process is challenging for conducting measurements, making CFD a valuable tool for providing insights into the novel coaxial-type cell design. The CFD simulation addresses the electric field distribution, oxygen gas evolution, and electrodeposition of carbon. The effect of gas bubble sizes (1, 0.8, and 0.6 mm) on the CO2 -electrolysis process was examined at different electrical current densities (0.15 ±0.01 A cm–2). The CFD results reveal that gas holdup increases by decreasing the bubble size and that the bubble size significantly impacts the current density distribution by affecting the two-phase flow dynamics.

The results also indicated that the current density distribution is not as uniform as anticipated with the coaxial setup. This uneven distribution causes the carbon deposition on the cathode surface to become uneven. Also, as of now, the numerical investigation only considers the main reactions of the carbon deposition by only considering the carbon and oxygen formation. Experimental work (in HYGCEL WP5.2) revealed that the presence of metallic impurities affects the carbon morphology.

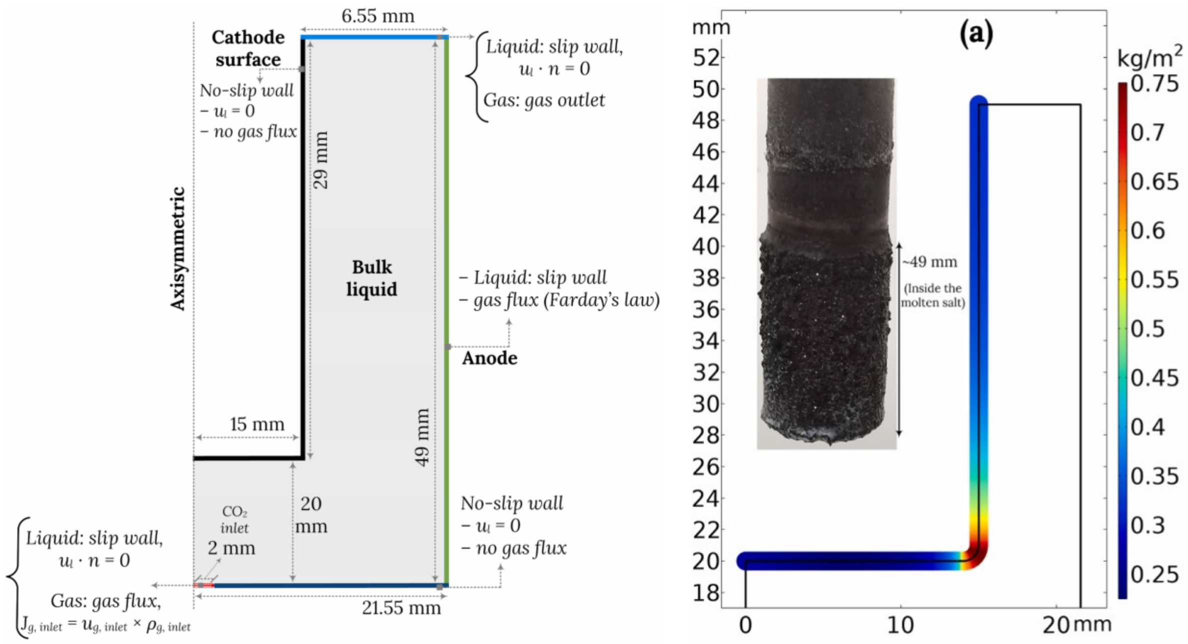


Figure 1. Left figure: Schematic illustration of the boundary conditions of the CFD analysis. Right figure: carbon deposition on the cathode surface obtained via CFD simulation and a photograph of the cathode from the experiment.

The current study successfully employed computational fluid dynamics to investigate the hydrodynamics characteristics and electrodeposition process of carbon in a molten lithium carbonate electrolysis cell. The study aimed to provide further insights into the high-temperature process occurring in the co-axial reactor, where currently no practically viable solutions exist for process monitoring. The challenges of model validation were addressed, and attempts were made to assess the validation quantitatively and qualitatively. The results

indicate that gas bubble size plays a critical role in the liquid electrolyte hydrodynamics and charge transfer mechanism, affecting the current density distribution at the cathode. Moreover, due to the design of the cell, the electric field distribution is stronger at the corners of the cathode, resulting in relatively larger carbon deposition in those regions.
The numerical study presented in this work has demonstrated the potential applications of CFD in high-temperature molten salt processes.
Study showed that the current ripples generated by power electronics do not have very significant effect on the product quality and current waveform control is not effective on the carbon morphology control. Current ripples were found to cause additional power consumption as already known in case of water electrolysis.

APPLICATIONS and IMPACT

Molten carbonate electrolysis is still not in commercial phase. The key aspect in the molten carbonate electrolysis profitability is the purity of end product in addition to the specific energy consumption of the process. Corrosion heavily affects the carbon quality, and it is challenging to reach low-cost stack structure to elevate system voltage in order to limit the current requirement and power supply cost.

MAIN CONTACT

Tero Joronen, TAU, tero.joronen@tuni.fi

AUTHORS

Tero Joronen, Jyrki Mäkelä, Miika Sorvali, TAU

Vesa Ruuskanen, Tuomas Koiranen, Emma Laasonen, Anafi Aini, Jero Ahola, LUT

WP6 TASK 6.1 and 6.2

Environmental and economic feasibility of PtX value chains

Report is combining T6.1 Possibilities and risks arising from climate issues and T6.2 Regulatory and financial risks threatening business

ABSTRACT

Tasks 6.1 and 6.2 had altogether three main research questions: (1) Does a product chain reduce greenhouse gas (GHG) emissions in a system level integrated to the existing infrastructure and how much studied product chain produces GHG emissions compared to its alternatives, (2) How cost effective it is to reduce GHG emissions by investing Power-to-X (PtX) solutions, and (3) How regulatory and financial risks threatens business? Most of the analyses were carried out in collaboration with HYGCEL WP1, WP3 and WP4.

The impact of electricity sources along with the different technological solutions, such as type of electrolyzers, H_2 delivery options and synthesis processes, and a possibility to reduce emissions compared to conventional fossil-based products were investigated using literature and life cycle assessment (LCA) as a method (question 1). Also cost efficiencies of value chains were evaluated by analysing H_2 delivery options (question 2). To reveal how the environmental and economic feasibilities of PtX value chains behaves in a system involving stricter criteria for renewable fuels of non-biological origin (RFNOB) (in practice H_2 production utilising temporal and regional renewable energy), a dynamic modelling with LCA and life cycle costing (LCC) was conducted from differently designed PtMethanol value chains (questions 1 and 3).

