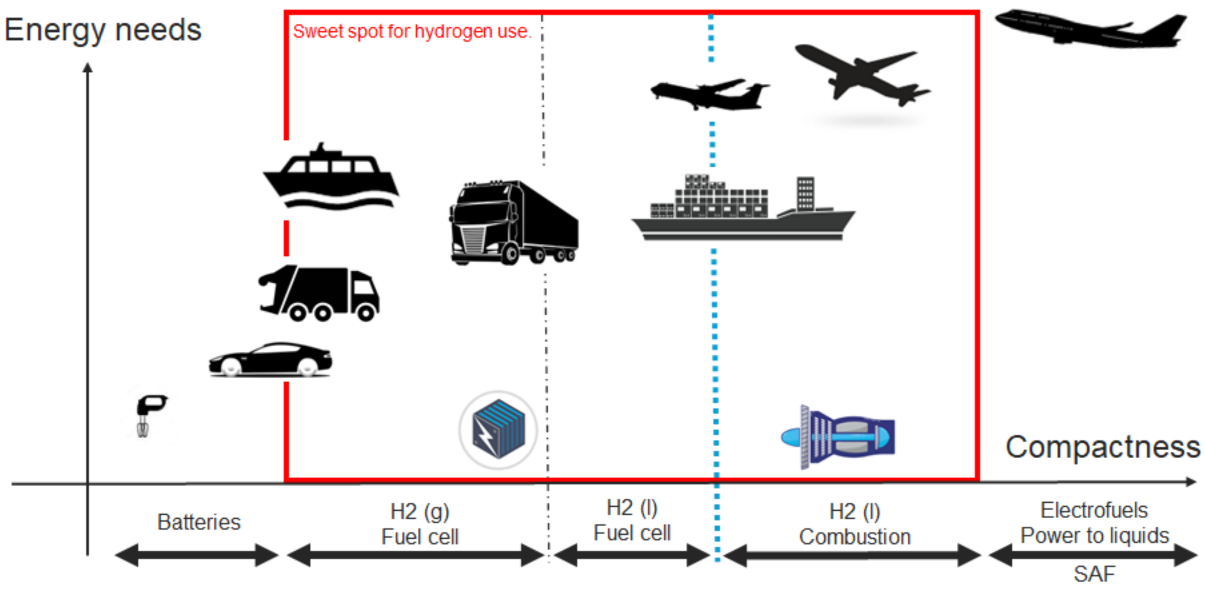
TechForH2 Annual Report 2024

Technologies and innovations for a future sustainable hydrogen economy

Diarienummer: M2 2025-0029

Annual report 2024: Technologies and innovations for a future sustainable hydrogen economy (TechForH2)



TechForH2 is a new competence center for multidisciplinary hydrogen research with the overall aim of developing new technology for greening heavy transport.

Revision history

2024-12-09 Date written

2025-02-18 Request for input from research leaders

2025-02-20 Circulation to TechForH2 board

2025-03-05 Integrated feedback from research leaders

Chalmers University of Technology
SE 412 96 Gothenburg, Sweden

Visiting address: Chalmersplatsen 4

Chalmers tekniska högskola AB
Reg.No: 556479-5598 VAT No: SE556479559801

Abstract

Transports generate about 25% of the global CO_2-emssions and represent about a third of the Swedish national emissions. To meet the Paris agreement targets, Sweden is aiming for net zero emissions by 2045. Although lighter transports are suitable for battery electric propulsion, there is today many arguments for expanding the hydrogen use in the heavier transport areas. A large potential for synergies across transport modes and for new innovations exist for new hydrogen propulsion solutions. For this reason, the TechForH2 excellence center was proposed and funded for start in 2022. TechForH2 is led by Chalmers University of Technology in collaboration with RISE and partnering with the member companies Volvo, Scania, Siemens Energy, GKN Aerospace, PowerCell, Oxeon, Stena Rederi, Johnson Matthey, Insplorion and MannTek.

The TechForH2 center concentrates its work around five multidisciplinary research arenas, (1) lightweight composite storage solutions for cryogenic hydrogen, (2) additive manufacturing for hydrogen fuel supply systems, (3) nanoplasmonic hydrogen sensor maturation, (4) fuel cell development and integration, (5) the future of hydrogen – societal challenges. The five areas were singled out by an initial matching between industry technical challenges for the transition against key research competences.

The center was started in 2022 with most of the recruiting performed at the end of 2022 and early 2023. Ten Ph.D. students have now been allocated to the five multidisciplinary research areas. Originally, the center planned for nine, but industry has committed an additional industrial Ph.D. student. Although the core research activities revolve around the Ph.D. projects, Chalmers university initially boosted the launch of TechForH2 by initiating seven hydrogen post doc projects in the transport field, with additionally two post docs allocated more recently. This investment has rendered a quite strong publication rate from the center, despite that it was started only in 2022.

Sammanfattning

Transporter genererar cirka 25% av de globala CO_2-utsläppen och står för ungefär en tredjedel av de svenska nationella utsläppen. För att klara Parisavtalets mål siktar Sverige på nettonollutsläpp till 2045. Även om lättare transporter lämpar sig för batterielektrisk framdrivning finns det idag många argument för att utöka vätgasanvändningen i de tyngre transportområdena. Det finns en stor potential för synergier mellan transportmoder och för nya innovationer inom vätgasområdet. Av denna anledning föreslogs kompetenscentret TechForH2 och erhöll därefter finansiering för start under 2022. TechForH2 leds av Chalmers tekniska högskola i samarbete med RISE och samarbetar med medlemsföretagen Volvo, Scania, Siemens Energy, GKN Aerospace, PowerCell, Oxeon, Stena Rederi, Johnson Matthey, Insplorion och MannTek.

TechForH2-centrat koncentrerar sitt arbete kring fem tvärvetenskapliga forskningsarenor, (1) lätta kompositlagringslösningar för kryogent väte, (2) additiv tillverkning för vätgasbränslesystem, (3) nanoplasmoniska vätegassensorer, (4) bränslecellsutveckling och integration, (5) vätgasens framtid - samhällsutmaningar. Dessa fem områden har identifierats genom att initialt matcha industrins tekniska utmaningar för omställningen med nyckelkompetenser inom forskningen.

Centret startades 2022, och de flesta rekryteringarna genomfördes i slutet av 2022 och i början av 2023. Nu har tio doktorander tilldelats de fem tvärvetenskapliga forskningsområdena. Ursprungligen var planen att ha nio doktorander, men utöver den ursprungliga planen har en industridoktorand tillkommit. Även om kärnan i forskningsverksamheten kretsar kring doktorandprojekten, gav Chalmers initialt en extra skjuts åt TechForH2 genom att initiera sju post doc.-projekt inom vätgas och transportsektorn. Sedan dess har ytterligare två postdoktorer associerats med centrat. Denna satsning har lett till en hög publiceringstakt för centret, trots att det startades först 2022.

TECHFORH2 ORGANIZATION

TechForH2 is today comprised of twelve partners, Chalmers as the coordinating body, and with Rise as an additional funding recipient. In addition, nine industrial partners contribute, ranging from large multinational companies to SMEs. The current complete partner listing is:

- Chalmers University of Technology
- RISE Research Institutes of Sweden
- Volvo Technology
- Scania
- Siemens Energy
- GKN Aerospace
- PowerCell
- Oxeon
- Stena Rederi
- Johnson Matthey
- Insplorion
- MannTek

During December 2024, MannTek signed the contract and formally joined the center on 2025-03-06.

The TechForH2 board

Upon submitting this report, the TechForH2 board has had twelve meetings (2022-04-29, 2022-05-23, 2022-12-01, 2023-03-09, 2023-05-25, 2023-08-24, 2023-11-27, 2024-03-07, 2024-05-22, 2024-08-22, 2024-12-02, 2025-03-06). Since the number of partners in TechForH2 is relatively moderate many partners have found it feasible to maintain two members per partner in the board, where one of the members has the representing vote and the other member is having the substitute vote. This allows for continuity and company internal dialogue. The current listing is:

Name / organization	Organization
Tomas Grönstedt, Director	Chalmers
Maria Grahn, Co-director	Chalmers
Selma Brynolf	Chalmers
Sinisa Krajnovic, Rector’s Delegate	Chalmers
Carlos Xisto, Area-of-advance transport	Chalmers
Nadia Tahir, Communication Partner	Chalmers
Anders Lundbladh	GKN Aerospace
Lucien Koopmans, Chairman of Board	Volvo
Monica Johansson	Volvo
Karl-Johan Nogenmyr	Siemens Energy
Annika Lindholm	Siemens Energy
Per Stålhammar	Scania
Ingergerd Annergren	Scania
David Mattsson	RISE
Karin Arrhenius	RISE
David Nilebo	Insplorion
Elin Langhammer	Insplorion
Hamed Abdeh	PowerCell
Andreas Bodén	PowerCell
Mikaela Wallin	Johnson Matthey
Jonas Edvardsson	Johnson Matthey
Per Björkborg	Stena Rederi
Andreas Martsman	Oxeon
Florence Morerau	Oxeon
Rickard Axelsson	MannTek
Emma Westsson	Energimyndigheten

Table 1: Members of the TechForH2 board

The research disciplines

To ensure academic excellence, industrial relevance and autonomy TechForH2 is organized around research disciplines, in total seven, led by a research leader/leaders. Several of the research leaders both have a strong scientific background and have worked in industry developing technology. All seven disciplines had substantial funded on-going research, prior the launch of TechForH2. The difference for the research projects run in TechForH2 is that they are frequently of a more multi-disciplinary nature and are typically also run with a larger number of industry partners. The seven different disciplines are:

1. **Materials technology** with research leader professor Martin Fagerström (computational fracture mechanics) and full professor Leif Asp (lightweight composite materials and structures) and
2. **Manufacturing technology** with research leaders Emmy Yu Cao (professor in materials technology) and Lars Nyborg (full professor in surface engineering)
3. **Cryogenics & heat management** with research leader Tomas Grönstedt (full professor turbomachinery)
4. **Vehicle level understanding** with research leader David Sedarsky (associate professor in experimental fluid dynamics)
5. **Transport & society** with research leaders Maria Grahn (associate professor in energy systems) and Selma Brynolf (researcher in energy and environmental analysis)
6. **Safety & sensors** with research leader Christoph Langhammer (full professor in chemical physics)
7. **Fuel cell technology** with research leader Anna Martinelli (professor in surface chemistry)

These seven research areas were defined in dialogue with industry during the application process of TechForH2. Critical research disciplines were singled out by industry. Areas where also a strong research competence existed were then prioritized to establish the seven areas listed above.