Results indicate that PtX value chains can provide extensive emission savings, which quantity is depending on end-product how the product is utilized (i.e., what it replaces). Green H2 results to least climate impacts as compared to blue H_2, turquoise H_2, and grey H_2. Carbon capture and utilization (CCU) applications cannot provide as extensive emission savings than green steel, e-ammonia* or green H_2. Green steel value chain was identified to provide the most emission savings. Notably, most of the investigated renewable based PtX solution can

provide up to 90% emission savings compared to their fossil-based reference products. When thinking emission savings from Finland's perspective, the quantity of consumable PtX products influence on overall emission savings. Finland can become an enabler for other regions climate targets, when exporting low-carbon products. In this case, Finland can gain "positive handprint" by providing low-carbon alternatives.

When evaluating H_2 transportation options, the H_2 pipeline transportation and on-site H2 production resulted to be the most feasible options compared to H_2 shipping or converting H_2 to e-methane and then back to H_2.

When evaluating the emission reduction costs and economic risks, H_2 production is the key factor determining the risks and costs in PtX value chain due to high CAPEX and OPEX costs. OPEX is mainly determined by electricity requirement to produce H_2. Because of these characteristics it seems to be difficult for a H_2 provider to achieve economic feasibility as an independent actor. To bring the H_2 production costs down, the price of electricity needs to be feasible, weighted average cost of capital should be low and or the provider needs investment subsidies. The predicted cost reductions of investments will also reduce the CAPEX related costs in the long or medium term. Due to high CAPEX costs, it can be reasonable to phase the investments to reduce economic risks. However, phasing the investments means that some of the emissions reductions are postponed compared to heavy one-time investment. For these results, see also results from HYGCEL WP1T3b.

* e-ammonia value chain can become CCU application, when refining ammonia to urea

MOTIVATION

Climate mitigation is one of the biggest reasons for the transition towards PtX economy. Green H_2 and its derivates have been shown to achieve greenhouse gas emission savings. However, to be truly sustainable the transition needs to be socially and economically feasible while being able to mitigate environmental and risks. For this it is important to identify which PtX value chains can achieve the highest emission savings and what are the "hotspots" for achieving economic feasibility. By knowing this it is possible to reach carbon neutrality while getting the most benefits out of this transition. Operational risks are discussed separately in HYGCEL WP6 task report 6.3.

RESULTS

Climate impacts of hydrogen production and delivery

An LCA study was made to compare climate impacts of different (differently produced) hydrogen. The investigated H_2 value chains were grey hydrogen, blue hydrogen, turquoise hydrogen (without carbon sequestration) and green hydrogen. The results (Figure 1) show that green hydrogen can achieve the lowest emissions per kg H_2 from the investigated value chains.

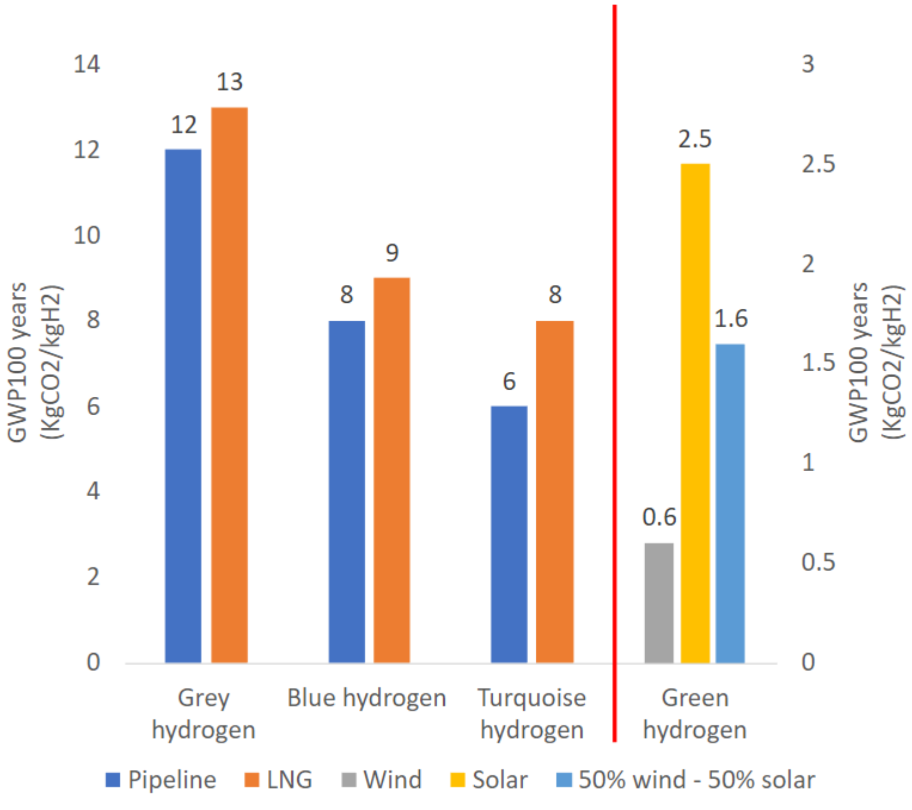


Figure 1. LCA results of examined hydrogen production technologies. Please note the different scales in left and in right.

Another LCA study was made to assess the climate impacts of green H_2 production by comparing different means to deliver hydrogen or its carriers. The investigated cases were **on-**

site H_2 production (case 1), H_2 pipeline distribution (case 2 and 4), H_2 shipping (case 5) and H_2 conversion to e-methane and back to H_2 (case 3) (Figure 2). The study involved a possibility to utilize waste heat from electrolyzers for local district heating network.

It was shown that on-site H_2 production via electrolysis and H2 pipeline delivery resulted to least emissions. Shipping option caused the most emissions and conversion to e-methane and back to H_2 the second most. Interestingly, if the CO_2 from thermal decomposition of methane (TDM) process is sequestered cand acts as a sink, the method can result to carbon negative way to deliver H_2. For these results, see also HYGCEL WP3T1 report.

The utilization possibility of local district heating network was studied in different locations as different locations can have different district heat carbon intensity depending on its production method. Substituting district heating heat with waste heat from electrolyzers can sometimes result in substantial amounts of avoided emissions.

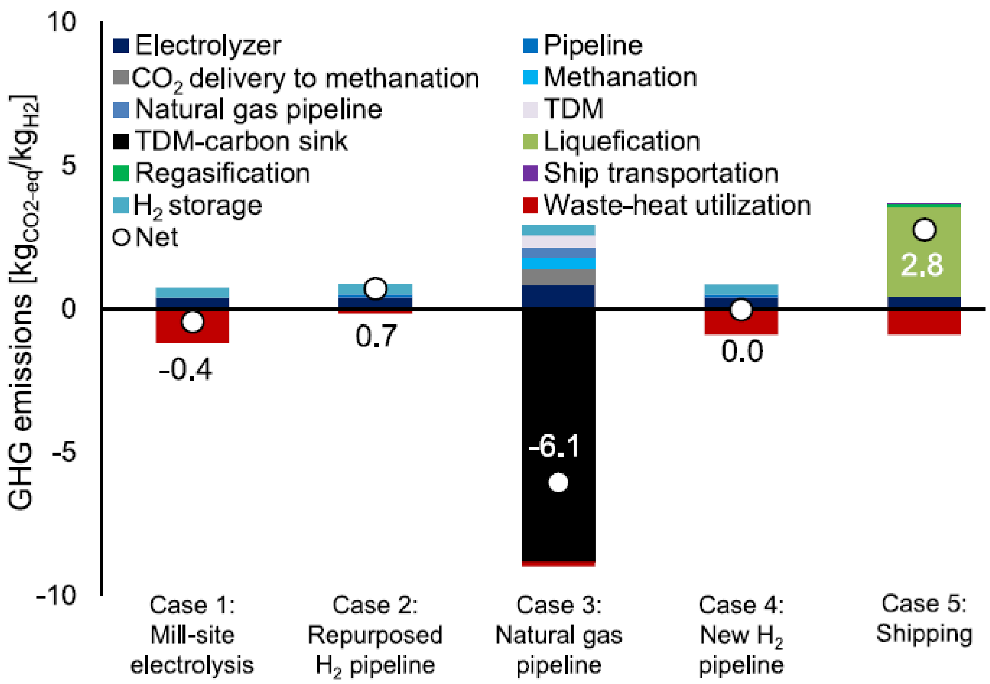


Figure 2. LCA results of H2 distribution methods.

Climate impacts of PtX value chains

The literature review was made on LCA studies to find out the climate impact of different PtX value chains. The study showed that when utilizing 1 kg renewable or nuclear based hydrogen, all the investigate PtX value chains can achieve up to 90% emission reduction as compared to their fossil-based reference products. The type of a reference product had a great impact on the magnitude of savings. (Table 1). PtSteel, PtAmmonia, PtHydrogen and PtFood can achieve the highest emission savings. From CCU pathways, PtMethanol and PtFuels seem to be the best performing value chains in terms of climate mitigation potentials. Power-to-Methane resulted to have the least emission saving potential. The literature review also revealed that typically e-fuels burns cleaner than fossil fuels, thus reducing outdoor air pollutants, such as NOx or particulate matter emissions, in addition to GHG emissions.

Table 1. Impact reduction potentials of different PtX pathways per 1 kg of H2 when using RE or nuclear to power H2 production

Ptx Value chain	H_2-required	Unit	Reference products	MIN, MAX [$kg_{CO2\text{-}eq}kg_{H2}^{-1}$]	MEAN [$kg_{CO2\text{-}eq}kg_{H2}^{-1}$]
PtHydrogen	1	kg_{H2}	H_2 From SMR; coal gasification	5.68–24.96	9.61; 22.96
PtSteel	0.051–0.059	kg_{H2}/kg_{Steel}	BF-BOF production route	21.4–38.96	31.97
Partial hydrogen injection	0.025	kg_{H2}/kg_{Steel}	BF-BOF production route	10.28–12.8	11.54
PtAmmonia	0.18–0.19	kg_{H2}/kg_{NH3}	Ammonia from natural gas	4.09–15.14	11.33
PtMethane	0.46–0.50	kg_{H2}/kg_{CH4}	Natural gas	1.28–6.8	3.91
Biogas upgrading	0.17–0.19	kg_{H2}/kg_{CH4}	Natural gas	9.52–15.35	12.43
PtSyngas	0.126	kg_{H2}/kg_{Syngas}	Syngas from natural gas or from coal	No reduction potential – 16.2	0.91; 8.11
PtMethanol	0.19–0.34	kg_{H2}/kg_{CH3OH}	Methanol from natural gas or coal	No reduction potential – 22.88	3.33; 8.92
PtFuel					
PtDiesel	0.30–0.64	kg_{H2}/kg_{Diesel}	Diesel	1.76–30.93	9.75
PtGasoline	0.48–0.64	$kg_{H2}/kg_{Gasoline}$	Gasoline	2.06–6.71	5.69
PtDME	0.23	kg_{H2}/kg_{DME}	Diesel (based on MJ)	5.03–8.49	6.37
PtJetfuel	0.20–0.64	$kg_{H2}/kg_{Kerosine}$	Kerosine	4.55–16,62	8.41
PtMethanol	0.22	kg_{H2}/kg_{CH3OH}	Diesel or Gasoline (based on MJ)	No reduction potential – 8.30	3.15
PtPlastics	0.50–0.58	$kg_{H2}/kg_{Plastics}$	Polypropylene from	No reduction	2.46

* Several different protein sources are present; thus, calculating the mean value is unreasonable. The reduction potential is highly dependent on what is substituted. Animal based protein sources can achieve the highest emission savings.

Reducing climate impacts versus timing the investments

The potential conflicts in investment timing from financial perspective and from climate perspective was studied using e-methanol production value chains as an example. The study was defined as follows; cumulative emission savings from 30-year timeline; different electricity prices and CO_2 sources; impact of H_2 leakage; avoided emissions due to waste heat utilization; value chains designed according to RFNOB criteria (temporal and regional renewable production). Dynamic modelling (Calliope) optimizing the PtMethanol infrastructure was applied.