The multidisciplinary research areas

TechForH2 was established, and may also be modified, by allowing the seven research disciplines introduced above to form new multidisciplinary research areas. The basic process is illustrated in Figure 1 below.

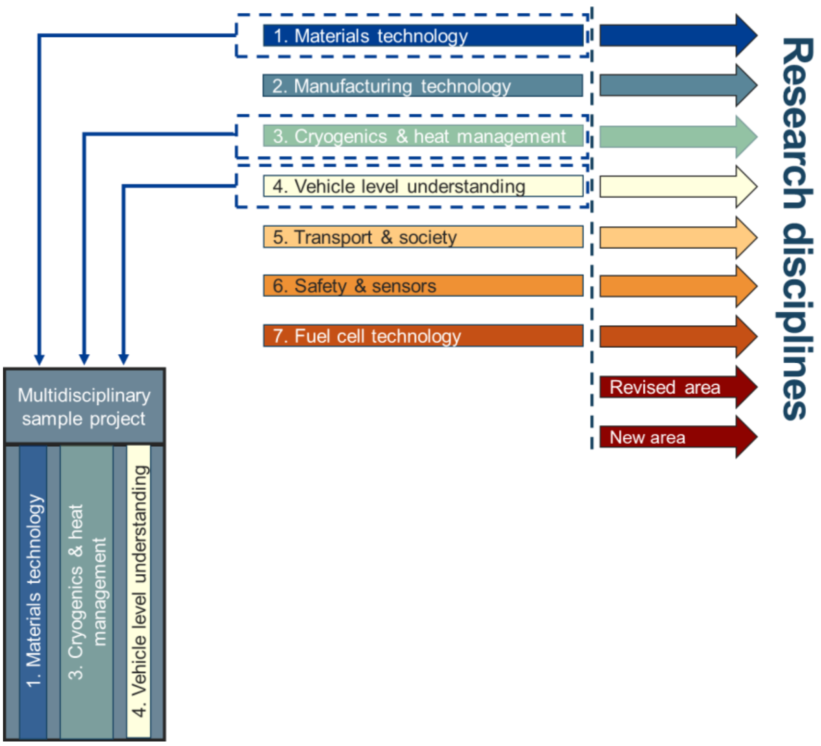


Figure 1: TechForH2 process for establishing new multidisciplinary research areas.

This center design logic allows TechForH2 to be dynamic against changes in the applied hydrogen area and enables some steering capability as the hydrogen economy evolves. In a potential extension, that is after the first five years, some of the areas above may be deleted, re-prioritized and/or new areas may simply be added to the center activities. This center design also allows clustering new partners around a few new projects and managing a number of IP-critical aspects without a too large administrative burden.

As the center was planned and applied for, it became evident that a focusing of the effort was needed. For instance, the national German research commitments only in the area of hydrogen technology (e.g. H2Giga, H2Mare, TransHyDe) are more than **an order of magnitude** larger than **all** the energy agency competence centers together. Hence, a national Swedish initiative may easily spread too thin, if it is attempting to cover the entire chain of development (production, use and large-scale storage). TechForH2s initial focus therefore concentrates on **hydrogen use** with an emphasis on vehicle integrated solutions.

The five multidisciplinary research areas where TechForH2 is active are:

1. **Lightweight composite storage solutions for cryogenic hydrogen** (combining the research disciplines materials technology, vehicle understanding and cryogenic & heat management)
2. **Additive manufacturing for hydrogen fuel supply systems** (combining manufacturing technology and cryogenic & heat management)
3. **Nanoplasmonic hydrogen sensor maturation** (safety & sensors as well as transport & society)
4. **Fuel cell development and integration** (fuel cell technology, cryogenics and heat management, vehicle level understanding and transport & society)
5. **The future of hydrogen – societal challenges** (transport & society with inputs from potentially all disciplines)

The international research network

TechForH2 faces several challenges to rapidly establish itself as a leading research center in the hydrogen area. One of TechForH2's strategies is to tackle this by limiting the research scope to certain aspects of hydrogen use, by establishing an application close research focus liaising with globally positioned Swedish industry and by pro-actively setting up a research network with hydrogen relevant internationally leading researchers. This was done during the application process isolating key collaborative partners in critical areas by signing bilateral letters of intent between the TechForH2 research leaders and each of the relevant researcher at the foreign university. The structure of the network is illustrated in Figure 2 below.

Figure 2: TechForH2 research collaboration network. TechForH2 has written individual LoIs with key hydrogen technology relevant researchers in Europe, to kickstart activities and make TechForH2 an internationally well-known research center.

The research leaders and their relation to the collaborative network is specified in Table 2 below.

Research leaders	Scientific network contacts
Martin Fagerström	Senior Lecturer, Soraia Pimenta, Imperial College London.
Fiona Schulz/Yu Cao	Full professor, Mariangela Lombardi, Politecnico di Torino.
Tomas Grönstedt	Associate professor Vishal Sethi, Cranfield Univ., Arvind Rao, Delft university.
Anna Martinelli	Full professor, Luis M. Varela, USC Santiago.
Lucien Koopmans	Professor of Technology, David Blekhman, Cal. State Univ, Los Angeles.
Maria Grahn, Selma Brynolf	Associate Professor, Iva Ridjan Skov, Ålborg University. Senior Research Ass. Dr Nishtabbas Rehmatulla, Bartlett Energy Institute, UCL, London.
Christoph Langhammer	Prof. Bernard Dam, Delft University, Ass. Prof. Andrea Baldi, Vrije Universiteit

Table 2: Research leaders' relation to the collaborative network (separate LoIs have been put in place)

Year 2024 highlights

Highlights during 2024:

- **16 journal papers** of which one of the papers co-authored by the TechForH2 Ph.D. student Athanasios Theodoridis and professor Christoffer Langhammer was published in Nature communications [1] and another in Nature Energy authored by Selma Brynolf and Maria Grahn [2].
- **Press release** during July 2024 resulting in 154 news articles predominantly in international press, e.g. Newsweek [3], citing hydrogen heat management solutions developed within TechForH2 [4].
- **Annual meeting** with 51 participants, Figure 3 above, including TechForH2 Ph.D. students, post docs, international invited speakers and Chalmers hydrogen associated researchers.
- **Strong participation** at Vätgaskonferensen (5 speakers + invited speaker + multiple posters)
- The first two **licentiate theses** defenses by TechForH2 Ph.D. students were held (December 2024).

Figure 3: TechForH2 3rd annual meeting at Jazy's, Gothenburg, 2024-12-02

Multidisciplinary research areas

Although the center was awarded to start early 2022, the final contract was drafted only 2022-08-09 and the last signature was received in 2022-09-23. In total 9 Ph.D. projects were initially planned for. Due to the long process of signing the contract, substantial financial risk was in place, and it was therefore decided to launch recruitment, initially commencing recruitment of 6 of the 9 Ph.D. positions in June 2022. Hence the projects have been launched gradually during 2022 and 2023 adding the 9th Ph.D. in August 2023. In addition, an industrial Ph.D. has been added to the center (Volvo) so TechForH2 now has 10 Ph.D. students:

- Area1: Light weight composite storage solutions for cryogenic hydrogen. 2 Ph.D. students
  - Luis Fernando Gulfo Hernandez (2023-02-01), Christian Svensson (2022-09-01).
- Area2: Additive manufacturing for hydrogen fuel supply systems. 2 Ph.D. students
  - Erika Thuneskog (2022-12-01), Vishnu Anilkumar (2022-12-01)
- Area3: Nanoplasmonic hydrogen sensor maturation
  - Athanasios Theodoridis (2022-09-01)
- Area4: Fuel cell development and integration
  - Christian Bosser (2022-10-10), Mina Bahraminasab (2023-05-01), Eva Dahlqvist (2023-08-21), Lahari Kothala Gnana (industrial Ph.D., 2023-10-23).
- Area5: The future of hydrogen – societal challenges. Hydrogen society
  - Joel Löfving (2023-03-01)

The multidisciplinary research areas are supported by seven post doc projects, funded by Chalmers University. These have been put in place to secure Chalmers' own investment for the center. The projects are:

- Vehicle On-board storage integrating liquid and compressed hydrogen tanks – Project area 1. Finished late 2023.
- Hydrogen in transport – Global, European, and Nordic perspectives – Project area 5
- Hydrogen diffusion combustion modeling – Project area 5
- Fossil-free ships: energy demand, production, storage, and consumption – Project area 5
- Systematic control of PEM fuel cells for vehicle applications – Project area 4
- Computational multi-scale platform for hydrogen utilization/storage/sensing – Project area 4
- Pathways for a sustainable introduction of hydrogen into the aviation sector – Project area 1

The total project commitment, for the first two years, is more than 19 MSEK to contribute to Chalmers' investment. Since then, additionally two post docs have been awarded:

- Optimal Heat Management for Aircraft high TEmperature fuel cells – Project area 1
- Potential for electrifying ships from a fleet perspective – understanding power demand and grid capacity – Project area 5

Recruited post docs and joint research activities are now presented below, summarizing the activities within each of the five multidisciplinary research areas.

Project area 1: Lightweight composite storage solutions for cryogenic hydrogen

Industry stakeholders

This multidisciplinary area is configured by collaborating across the disciplines of materials technology and cryogenics & heat management. Initially Chalmers, RISE, GKN Aerospace, Oxeon and Scania collaborated to define the content. As the work has progressed increased interest from Volvo has also been noted.

Basic disciplines

The **materials technology discipline** interfaces with a large number of hydrogen-driven research challenges, such as developing ultra-low weight polymer composites, exploiting benefits from 2D materials (e.g. graphene and ultra-thin carbon fibre tapes), creating barrier layers and coatings, developing material design methods to avoid liquid hydrogen leakage and tank failure, developing engineering guidelines for the design of linerless liquid hydrogen tanks, developing and exploiting metallic materials for mid-to-high temperature applications for hydrogen rich environments and studying the embrittlement of metallic materials subject to hydrogen.