The studied value chains:

- Case1: Point source of CO_2 using monoethanolamine technology (MEA) technology
  - A big one-time investment (750 MW electrolyzer)
  - Phased investments (first 150 MW electrolyzer is invested and after 10 years the capacity is increased to 750 MW)
- Case2: CO_2 from ambient air using direct air capture (DAC) technology
  - A big one-time investment (750 MW electrolyzer)
  - Phased investments (first 150 MW electrolyzer is invested and after 10 years the capacity is increased to 750 MW)

Optimisation results (Table 2) indicate that the cheaper the electricity price is the more e-methanol is produced resulting to higher cumulative emission reduction. However, the change is not significant. Similarly, the source of CO2 slightly affected the results: more e-methanol can be produced using direct air capture (DAC) instead of point-source utilisation (MEA) resulting in higher cumulative emission reduction.

The big one-time investment causes more cumulative emission savings compared to investing in phases: when comparing the lifetime emissions of produced e-methanol to natural gas derived fossil methanol production, the e-methanol causes 87% to 91% less GHG emissions. The DAC value chain can result in better cumulative emission reduction compared to MEA due to higher production quantities, but MEA value chain can achieve higher emission saving per produced kg of e-methanol, because less energy is required for capturing CO2 compared to DAC. H_2 leakage was found to cause approximately 0.5% to 0.7% from total emissions in e-methanol value chains, which is not a determining factor for environmental feasibility. Green H_2 production and compression were the most determining factors impacting to total GHG emissions. The avoided emissions through waste heat utilization can further decrease the system level emissions.

Table 2. Cumulative emission reductions during 30-year operation without waste heat utilization. Normal, low and lowlow means electricity prices for renewable energy generation. Case 1 investigates MEA application as a carbon capture technology and Case 2 utilizes DAC (results under review process).

System boundary	Case 1			Case 2
	Normal	Low	Lowlow	Low
Emission reduction (Cradle-to-Gate)				
One-time Investment [$Mt_{CO2\text{-}eq}$/30y]	-5,8	-6,2	-6,7	-6,5
Investing in phases [$Mt_{CO2\text{-}eq}$/30y]	-4,0	-4,2	-4,6	-4,2
Emission reduction (End use)				
One-time Investment [$Mt_{CO2\text{-}eq}$/30y]	-19,1	-20,2	-21,9	-23,3
Investing in phases [$Mt_{CO2\text{-}eq}$/30y]	-13,3	-14,0	-15,0	-15,3

A complementary study was made to investigate how much GHG emission savings can be achieved in Finland (domestic consumption) and outside of Finland (export), if Finlandutilizes 68.5 TWh of renewable electricity to H_2 production and utilizes it one at one time to produce different PtX products (article related to this is in a review process at the time of writing). The amount available electricity for H_2 production was based on a scenario provided by Transmission System Operators, TSOs, Fingrid and Gasgrid[1], as part of HYGCEL project.

The relative emission reductions per used kg of H_2 among different PtX value chains behaves similarly than the results in Table 1 (relative emissions per kg of product). However, the production and consumption quantities of different PtX products determines the total amount of emission reduction. For instance, fossil-based ammonia is consumed roughly 200kt in Finland in a year, but the total e-ammonia production potential far exceeds the domestic needs (Figure 3). This means that the most consumption-based emission reductions would realise outside of Finland. Interestingly, the current available biogenic CO_2 sources in Finland did not become a limiting factor for PtX value chains in this study. However, this changes if there is more available green H_2 to be used for CCU applications or some currently produced biogenic CO_2 sources will be disabled. Depending on whether the target is to achieve domestic carbon neutrality or to maximize global emission reduction potential, PtX value chains should be constructed differently.

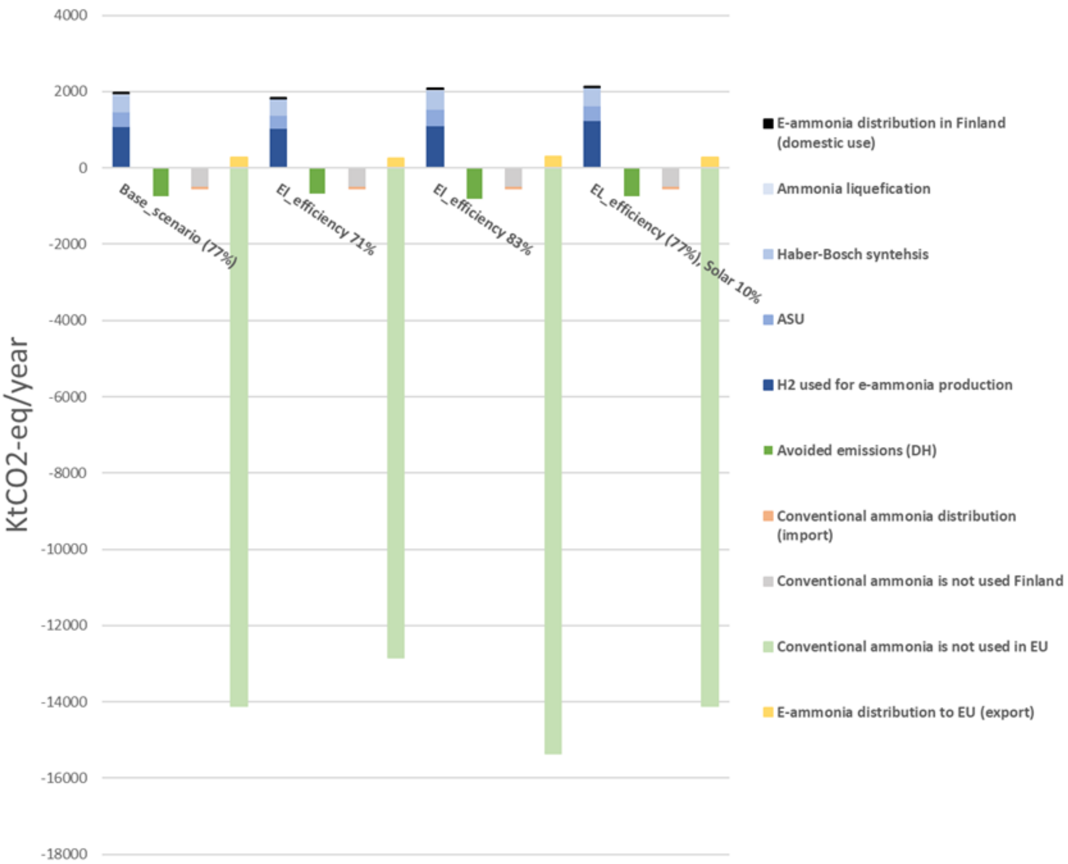


Figure 3. Comparison (LCA) of climate impacts of e-ammonia production and consumption substituting conventional ammonia within Finland (blue, dark green and grey bars) and outside Finland (light green and yellow bars)

Cost of GHG emissions savings and economic hotspots

The economic feasibility of PtX projects is important in achieving the climate goals. The most determining factor of economic feasibility in PtX value chains is H_2 production due to high CAPEX and OPEX costs. Those are expected to be lower in future. For example, electrolyzer CAPEXs are estimated to reduce even 60%, which then would significantly reduce the overall costs of a PtX value chain. However, the cost reduction is dependent on many factors and is uncertain. For instance, recently the electrolyzer prices have gone up instead of going down. Another factor having a major impact on economic feasibility is the cost of capital. One-time investments are capital intensive, and the economic risk is high. Overall, the high interest rates have slowed down the phase of energy transition. In addition to high CAPEX costs, green H_2 production is an energy intensive process. Thus, the electricity price has the most impact to the price of H_2 and to the price of final product.