The **cryogenics & heat management discipline** targets to develop models and methods to predict performance of cryogenic tanks, including thermal and fluid modelling, fluid sloshing, boil-off, influence of tank design parameters on mission performance, experimentally validated solutions, integration of turbomachinery in the fuel systems, heat management including optimal use of liquid/supercritical hydrogen as a heat sink, heat exchanger design, thermal performance of tank designs, modelling of vacuum and foam filled tanks, fluid aspects of composite tank design, dynamic cryo-tank modelling integrated into vehicles.

Joint projects and recruitment

During 2022 two Ph.D. projects have been defined and two Ph.D. students have now also been recruited. In addition, Chalmers has supported the project by defining and the funding two post doc project as stated earlier in this section.

The two Ph.D. projects funded by the center are:

- PhD1: Composite technology for lightweight solutions of cryogenic/pressurized hydrogen tanks
- PhD2: Integration of lightweight solutions in complete aircraft and system evaluations

The PhD1 project was appointed in 2023-02-01 with Luis Fernando Gulfo Hernandez, a student with strong composite materials competence. In 2022-09-01, the PhD2 project was launched with Christian Svensson as PhD student. Christian is a former Chalmers student and has a background also in the Chalmers automotive formula student project.

In addition, the center funds efforts at RISE surveying and exploring a number of critical tank features for primarily road vehicle applications.

The research production from the area

In 2022-08-15 Ioannis Katsivalis was recruited as post doc in the project “vehicle on-board storage integrating liquid and compressed hydrogen tanks”. So far three journal publications and one conference contribution have been published [5, 6, 7, 8]:

- Katsivalis I., Persson M., Johansen M., Moreau F., Kullgren E., Norrby M., Zenkert D., Pimenta S., Asp L.E.: Strength analysis and failure prediction of thin tow-based discontinuous composites (2024) Composites Science and Technology, 245, art. no. 110342 DOI: 10.1016/j.compscitech.2023.110342
- Katsivalis, I., Norrby, M., Moreau, F., Kullgren, E., Pimenta, S., Zenkert, D., & Asp, L. E. (2024). Fatigue performance and damage characterization of ultra-thin tow-based discontinuous tape composites. *Composites Part B: Engineering*, *281*, 111553.
- Katsivalis I., Signorini V., Ohlsson F., Langhammer C., Minelli M., Asp L.E.: Hydrogen permeability of thin-ply composites after mechanical loading (2024) Composites Part A: Applied Science and Manufacturing, 176, art. no. 107867. DOI: 10.1016/j.compositesa.2023.107867

- I Katsivalis, V Signorini, F Ohlsson, M Minelli, LE Asp: Hydrogen diffusion through thin-ply composites. Proceedings of 11th International Conference on Composite Testing and Model Identification, Girona, Spain 2023.

In 2022-01-10 Alexandre Capitao Patrao was recruited as post doc in the project "Pathways for a sustainable introduction of hydrogen into the aviation sector". Alexandre has a background in aerospace from Chalmers but was at the time of recruitment working as an engineer at GKN Aerospace. Alexandre was on leave of absence during the post doc, which has now finished. Alexandre has published three journal articles [9, 4, 10] as listed below:

- Patrao, A. C., Jonsson, I., Xisto, C., Lundbladh, A., Grönstedt, T. (2024). Compact heat exchangers for hydrogen-fueled aero engine intercooling and recuperation. Applied Thermal Engineering, 243, 122538.
- Patrao, A. C., Jonsson, I., Xisto, C., Lundbladh, A., Lejon, M., Grönstedt, T. (2024). The heat transfer potential of compressor vanes on a hydrogen fueled turbofan engine. Applied Thermal Engineering, 236, 121722.
- Patrao, A. C., Jonsson, I., Xisto, C., Compact Heat Exchangers with Curved Fins for Hydrogen Turbofan Intercooling, Journal of Engineering for Gas Turbines and Power 146 (11), Nov. (2024)

The PhD1 project was appointed in 2023-02-01 with Luis Fernando Gulfo Hernandez. In the first instance, the research will focus on developing more refined computational analysis methods for composite materials composed of ultra-thin discontinuous tapes. The project published a journal paper during 2024 [11]:

- Gulfo, Luis, et al. "A 3D voxel-based mesostructure generator for finite element modelling of tow-based discontinuous composites." *Composites Part B: Engineering* 278 (2024)

In 2022-09-01, the PhD2 project was launched with Christian Svensson as PhD student. Christian is a former Chalmers student and has a background also in the Chalmers automotive formula student project. Christian has now published a journal paper as well as a conference contribution in addition to defending his licentiate [12, 13, 14]:

- Svensson, C., Oliveira, A. A., Grönstedt, T. (2024). Hydrogen fuel cell aircraft for the Nordic market. International Journal of Hydrogen Energy, 61, 650-663.
- Svensson, C, Miltén, P. Grönstedt, T.,"Modelling Hydrogen Fuel Cell Aircraft in SUAVE", *ICAS Proceedings*. Florence, Italy, 2024.
- Svensson, C., "Hydrogen Fuel Cell Aircraft for Regional Travel", Licentiate thesis, 2024

The main findings of the journal paper was also summarized on the SHDC hydrogen aircraft seminar on the 10th of April 2024 (https://www.ri.se/en/shdc/events).

RISE has also contributed to the scientific production by publishing several articles [15, 16, 17]:

- Olsson, R., Marklund, E., Merzkirch, M., Ramantani, D., Characterization of a filament wound thin-ply composite for a cryogenic tank for liquid hydrogen, 11th International Conference on Composites Testing and Model Identification, Girona, Italy, 2023.
- Loukil MS, Xu J, Marklund E, Merzkirch M, Moreau F, Ohlsson F., Thermal and mechanical cycling of thin-ply composites for cryogenic applications, 34th Congress of the International Council of the Aeronautical Sciences, ICAS, Florence, Italy, Sept. 2024.
- Olsson, R., Cameron, C., Moreau, F., Marklund, E., Merzkirch, M., & Pettersson, J., Design, Manufacture, and Cryogenic Testing of a Linerless Composite Tank for Liquid Hydrogen. *Applied Composite Materials* (2024): 1-24.

Summary of research achievements

- A conceptual aircraft design study targeting the 2045 Nordic aircraft market indicates that mission study based on a future market analysis indicates that 58% of all Nordic travel could be carried out with fuel cell aircraft.
- System level studies for future hydrogen propelled turbofan-based aircraft may achieve as much as 7.7% SFC reduction through advanced heat management solutions, of which a maximum of 0.8% can be attributed to advanced compressor heat management.
- A new analytic and experimental framework for the identification of key properties of Tow Based Discontinuous Composites (TBDCs) has been developed and applied to the study of TBDC strength and stiffness increases.
- Initial results on permeability of thin tape composites have been reported including H2 permeation/diffusion of thin-ply-laminates including after loading.

The research topic

Efficiency improvements and use of SAF promise to green the heavy transport sector. This is however generally not believed to be sufficient but other fuels and electrification is needed as a complement to SAF. Hydrogen is an attractive fuel, being enabled by the trend of ever decreasing production cost of green electricity observed over the last few decades. Back of the envelope calculations also show that the resulting energy density of the whole fuel system is substantially higher than battery-based concepts. This makes it a potential source of energy for heavy transport, for which battery-based electrification may not be sufficient. Additionally, it may also prove to be substantially more energy efficient than going all the way to the use of electrofuels. This is particularly true if a substantial amount of energy is needed to capture CO_2 from the atmosphere.

To allow efficient use in vehicles compact and cost-effective storage is key. Several aspects related to enabling these aspects are explored in this multidisciplinary research area. The PhD1 project is targeting the development of efficient computation methods for thin-walled structures made from thin-ply composites. Given the dimensions of the tanks (meters) and the wall thickness (millimeters) and thin-ply CFRP tape thickness (micrometers) multiscale methods are required. The work builds on the conceptual studies at Chalmers performed in project LH2-Tanks (Energy Agency 52439-1, 2021). Furthermore, the research will be conducted collaboratively, with a postdoc via the AoA Transport project "Vehicle On-board storage integrating liquid and compressed hydrogen tanks".

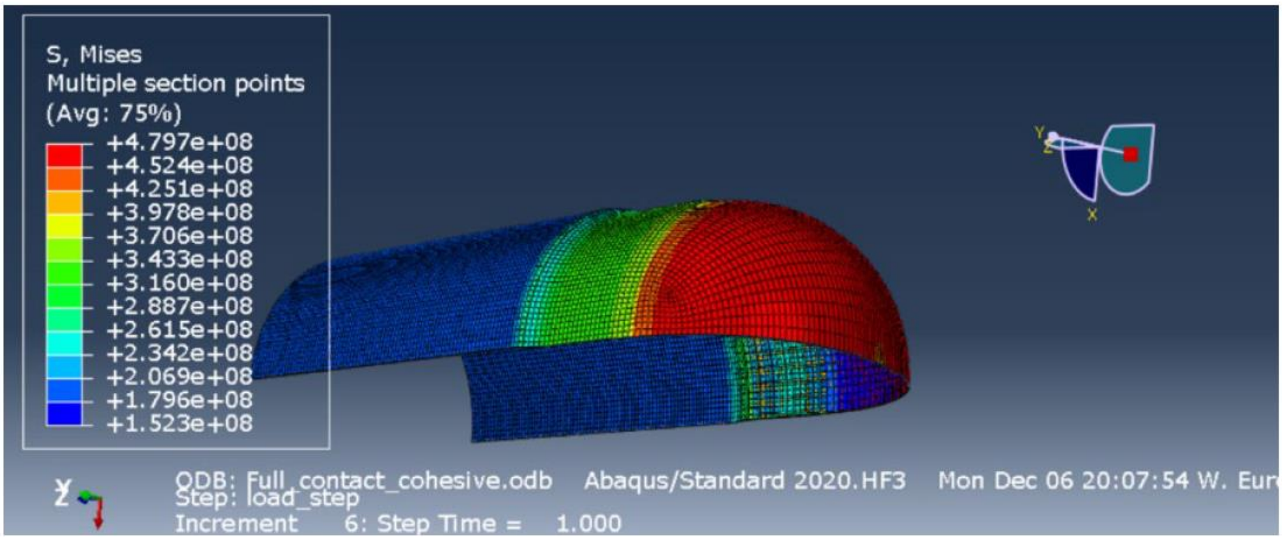


Figure 4: Stress analysis of a liner-less CFRP tank for liquid hydrogen storage, stresses in the overwrap. Results produced by Chalmers in the project LH2-Tanks.

The PhD1 project will develop mechanical design methods allowing conceptual designs studies planned in the PhD2 project. Linerless tanks show a great potential to become lighter than corresponding metal-lined concepts. Challenges are cost in large scale production, proving thermal cycling resilience, ways to avoid undetectable tank damage and proving that the tanks do not leak.

Several alternatives for on-board storage of hydrogen exist:

1. Pressurized hydrogen and fuel cell
2. Pressurized hydrogen and combustion
3. Cryogenic hydrogen and fuel cell
4. Cryogenic hydrogen and combustion

This project is focussing primarily on "4. Cryogenic hydrogen and combustion", but it will to some degree also evaluate option "1. Pressurized hydrogen and fuel cell" and "3. Cryogenic hydrogen and fuel cell". For the case "4. Cryogenic hydrogen and combustion" the focus will be placed on the conceptual design of the vehicle and the integration of the tank system / fuel system. For PhD2, the prime transport mode studied is aviation.

In addition to the four combinations above, the option of cryo-compressed tanks is a potential candidate. This concept allows increasing the power density further, but at the cost of a much higher weight than for the cryogenic option. This makes them a candidate for areas where the weight penalty is not too great but where the effect of increasing storage volume may increase profitability. Hence, primarily for heavy road transport but also for naval transport.

A conceptual design sketch of a previous study on cryogenic hydrogen for aviation is shown in Figure 5 [18] together with a more recent rendering used to create a physical mockup of a future hydrogen aircraft.

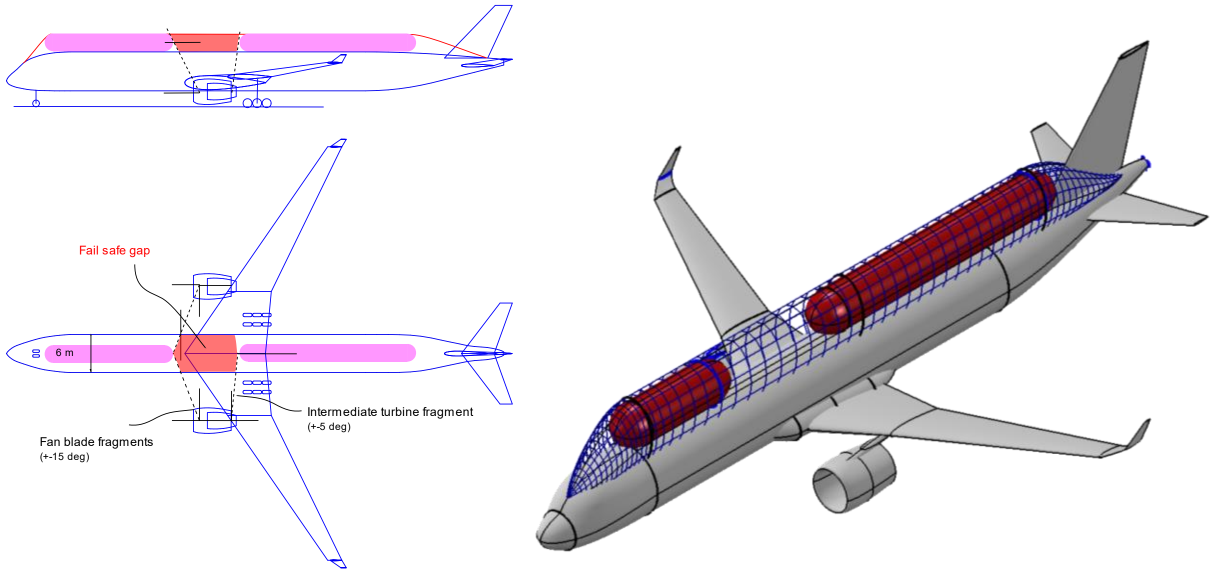


Figure 5: Conceptual design of hydrogen tank integration into tube-and-wing turbofan engine aircraft architecture [18] (left) and 3D rendering of concept (right)

An early step in the project has been to define which conceptual design tool to use for airframe tank integration. Initially it was planned to use the Pacelab software [19], but to increase flexibility and make sharing of models easier another software, SUAVE [20], has been chosen over Pacelab. This tool is open source and allows previous work on conceptual tank modelling to be integrated into the software. Aircraft models developed at Chalmers within the project NordicZero [21, 22] and EnableH2 [23] have been inherited.

3

Project area 2: Additive manufacturing for hydrogen fuel supply systems

Industry stakeholders

This multidisciplinary area is configured by collaborating across manufacturing technology and cryogenics & heat management. Chalmers, Siemens energy, RISE and Scania collaborated to define the content.

Basic disciplines

This research area focuses on the application of additive manufacturing to create tailored, optimized, and sustainable production solutions to implement hydrogen in energy, heat management, and transportation applications. Research challenges are to enable conversion of existing gas turbine solutions to hydrogen fuels, optimize post-AM (Additive Manufacturing) technologies to mitigate degradation by hydrogen, perform experimental validation and testing under realistic integrated conditions, incorporate additional aspects such as sensor technology into designs, develop models and treatments/methods to fight corrosion/oxidation and hydrogen embrittlement as well as electrical/thermal surface conductivity related problems. The long-term ambition is to develop and experimentally verify novel manufacturing and product solutions for hydrogen use, required for manufacturability in terms of materials, geometrical capabilities, and product performance.

Joint projects and recruitment

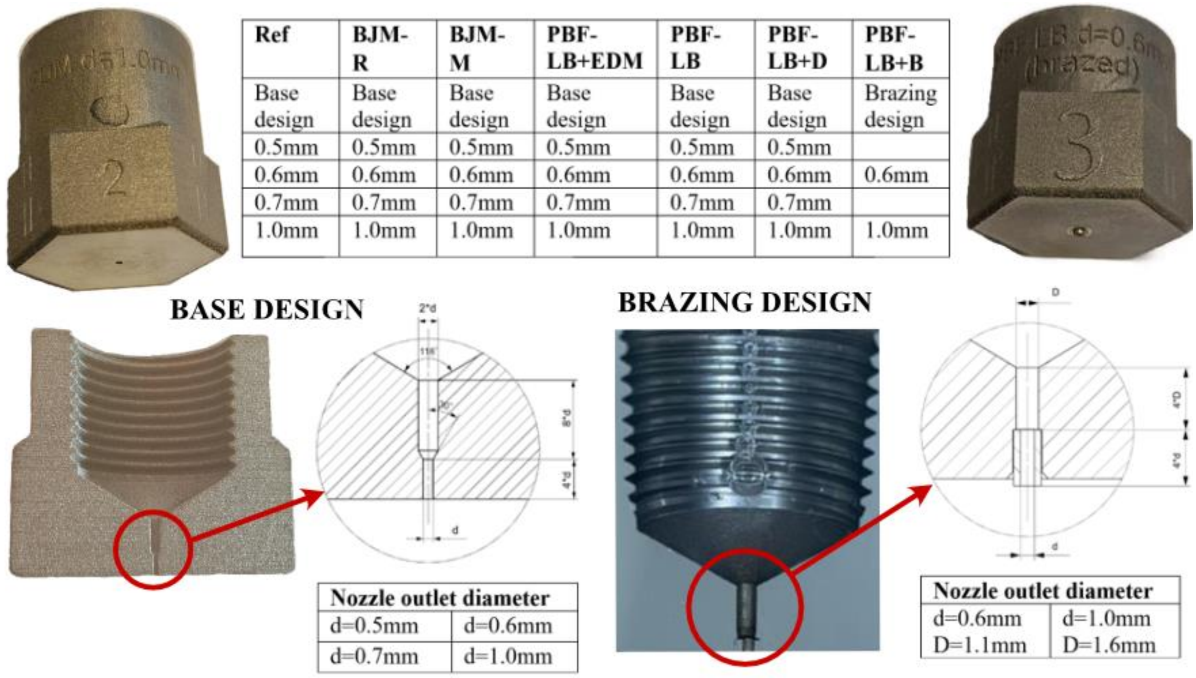
So far, three Ph.D. projects have been defined, and three Ph.D. students are working in the thematic area. Two postdoc projects, “Design for metal additive manufacturing” and “Surface roughness minimization of additively manufactured spray nozzles” were supported partly (finished). A postdoc project, “Hydrogen Embrittlement in H2 - Internal Combustion Engine” has started since March 2024. In addition, Chalmers has supported the project through Production AoA and Faculty funding. Currently, this thematic area involves 2 women, reaching a reasonable gender balance.

The ongoing projects are summarized as follows:

- **PhD1:** Metal Additive Manufacturing for Hydrogen Fuel Supply Systems. Erika Tuneskog was appointed to work in PhD1 project on 2022-12-01. She graduated from Linköping University. She is a student with strong gas turbine engine background and AM competence.
- **PhD2:** Characterizing the effect of hydrogen on mechanical performance of alloys used in gas turbines. Vishnu Anilkumar was appointed to work in the PhD2 project on the same day (2022-12-01). Vishnu is a former Chalmers Master student. He has a background in engineering materials and competence in AM.
- **PhD3:** Effect of hydrogen on the mechanical properties and corrosion behaviour of Austenitic stainless steels. Ph.D. student Xiao Qin is currently working on research relevant to hydrogen-fuelled internal combustion engines. Xiao has a background in engineering materials and competence in material characterization.
- **Postdocs:**
  - Saeed Khademzadeh was active as a postdoctoral researcher within the time frame 2022-10-01-2023-04-30, together with
  - Jitendar Tiwari Kumar 2023-10-01-2024-09-30. Both were financed by Chalmers.
  - Bala Malladi has been employed as a postdoctoral researcher since 1st March 2024 for 3 years, fully supported by Scania. Bala has a background in additive manufacturing and Material science.

The research topics

The first target is to use additive manufacturing (AM) as a means for high-performance metallic parts in the section of gas turbines. The focuses are the design, manufacturing, postprocessing, spray behavior of the fuel and final implementation and demonstration of the metal parts that would benefit significantly from the design freedom of AM. The goal is to develop novel approaches to produce the fuel nozzle; to optimize AM-processes for intended metal parts; to establish process parameter and quality control; and to manufacture a prototype demonstrator. The cross-correlation between these goals and the joint efforts targeting high performance metallic parts comprises the core of the project involving a constellation with key industrial partners (Siemens Energy) and core research providers in additive manufacturing, materials science and fluid dynamics (Chalmers and RISE). The results developed in the project will be useful for electricity generation, aviation and shipping/heavy road and rail.