The previously discussed e-methanol value chain study revealed that when compared to fossil-based methanol, the e-methanol value chain can become feasible without subsidies, when the price (of a fossil-based-) product is high, and electricity price is 27 €/MWh but requires money transfer along the value chain or some actors in the value chain need subsidies. One option is that one entity owns the H_2 and synthesis facilities, because the potential premium from the green product more clearly benefits the whole manufacturing chain. But then again, due to the capital intensity of these value chains, the economic risk for that entity would increase. For these results, see also HYGCEL W1T1.3b task results.

H_2 delivery methods affects to cost of delivered H_2. The cost analysis made for H_2 distribution methods revealed that conversion processes reduce economic feasibility. However, the cost of H_2 delivery is case dependent, thus no straightforward conclusion can be made from the analysis. For instance, the distance of H_2 delivery affects the order of preference. The TDM process provided additional benefits in the form of emission savings due to the possibility to use sequestered carbon as a carbon sink (Figure 2). However, the option was the least appealing method from an economic point of view. The shipping option was also found infeasible. Compared to on-site H_2 production or H_2 pipeline delivery, the price of H_2 increased 1.5 € to 5 € per kg H_2 for shipping and TDM option, respectively. However, it should be kept in mind that the investigation used fixed prices for electricity, which was 40 €/MWh. For more information, see HYGCEL WP3T1 task results.

With current fossil-based product costs, it will be a challenge for a PtX value chain to achieve economic feasibility. However, the gap between the cost of fossil-based products and PtX products is expected to narrow due to tightening regulations. For instance, the price of carbon permits is expected to be applied also in the transportation sector. However, the regulation development is dependent on politics, which is uncertain.

APPLICATIONS/IMPACT

The results indicate that properly designed PtX economy can not only help to achieve carbon neutrality targets in Finland and generate export products but also help other regions to achieve their targets. The environmental evaluations have shown that benefits from the transition are highly depended on how the H_2 is utilized in a value chain. For instance, e-methanol and green steel can achieve higher emission reductions than e-methane. The results also reveal that it will be a challenge for a H_2 provider to reach economic feasibility. Finland should focus on those PtX value chains achieving the highest emission reductions and produces the most economic added value. Based on the economic evaluation there is a need for public support, low-cost capital, cost reduction development and/or regulatory changes to start the transition, because with the current prices most of the PtX value chains cannot compete against fossil-based ones. PtX economy is in its starting phase, thus, there is still time to make smart decisions to obtain most of the benefits of it.

MAIN CONTACT

Jani Sillman, LUT, School of Energy Systems, jani.sillman@lut.fi

AUTHORS

WP6 authors: Jani Sillman, Husain Patel, Rami Alfasfos, Jouni Havukainen, Risto Soukka

Other authors: Satu Lipiäinen, Jaakko Hyypiä, Antti Ylä-Kujala, Nashmin Elyasi, Miro Lilja, Vesa Ruuskanen, Emma Laasonen, Lauri Leppäkoski, Hannu Karjunen, Ville Uusitalo, Esa Vakkilainen, Mari Tuomaala

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WP6 Task 6.3

Operational risks and cybersecurity

ABSTRACT

Task 6.3 had two main research questions. Research question 1 was dedicated to operational risks of hydrogen production value chain: What are the primary operational risks associated with transitioning from small-scale to large-scale hydrogen production and distribution, and how can these risks be effectively mitigated? Research question 2 focused on cybersecurity in hydrogen infrastructure: What are cybersecurity vulnerabilities in the hydrogen production and distribution value chain, particularly in regions with advanced smart grid systems like Finland and how can they be identified and mitigated?

The first research question was analysed by reviewing past accidents and incidents within the hydrogen value chain, focusing on learning from recorded events and identifying the root causes associated with hydrogen-related risks. The second question analysed historical cyberattacks in the energy market, with a focus on understanding the types of cyberattacks, their motives, and the stakeholders targeted. This analysis also examined the potential consequences of such attacks to suggest and develop strategies for preventing or mitigating future threats. In this context, the work involved collaboration with HYGCEL WP 4 task 3 on "Cybersecurity in the Hydrogen Economy: Enhancing Safety and Resilience with IoT and Edge Computing," where we proposed a suggested solution to improve cyber safety and resilience using IoT systems. The findings from these studies emphasises the importance of robust safety and cybersecurity measures as hydrogen infrastructure scales up and becomes more integrated into energy systems.

MOTIVATION

The rapid growth of the hydrogen economy, driven by the global aim to achieve net-zero emissions by 2050, highlights the need for thorough safety and risk assessments, especially as large-scale hydrogen infrastructure is being planned, but is still relatively new and untested. This study is motivated especially by the urgent necessity to address safety concerns that could for example impact public acceptance, a critical factor in the successful deployment of hydrogen technologies. Additionally, as the hydrogen sector increasingly relies on digital systems, the study focuses on identifying ways to enhance cybersecurity to protect against potential threats that could jeopardize both safety and the reliability of energy supply. By addressing these challenges, the study aims to support the secure and sustainable development of the hydrogen economy, crucial for achieving long-term environmental and economic goals.

RESULTS

Results regarding safety and risks

The findings from the safety studies present a detailed analysis of hydrogen-related incidents and accidents, with a particular focus on the critical areas of storage, distribution, and human factors within the hydrogen value chain. This investigation also addresses the aspects related to transition from small-scale to large-scale hydrogen usage and drawing valuable lessons from historical events.

The analysis covered 82 pcs of hydrogen-related events. Based on the results, most accidents occur during the storage and distribution phases of the hydrogen value chain.

The hydrogen value chain consists of multiple components, and each component presents unique risks that require targeted safety measures. Specifically, components such as piping, valves, fittings, and other connection points were identified as particularly vulnerable, frequently contributing to these incidents. These findings can be explained, for example, by the known physical properties of hydrogen, such as high diffusivity and low molecular weight, which make hydrogen prone to leaks and failures at connection points and containers. This is further explained in **Error! Reference source not found.**, where the gaseous distribution (40%)

and gaseous storage (24%) stages are highlighted as critical points where most hydrogen-related events occur.

Despite the high energy and pressure involved in compression, this phase accounted for 11% of the incidents (see supplementary material of Alfasfos et al. 2024[1]), suggesting better management practices compared to storage and distribution. Incidents related to electrolysis were minor (9%), possibly reflecting the early stage of hydrogen production through this method. The study underscores the vulnerability of gaseous hydrogen distribution components i.e., the pipelines (22%) and storage facilities (18%), suggesting a need for enhanced safety measures in these areas.

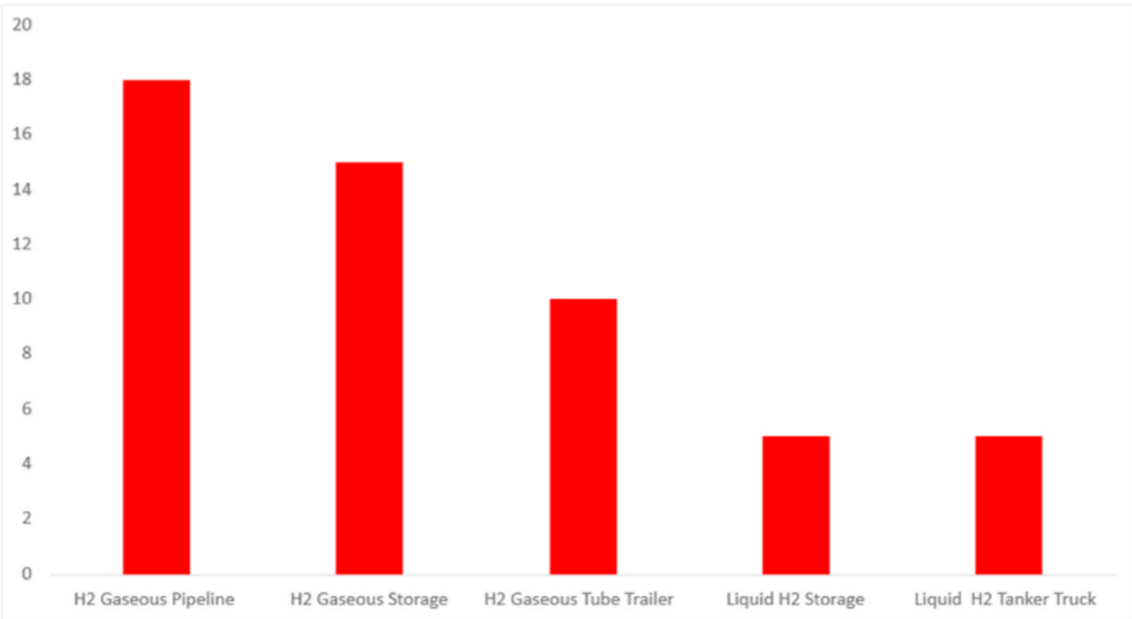

Figure 1 Gaseous and liquid hydrogen events occurring in the storage and distribution stages (number of events).

A significant portion of hydrogen-related incidents can be traced back to human error (Figure 2 parts 1 and 3), which were found to be the predominant root cause of accidents within the hydrogen value chain. Human errors are often linked to insufficient training, inadequate safety procedures, and poor operational oversight, highlighting the critical need for continuous education and training for all personnel involved. Organizational and managerial shortcomings also play a substantial role in these incidents. Common issues include deficiencies in safety management, poor maintenance practices, and a general failure to adhere to established safety standards (lack of standards is discussed in later paragraphs).

To summarise, the study found that human and organizational errors account for 87% of the incidents analyzed, as illustrated in Figure 2, with maintenance operations being a particularly significant factor. Equipment failures, especially in piping, valves, and storage systems, are frequent and often result in dangerous hydrogen leaks. These leaks can escalate into explosions or fires, leading to severe economic and social impacts. For instance, a hydrogen leak at an ammonia plant caused a fire that resulted in substantial equipment damage and financial losses. The findings underscore the urgent need for enhanced safety training, improved maintenance protocols, censors and better design and materials for critical components to mitigate these risks.