Ref	BJM-R	BJM-M	PBF-LB+EDM	PBF-LB	PBF-LB+D	PBF-LB+B
Base design	Base design	Base design	Base design	Base design	Base design	Brazing design
0.5mm	0.5mm	0.5mm	0.5mm	0.5mm	0.5mm	
0.6mm	0.6mm	0.6mm	0.6mm	0.6mm	0.6mm	0.6mm
0.7mm	0.7mm	0.7mm	0.7mm	0.7mm	0.7mm	
1.0mm	1.0mm	1.0mm	1.0mm	1.0mm	1.0mm	1.0mm

Figure 6: Overview of spray nozzles manufactured for testing at RISE Piteå

Hydrogen gas turbines and internal combustion engines represent ingenious solutions for sustainable power generation, but the compatibility of existing metallic alloys with hydrogen-rich environments remains a concern. This research area also aims to comprehensively characterize the environmental impacts which are relevant to the application condition of the metallic alloys, such as hydrogen embrittlement including both fatigue and tensile, oxidation/corrosion behaviour, and surface engineering to improve material properties in hydrogen application. The ultimate objective is to establish a robust correlation between microstructural alterations and resultant mechanical and other properties, thereby furthering our understanding of material behaviour in hydrogen applications; to establish efficient approaches for improving material properties in the conditions concerned; to build confidence to use additive manufacturing for high-performance compo*nents that would benefit significantly from the design freedom of AM. By comprehending the influences of hydrogen, we can pave the way for the safe and efficient utilisation of existing infrastructure during the transition towards hydrogen-fueled power generation. Successful implementation of project results is expected to bring the TRL level in these cases from TRL4 towards TRL6 for specific parts. The results developed in the project will be useful for electricity generation, aviation and shipping/heavy road and rail.

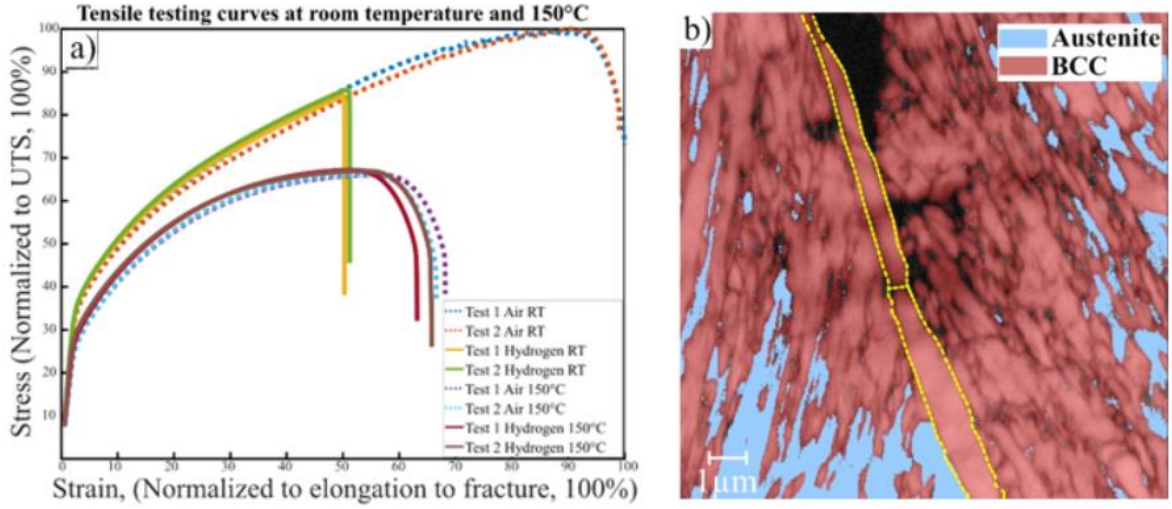


Figure 7: a) Stress-strain curve tested in air and H_2 at room temperature and 150°C for 321 steel samples; b) EBSD phase map overlayed with band contrast image revealing crack formation along δ-ferrite-martensite interphase

Activities during 20204

- Design and additive manufacturing of a test model aiming at calibrating LPBF setup, printability assessment, and surface roughness investigation.
- A total of 26 nozzles have been produced. The nozzles are divided into 7 different groups of nozzles manufactured using conventional machining, Binder Jetting (BJM), Powder Bed Fusion - Laser Beam (PBF-LB). Among these groups, 3 nozzle groups underwent additional post-processing on the outlet hole using methods such as EDM, drilling, and brazing. Each group features up to 4 different outlet hole sizes.
- The first test screening of nozzles and the second part of the test campaign focusing on more detailed analysis at RISE was completed.
- 3 nozzles have been selected for further testing with Phase Doppler Anemometry (PDA) and more detailed camera imaging. PDA is an advanced tool for characterizing sprays and can measure:
    - The distribution of statistical size and velocity moments in a flow field
    - Particle concentration and local size-velocity correlation
- Design of experiments in order to reduce surface roughness in PBF-LB through contour strategy coupled with melt pool monitoring, aiming at the improvement of the spray nozzle performance.
- Comparison of various electrochemical hydrogen charging methods on hydrogen-induced cracking and microstructure variation; Identified proper electrochemical hydrogen charging method and related parameters for tensile and fatigue test.
- In-house low cycle fatigue testing of electrochemical hydrogen-charged specimens and hydrogen-free specimens.
- Siemens Energy facilitates the crucial in-situ pressurised hydrogen low-cycle fatigue and tensile testing. These tested samples, including both steels and Ni base superalloy (conventional and AM manufactured Hastelloy X), were transported to Chalmers. In-depth characterization has been performed, utilising a broad array of advanced characterisation techniques.
- Pinpoint the specific microstructural features responsible for the degradation of commercial austenitic stainless steels.
- Evaluated the feasibility of low-temperature carburizing on the alleviation of hydrogen embrittlement for commercial austenitic stainless steels with hydrogen uptake; Created the correlation between surface treatment, microstructure alterations and the corresponding changes in tensile properties;
- Hydrogen embrittlement sensitivity of 3015 steel valve and cast iron cylinder heads was evaluated by electrochemical cathodic hydrogen charging and slow strain rate tensile tests.
- Hydrogen permeation experiments on 3015 alloy are being conducted to obtain hydrogen diffusivity.
- Obtained beam time for neutron and X-ray imaging to investigate hydrogen distribution in cast irons at ILL, France.

Current studies and publication plan
With respect to dissemination, several publications have already been prepared. So far a journal paper and six conference contributions are reported [24, 25, 26, 27, 28, 29, 30, 31]:

- Himani Garg, Guillaume Sahut, Erika Tuneskog, Karl-Johan Nogenmyr and Christer Fureby, Large Eddy Simulations of Flow over Additively Manufactured Surface: Impact of Roughness and Skewness on Turbulent Heat Transfer, Physics of Fluids 36, 085143 (2024).
DOI: https://doi.org/10.48550/arXiv.2406.05430
- Lindbäck, M., Frankolin, K., Tuneskog, E., Karlsson, B., Wang, L., Development and Validation Under Engine Operation Environment of Additively Manufactured Hot Turbine Parts. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 87103, p. V13CT32A037). American Society of Mechanical Engineers.
- Erika Tuneskog, Lars Nyborg and Karl-Johan Nogenmyr, Assessment of Surface Roughness in Additively Manufactured Channels for Fluid Applications, EuroPM2024 Conference Proceedings, 2024
- Erika Tuneskog, Karl-Johan Nogenmyr, Daniel Moëll, Marcus Gullberg and Lars Nyborg, Exploring Surface Roughness Effects on Spray Performance in Metal Additive Manufactured Spray Nozzles for Gas Turbine Applications, WorldPM2024 Conference Proceedings, Yokohama, Japan, 2024
- Vishnu Anilkumar, Lars Nyborg, Yu Cao. Assessing fracture surfaces and microstructure of stainless steel 321 tested in hydrogen gas, European Conference on Fracture 2024, Aug. 2024, Zagreb, Croatia
- Xiao Qin, Lars Nyborg, Huiqun Liu and Yu Cao. Corrosion behaviour of low-temperature carburized AISI 304 austenitic stainless steel with hydrogen uptake. ECASIA2024, European Association on Applications of Surface and Interface Analysis, June 2024, Sweden.
- Vishnu Anilkumar, Lars Nyborg, Yu Cao. Impact of gaseous hydrogen on low cycle fatigue performance: Fractographic insights from surface analysis, ECASIA2024, European Association on Applications of Surface and Interface Analysis, June 2024, Sweden.
- Vishnu Anilkumar, etc. Hydrogen embrittlement in alloys used in gas turbines. UTMIS25 February 5-6, 2025, Husqvarna, Swedish annual network meeting on fatigue.

In progress:
- Impact of temperature on hydrogen embrittlement during low cycle fatigue of stainless steel 321 (submitted to International Journal of Hydrogen energy)
- Investigating the role of temperature on hydrogen embrittlement under tensile testing of stainless steel 321 (In manuscript)
- Low-temperature carburizing improves hydrogen embrittlement resistance of cold worked 304 austenitic stainless steel (Submitted to Journal of Materials Research and Technology)
- Microstructure evolution induced by cathodic hydrogen charging of low temperature carburized 304 austenitic stainless steel (In manuscript)

Licentiate thesis:
- Hydrogen embrittlement and corrosion behavior of low-temperature carburized austenitic stainless steel, Xiao Qin, Thesis for the degree of licentiate, Chalmers, January 2024
- Characterizing and Modelling of Surface Roughness and its Impact on Additively Manufactured Fluid Components, Erika Tuneskog, Thesis for the degree of licentiate, Chalmers, December 2024.

Project area 3: Nanoplasmonic hydrogen sensor maturation

Industry stakeholders

This multidisciplinary area is configured by collaborating with materials technology and strong collaboration with Insplorion AB.

Basic disciplines

The plasmonic hydrogen sensors discipline is of critical importance for the entire hydrogen energy value chain from both a safety and process monitoring perspective. Examples are safety sensors that detect leaks at ultralow concentrations to enable timely and effective leak control and process monitoring sensors in the high humidity environment of electrolyzers or fuel cells.

Key research challenges that we address are to develop ultrafast response sensors with seconds to sub-second response times that can detect hydrogen concentrations in the low ppm range in inert (oxygen starved), in air and in chemically complex environments, such as widely varying relative humidity conditions and/or the presence of deactivating species like CO, NOx or SOx, to facilitate long-term stable sensor operation without significant deactivation/ageing/sensitivity loss. Employing tailored deep learning models for sensor data treatment is a key concept together with the exploration of new alloy formulations to address these challenges.

Joint projects and recruitment

During 2022 one Ph.D. project has been defined and one Ph.D. student has been recruited.

The Ph.D. project funded by the center is:

- PhD1: Plasmonic hydrogen sensors

The PhD1 project was appointed in 2022-09-01 with Athanasios Theodoridis, a student with strong nanoscience and nanotechnology background with a corresponding master from Chalmers, as well as hands-on experience with industry collaboration via his master thesis project. He will defend his licentiate thesis on April 4th 2025.

As part of this PhD project, we have during the past year:

- Published a collaborative work with Prof. Paul Erhart at Chalmers that demonstrates how the use of a tailored deep-learning model for the analysis of plasmonic hydrogen sensor data enables the acceleration of the sensor response by more than a factor 40 by predicting the response of the sensor before it physically reaches it. Furthermore, the developed machine learning model also eliminated the hydrogen concentration dependence of the sensor response.
- Published a paper in which we demonstrate how a combination of elevated sensor operation temperature and deep learning sensor data treatment enable long-time stable plasmonic hydrogen sensor operation in high humidity environments (80 % relative humidity, RH) in air with a limit of detection of only 100 ppm H_2 and compliant with the ISO 26142:2010 standard for sensor stability.
- Finalized our collaborative work with Prof. Elad Gross at the Hebrew University in Jerusalem on the understanding of SOx species deactivate Pd-based plasmonic H2 sensors by using in situ nanoIR spectroscopy. This work is summarized in a manuscript that will be submitted 2025.
- Finalized our extensive investigation of utilizing Pt as a catalytic-plasmonic H2 sensor for operation in high humidity environments with highly convincing results that show that Pt-based plasmonic hydrogen sensors can operate at 80 % RH in air with high sensitivity and long-term stability. Using Pt (instead of Pd) is a completely new paradigm for the field of plasmonic H2 sensors that exploits a mechanistically very different sensing mechanism, which, as one key trait, in fact delivers higher sensitivity/lower limit of detection at high humidity. Therefore, it constitutes a superior solution for H2 sensing in humid environments and contrast any know H2 sensing technology in this respect. A manuscript is written to be submitted 2025.
- Further developed the PdTa alloy plasmonic H2 sensor nanofabrication in collaboration with Asst Prof. Lars Banenberg at TU Delft with the goal to develop PdTa alloy-based plasmonic hydrogen

sensors with unprecedented dynamic range by also employing surface lattice resonances. We plan to submit a manuscript 2025.

The research production from the area

The PhD1 project was appointed in 2022-09-01 with "Athanasios Theodoridis". He is currently investigating Pt-co-catalyzed hydrogen sensors for operation in highly humid air, developing PdTa alloy-based sensors with ultrahigh dynamic range in collaboration with the Bannenberg/Dam team at TU Delft and is investigating the impact of sulfur on the deactivation of plasmonic hydrogen sensors in collaboration with the group of Prof. Elad Gross at Hebrew University in Jerusalem.

In terms of publications the multidisciplinary research area has already provided three contributions in very distinguished journals [32, 1, 33]:

- F. A. A. Nugroho, P. Bai, I. Darmadi, G. W. Castellanos, J. Fritzsche, C. Langhammer, J. G. Rivas, A. Baldi, "Inverse designed plasmonic metasurface with parts per billion optical hydrogen detection.," *Nature Communications*, , vol. 13, no. 1, p. 5737., 2022.
- Tomeček, D., Moberg, H. K., Nilsson, S., Theodoridis, A., Darmadi, I., Midtvedt, D., ... & Langhammer, C. (2024). Neural network enabled nanoplasmonic hydrogen sensors with 100 ppm limit of detection in humid air. *Nature Communications*, 15(1), 1-15, 2024.
- V. Martvall, H. Klein Moberg, A. Theodoridis, D. Tomecek, P. Ekborg-Tanner, S. Nilsson, G. Volpe, P. Erhart and C. Langhammer, "Accelerating Plasmonic Hydrogen Sensors for Inert Gas Environments by Transformer-Based Deep Learning.," *ACS Sensors.*, vol. 10, pp. 376-386, 2025.

For the upcoming year, the multidisciplinary research area plans to focus on:

- (i) a paper on the topic of the impact of sulphur species on the deactivation of plasmonic hydrogen sensors in collaboration with the group of Elad Gross in Israel,
- (ii) a paper on the topic of Pt-co-catalyst for plasmonic hydrogen sensor operation in high humidity environments,
- (iii) a paper on the topic of PdTa alloy plasmonic hydrogen sensors with ultrawide dynamic range in collaboration with the Dam/Bannenberg team at TU Delft and
- (iv) a paper that establishes a multiplexed plasmonic H2 sensor that is comprised of multiple active sensor areas that consist of different sensing materials, such as Pd, Pd-alloys, Pt and Pt-alloys to enable H2 sensor operation in chemically very complex environments, such as humid air with traces of CO, NOx, SOx.

The research topics

The need for accurate and rapid sensing techniques both for measuring hydrogen contents in process monitoring and for taking safety measures by leak detection is high in all modes of transport. However, to date, no hydrogen sensor technology exists that can meet all the hydrogen (safety) sensor performance targets defined by the US DoE, despite significant global R&D efforts. Hydrogen detection in complex chemical and/or humid conditions, as well as in the ultralow and high-pressure ranges constitute the toughest challenges here. This development is driven, among other, by the US DoE hydrogen sensor performance targets summarized in the Figure 8 below.

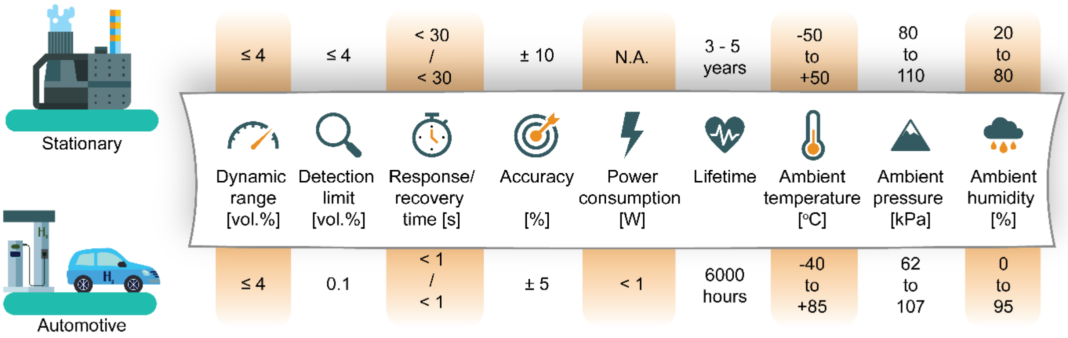


Figure 8: The DoE hydrogen safety sensor performance targets for stationary and mobile applications.

This PhD project is currently focusing primarily on developing nanoplasmonic hydrogen sensors that have the capability to operate in complex gas environments that, e.g., contain O_2, H_2O, CO, NOx and SOx (Figure 9). To achieve this ambitious overarching goal it explores three strategies: (i) the use of new sensing materials based on hydride forming alloys based on Pd, or catalytic materials like Pt (Figure 10), or alloys between the two; (ii) the use of deep learning-based data analysis to enhance sensor performance in terms of both response time, stability and limit of detection in complex chemical environments (Figure 11, Figure 12 and Figure 13); (iii) the concept of multiplexing by combining different sensing materials from the ones available according to (i) in one and the same platform to create a sensor where at least one component always is responsive and where the combination of responses from the different sensing materials constitutes an unique fingerprint characteristic for a specific environment that can be learnt by deep learning models as developed as part of (ii) (Figure 14).

As the second main aspect, this PhD project focuses on the development of sensors in the low (10-5 - 10-3 bar) pressure range, by implementing new nanoparticle array designs that, for example, explore surface lattice resonances to improve the limit of detection and develop protocols to implement SLR-based sensors based noble-metal and rare-earth metal alloy nanoparticles. Here, a first study we have executed together with collaborator Prof. A. Baldi at VU has demonstrated that detection limits in the ppb range become available already when using pure Pd as sensing material (Nature Communications 2022, 13 (1), 5737). This is a very strong foundation to further explore this concept using PdTa alloys developed together with our collaborators at TU Delft and Prof. Paul Erhart at Chalmers for the optimization of the SLR-arrays.

As the third aspect for the upcoming year, we will start exploring a new generation of carbene-based H_2-transparent nanolayers to prevent competitive H_2O adsorption on and ageing of the plasmonic nanoparticles in humid environments in the hope of identifying a third strategy for how to make plasmonic hydrogen sensors compatible with high humidity environments. This development will take place in collaboration with the group of Prof. Elad Gross at the Hebrew University in Jerusalem, who have developed these adlayers.

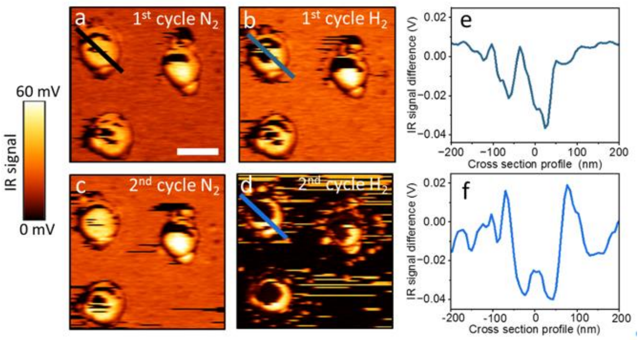


Figure 9: AFM-IR mapping of SOx poisoned Pd nanoparticles acquired at 1108 cm^{-1} after exposure to N2 (a) and H2 (b) and a second cycle of N2 (c) and H2 (d). IR signal differences were measured after the first and second H2 exposure cycles plotted in e) and f), respectively. IR signal differences shown in e) and f) were measured across the lines marked in a)-d). The scale bar represents 200 nm. These results are part of a manuscript put together with our collaborator Prof. Elad Gross at the Hebrew University of Jerusalem.