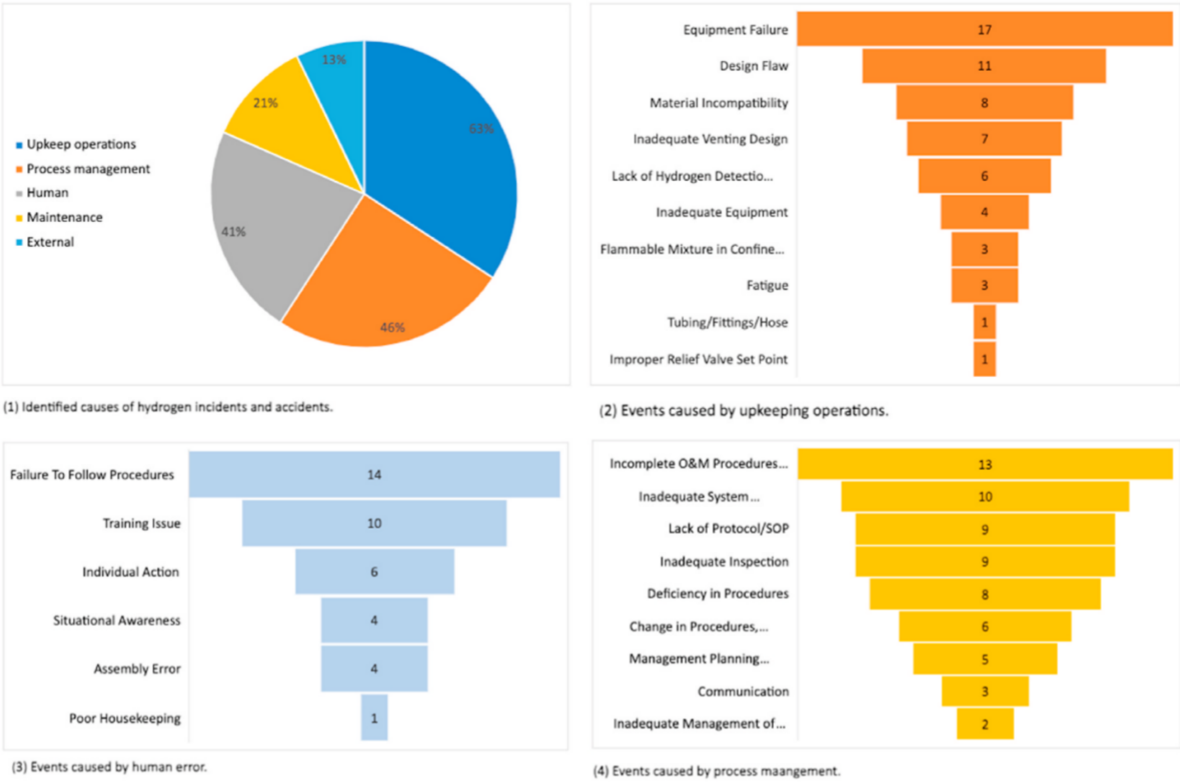

Figure 2 Identified causes of hydrogen incidents and accidents.

The study further highlighted the increased risks associated with transitioning from small-scale to large-scale hydrogen usage. While hydrogen has a long history of safe use in smaller, controlled environments, scaling up its production, storage, and distribution amplifies the potential for accidents. This escalation in risk is particularly evident in the increased operational challenges associated with managing large quantities of highly pressurized Hydrogen with more personnel handling it. Other studies indicate similar findings [2].

Moreover, the study identifies gaps in the current safety legislation and regulatory framework for hydrogen. While regulations like ATEX (Atmosphères Explosibles) provide a foundational framework for safe hydrogen handling, they are not sufficiently comprehensive to address all the unique risks associated with hydrogen, especially as its use scales up. The research points out the need for more specific and stringent regulations that cater to the unique challenges posed by hydrogen and its specific applications [3], including storage, distribution, and integration into existing energy infrastructures.

The analysis of past hydrogen incidents provides valuable lessons for the future development of the hydrogen economy, leading to several key recommendations.

First, enhancing safety training and education is crucial, given that human error is a leading cause of hydrogen incidents. Ongoing, comprehensive training programs are necessary to cover both the technical aspects of hydrogen handling and the importance of adhering to safety protocols.

Second, improving maintenance and inspection practices is essential to prevent incidents. The study recommends the implementation of stricter maintenance schedules and the adoption of advanced monitoring technologies to detect potential issues before they lead to accidents.

Third, as the hydrogen economy scales up, conducting thorough safety assessments and developing management strategies to effectively mitigate the risks associated with large-scale hydrogen storage and distribution are critical steps for ensuring safety and public confidence in hydrogen technologies. It should be noted that with proper safety management and good practices the risks can be mitigated.

Fourth, there is a clear need for more robust safety regulations specifically tailored to the risks associated with hydrogen. This includes updating existing frameworks like ATEX and developing new standards suited to the hydrogen economy. Additionally, addressing these issues requires not only improving individual competencies but also strengthening the overall safety culture and processes within organizations. Beyond technical measures, creating a proactive approach to risk management and safety innovation is essential.

Results regarding cyber security

The findings from the study on hydrogen-related incidents and the broader energy sector underscore the critical importance of addressing not only the physical and human factors but also the growing cybersecurity threats that could severely impact the hydrogen economy. The year 2010 marked a pivotal moment in the cybersecurity threat landscape against the energy sector, signalling the urgent need for initiative-taking measures to ensure a secure energy transition. Notably, cyberattacks such as the Stuxnet worm deployment on Iran's Natanz uranium enrichment facility demonstrated the capability of cybercriminals to inflict physical damage on energy infrastructure. This attack, along with others analysed, highlighted the devastating potential of cyberattacks as tools in political conflicts and emphasized the need for resilient cybersecurity systems.