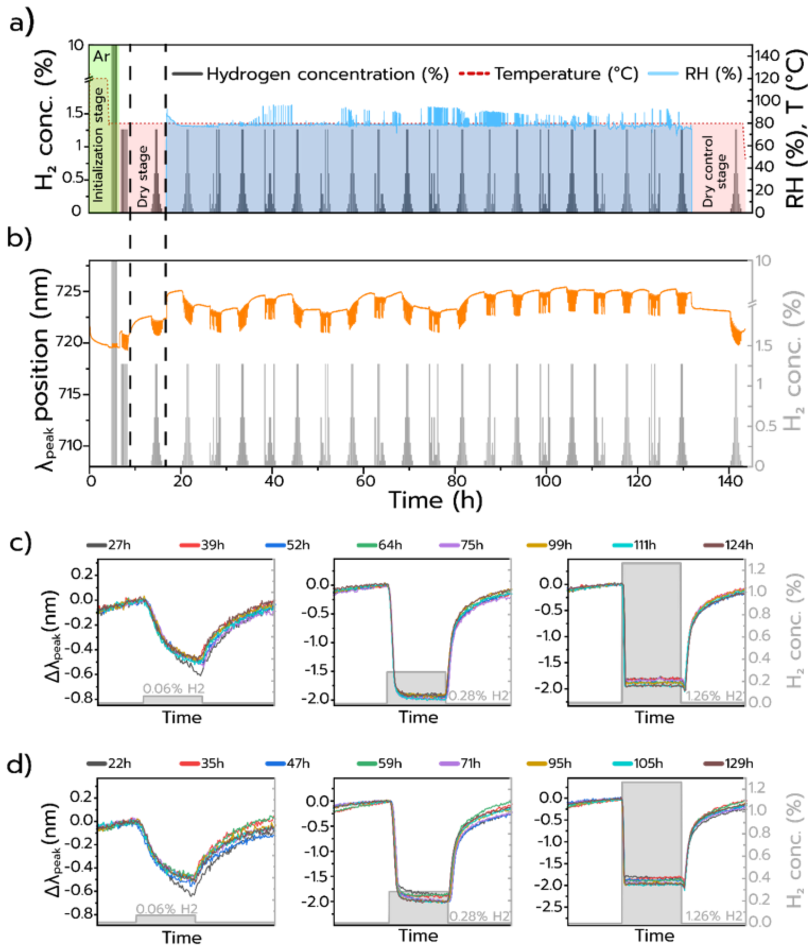


Figure 10: Long-term stability test of a Pt catalytic-plasmonic hydrogen sensor operated in humid air with 80 %RH over 143 h. We note the consistent response to hydrogen pulses both in regular and randomized sequences.

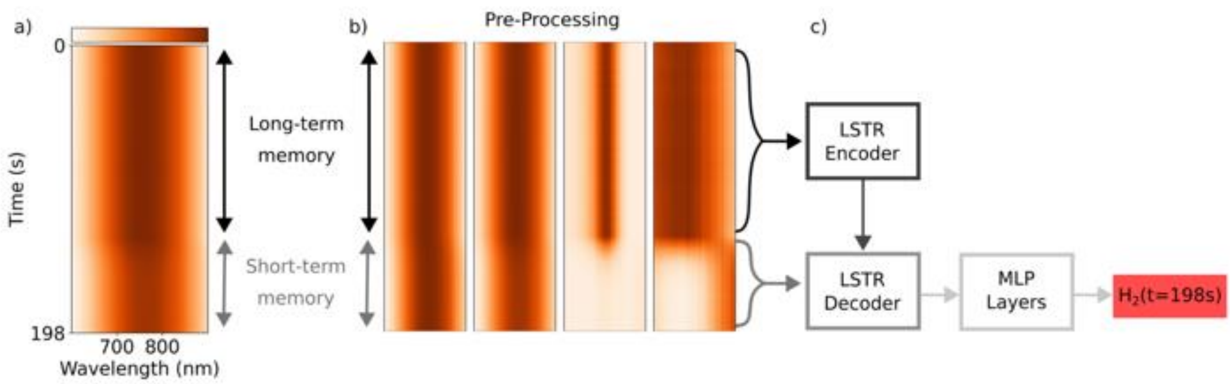


Figure 11: Long Short-term Transformer Ensemble Model for Accelerated Sensing (LEMAS). Illustration of the deep learning model used to accelerate the response of plasmonic hydrogen sensors by predicting the sensor response before the hardware physically reaches it. Adopted from our recent publication: *ACS Sensors.,* vol. 10, pp. 376-386, 2025.

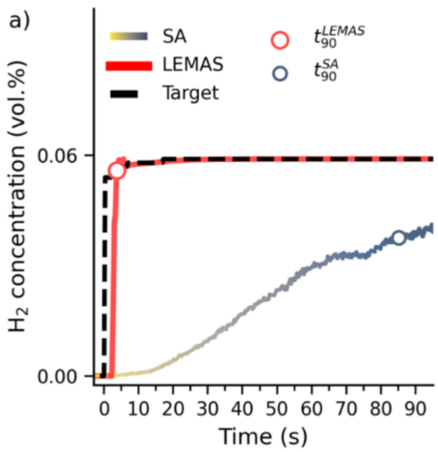


Figure 12: Accelerating sensor response time to a simulated H2 leak in inert gas environment using the LEMAS deep learning model. The figure depicts a comparison of the prediction of LEMAS and the standard analysis (SA) readout of the sensor for a pulse of 0.06 % H2 in inert Ar environment. Adopted from our recent publication: *ACS Sensors.,* vol. 10, pp. 376-386, 2025.

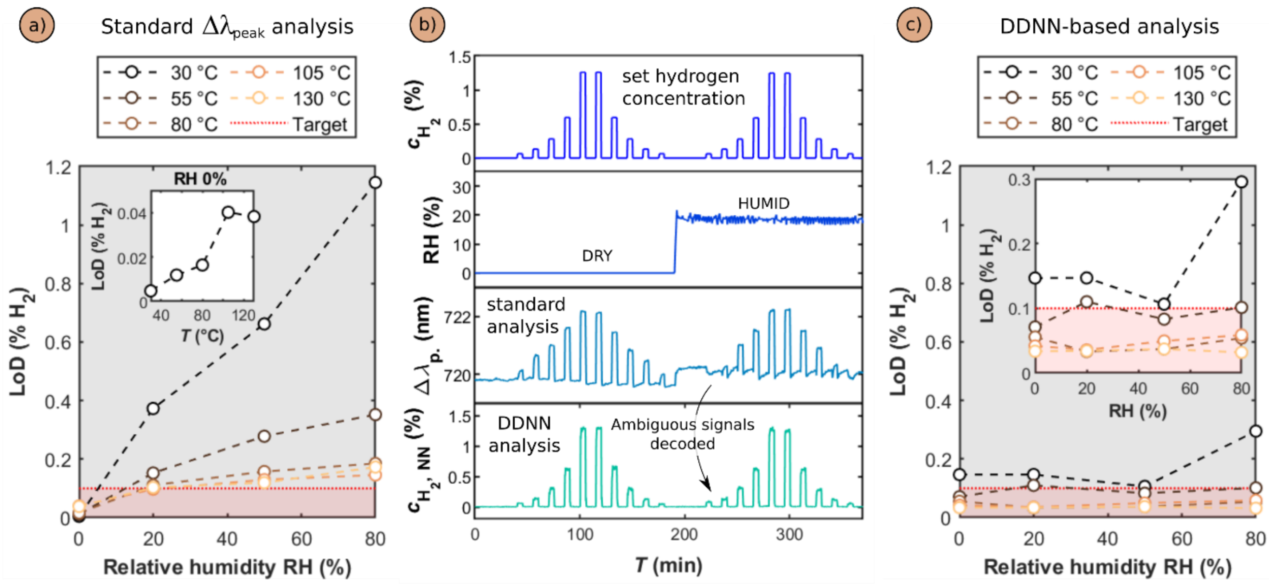


Figure 13: a) Sensor limit of detection (LoD) as obtained by the standard Δλpeak readout for different sensor operating temperatures and RH. Note that above 20% RH all sensors fall short on the US DoE target of LoD < 0.1% H2. b) Comparison of sensor response to c_{H_2} pulses at dry and 20% RH conditions at 80°C operating temperature, as obtained by the standard Δλpeak readout and the deep dense neural network (DDNN) architecture-based readout, $c_{H_2,NN}$. c) Sensor LoDs obtained by the DDNN architecture-based readout revealing that an essentially RH-independent LoD that lies significantly below the DoE target of 0.1% H2 is obtained for sensor operating temperatures of 80°C and above. Adopted from our recent publication: *Nature Communications*, *15*(1), 1208, (2024).

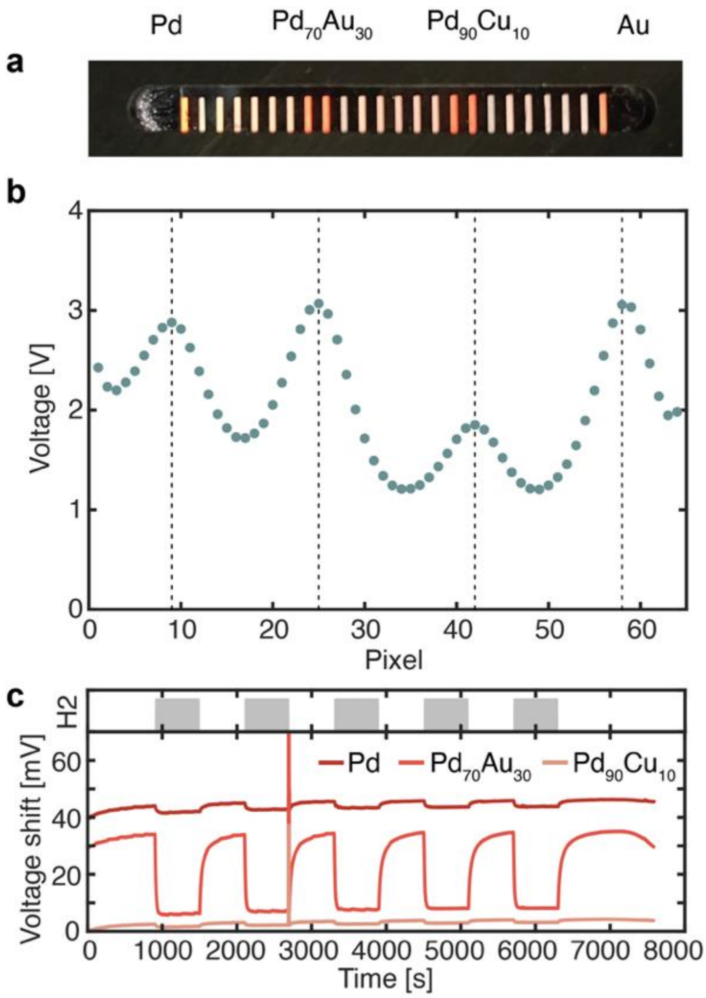


Figure 14: (a) A photograph of a multiplexed plasmonic hydrogen sensor comprised of a number of parallel “stripes” that consist of nanoparticle arrays of different materials, as indicated from the left: Pd, $Pd_{70}Au_{30}$, $Pd_{90}Cu_{10}$ and Au. (b) The voltage readout from the photodiode arrays 64 pixels that corresponds to the intensity profile of light scattered from the nanoparticle arrays. Since the particle arrays are well-separated, four distinct peaks can be observed. The center pixels, around which 5 pixels are averaged to find the scattered intensity from each particle array, are marked by dashed lines. (c) The average voltage shift collected on the photodiode array above the nanoparticle arrays of Pd, $Pd_{70}Au_{30}$, and $Pd_{90}Cu_{10}$, during five 40 mbar H_2 pulses of 10 minutes. The scattering from the Au array is used as a reference to remove drift in the baseline. These are preliminary results.

In terms of *dissemination*: this multidisciplinary research area has contributed to three journal articles in very prestigious journals [32, 1, 33]:

- F. A. A. Nugroho, P. Bai, I. Darmadi, G. W. Castellanos, J. Fritzsche and C. .. a. B. A. Langhammer, "Inverse designed plasmonic metasurface with parts per billion optical hydrogen detection.," *Nature Communications,* , vol. 13, no. 1, p. 5737., 2022.
- Tomeček, D., Moberg, H. K., Nilsson, S., Theodoridis, A., Darmadi, I., Midtvedt, D., Volpe , G., Andersson, O., Langhammer, C.. Neural network enabled nanoplasmonic hydrogen sensors with 100 ppm limit of detection in humid air. Nature Communications, 15(1), 1208, (2024)
- Martvall, V.; Klein Moberg, H.; Theodoridis, A.; Tomeček, D.; Ekborg-Tanner, P.; Nilsson, S.; Volpe, G.; Erhart, P.; Langhammer, C., Accelerating Plasmonic Hydrogen Sensors for Inert Gas Environments by Transformer-Based Deep Learning. ACS Sensors 2025, 10 (1), 376-386.

Project area 4: Fuel cell development and integration

Industry stakeholders

This multidisciplinary area combines low-level understanding of fuel cell materials, fuel cell stack modeling and validation testing, and powertrain system modeling to enable comparison of component sizing choices, control strategies, and optimal operating conditions for proton exchange membrane fuel cell (PEMFC) hybrid powertrains. The methods developed focus primarily on heavy road transport, but the results and model framework should be adaptable for use also for shipping/rail and aviation applications Initially, Chalmers Volvo AB, Volvo Penta, and Scania collaborated to define the content. As the work has progressed increased interest from Johnson Matthey and PowerCell has also been noted.

Basic disciplines

The development of fuel cell systems that can operate at the scales and power densities required for vehicle powertrains requires linking the understanding of ion transport, gas-exchange, electrochemical and catalytic action at the cell level to the fuel cell stack response in the context of the power demands of the vehicle. This calls for a combined approach integrating input from low-level physics and thermodynamic and electrochemical system modeling to address FC stack level challenges, such as how alternate cooling or humidity profiles will impact stack power and longevity and how time-dependent stack temperature and relative humidity will modulate heat production, cell impedance and losses, as well as durability/degradation of the membrane and catalyst structures.

Key research challenges are to develop proton exchange membrane fuel cells (PEMFCs) solutions that radically reduce the use or entirely remove the use of scarce noble metals, as well as to develop novel PEMFCs that can substitute perfluorinated polymers, like Nafion, which are costly to produce and difficult to recycle. A correlated aspect is the need for finding non-volatile proton conducting electrolytes alternative to acidic water which may be able to operate at intermediate temperatures (80 – 200 °C) and thus enable the use of cheaper and more abundant catalysts.

The detailed PEMFC cell-level and stack-level understanding in turn must be integrated with a system model for fuel-cell hybrid electric powertrains in order to address the tradeoffs and performance of specific hardware choices and the energy balance of a powertrain for relevant vehicle operating conditions and power demand. The long-term research ambition is to develop models to optimize and experimentally validate the impact of design choices and predict top-level vehicle performance for hydrogen propelled vehicles and to develop low cost, durable fuel cell stacks with a high degree of sustainability.

Joint projects and recruitment

During 2022 two Ph.D. projects have been defined and two Ph.D. students have been recruited. In 2023, two additional Ph.D. projects were defined and staffed. In addition, Chalmers has supported the project by defining and funding the postdoctoral research project Systematic control of PEM fuel cells for vehicle applications.

The four Ph.D. projects funded by the center are:

- PhD1: PEMFC time-response and lifetime analysis
- PhD2: PEMFC temperature management for high performance
- PhD3: MATerials for proton conduction at Intermediate Temperatures (MATITE)
- PhD4: DROAS: Degradation resistant operation and shutdown

The PhD1 project has accepted Mina Bahraminasab for the position. Her start date was 2023-05-01. Mina is a graduate of AL-Zahra University, Iran with a strong background in mechanical engineering and experience with biological fuel cells.

The PhD2 project was launched on 2022-10-10, the with Christian Bosser appointed to the position. Christian is a graduate of RWTH Aachen, Germany with a specialization in propulsion technology. He has experience in powertrain modeling and experience with fuel cells from his Erasmus work at Aalto University, Finland.

The PhD3 project was launched on 21st of August 2023, with the appointment of Eva Dahlqvist as a Ph.D. student.

The PhD4 project was launched on 1st of September 2023, with the appointment of Lahari Kothala Gnana, industrial Ph.D. student at Volvo.

The research topics

Polymer electrolyte membrane fuel cells (PEMFC) are currently the most promising fuel cell design for flexible, robust, and cost-effective use of hydrogen fuel for transport applications. PEMFCs operate at low temperatures which ease handling and enable reasonable system response times, as well as idling, and cold-start which are comparable to conventional ICE vehicle capabilities. In addition, PEMFCs produce only water and excess heat under normal operation and directly generate electrical power which can yield peak efficiencies in excess of 60%. While this efficiency and emissions profile is highly favorable, a number of challenges remain in order to compete with conventional heavy-duty powertrains, especially with regard to durability which factors heavily in vehicle total cost of ownership.

The current state of PEMFC stack durability and lifetime for automotive powertrains varies widely by application, with assessments ranging from 1200 to 12000 hours. Figure 15 shows the disparity of estimated run-time durability reported (A) or predicted (B, C, D) by experts elicited from academia, government, and industry, with a median reported value at roughly 4000 hours.

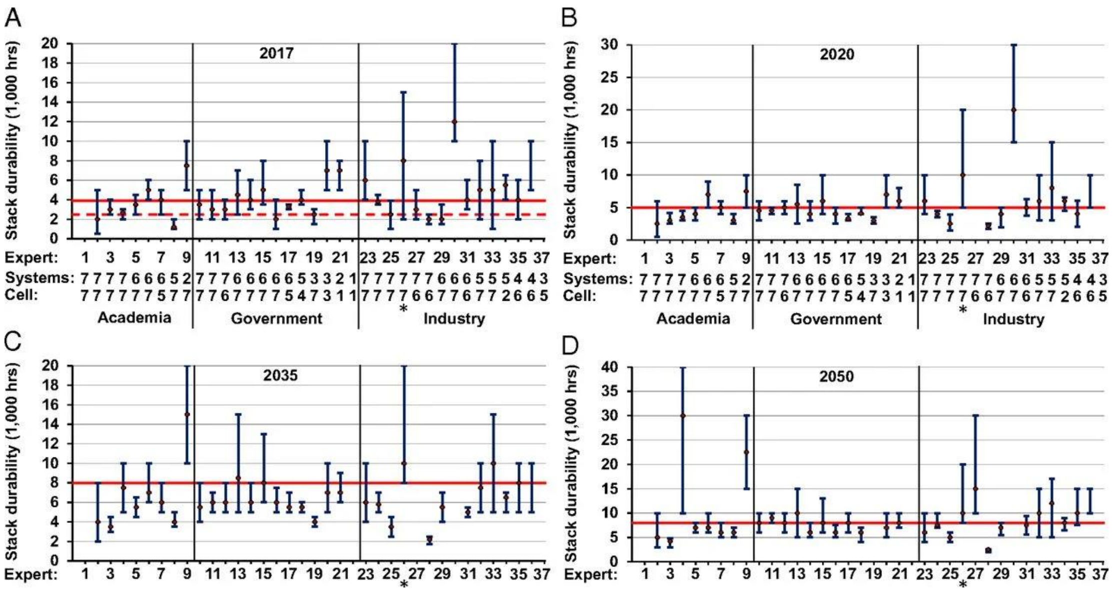


Figure 15: Assessment of PEMFC stack durability (A) 2017 values. (B) 2020 values. (C) 2035 estimate. (D) 2050 estimates. The solid lines represent DOE targets for stack durability. Courtesy of PNAS 2019, 116(11) 4899-4904.

It is clear that transients can severely impact the useful lifetime of PEMFC systems. In general, unsteady conditions promote imbalances in the chemistry, temperature, pressure, and humidity control which lead to small scale changes in the fuel cells which gradually contribute to performance degradation.
A large body of individual mechanisms which can lead to degradation in fuel cells are covered in the literature, especially reactions and physical changes which reduce electro-catalyst surface area. However, the combined MEA disturbances distributed throughout the stack which interfere with the system performance over time often depend strongly on