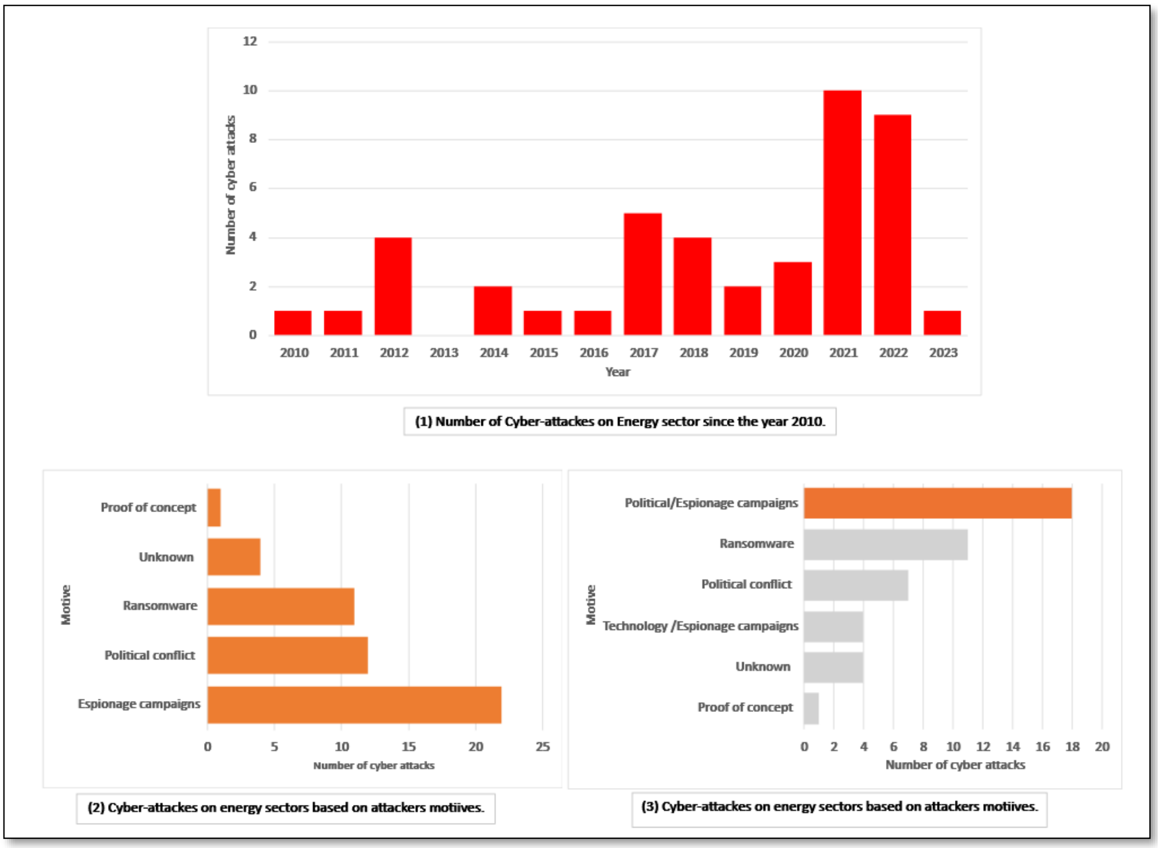

Figure 3 Analysis of 44 major cyberattacks on energy sector since the year 2010, numbers and motives.

An analysis of 44 major cyberattacks on the energy sector since 2010 reveals a consistent increase in such incidents, peaking in 2021 and 2022, as shown in **Error! Reference source not found.**. The predominant motivations behind these attacks were political and espionage efforts, although other motives such as ransomware and proof-of-concept demonstrations were also identified.

Major energy companies, particularly in the electricity and oil sectors, have been the primary targets, with severe consequences including widespread power outages, data destruction, and significant economic disruptions. For instance, the 2015 cyberattack on Ukraine's electricity grid, which used the BlackEnergy malware, resulted in a power outage affecting over 220,000 people, underscoring the perilous implications of cyberattacks on public well-being. The integration of cybersecurity into the hydrogen value chain is increasingly vital as the energy sector becomes more digitized, particularly with the adoption of smart grids and IoT technologies as **Error! Reference source not found.** illustrates.

Finland, with its advanced smart grid infrastructure, exemplifies the heightened risk of cyberattacks in the energy sector. However, these risks can be mitigated through well-designed safety procedures, increased awareness and education among workers, and effective communication among stakeholders across the value chain. Cybersecurity risk assessments were conducted in collaboration with HYGCEL WP 4task 3, have identified the importance of limiting the consequences of attacks and ensuring robust data communication to protect the hydrogen economy.

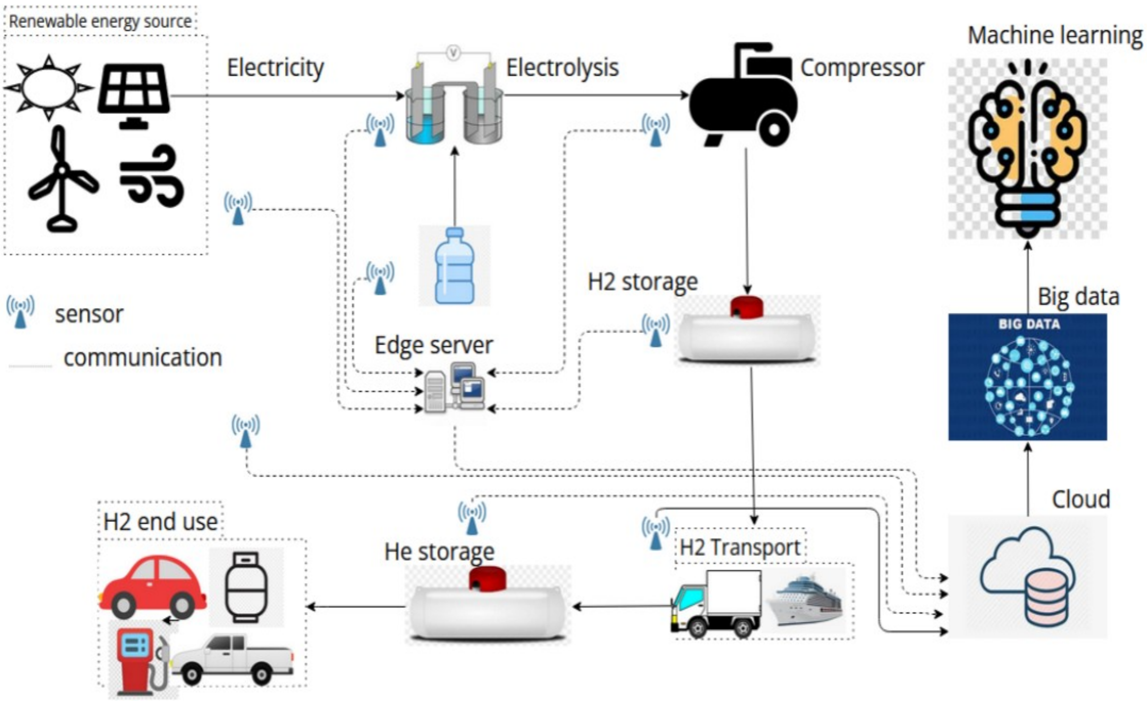

Figure 4 Hydrogen process from generation, storage, transportation to end use, using the renewable energy sources.

As the hydrogen economy continues to expand, integrating cybersecurity measures into all aspects of the energy transition is not just advisable but necessary. Efforts are ongoing to quantify the costs of risk mitigation, with preliminary literature suggesting that these could constitute 5% to 10% of total investments, depending on the value chain.

The role of cybersecurity in safeguarding the future of energy, particularly in hydrogen production and distribution, cannot be overstated, and proactive measures must be prioritized to prevent catastrophic disruptions

APPLICATIONS/IMPACT

The findings emphasize the critical need for integrating robust safety and cybersecurity measures as the hydrogen economy scales up. The transition to large-scale hydrogen usage and the increasing digitization of the energy sector highlight vulnerabilities that could have severe consequences if not properly managed. The impact of this research is evident in the call for enhanced safety protocols and comprehensive training programs due to high share of human factor as a root cause of hydrogen events. In addition, strengthened cybersecurity frameworks to protect both physical infrastructure and data integrity is needed. Ensuring that these measures are in place will be crucial for gaining public trust and securing investment, which are essential for the successful development and expansion of hydrogen facilities globally.

MAIN CONTACT

Jani Sillman and Risto Soukka, LUT Energy systems

AUTHORS

WP 6 authors: Rami Alfasfos (main author in HYGCEL safety research), Jani Sillman, Esa Vakkilainen, Risto Soukka

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The HYGCEL project final results
and task reports available online: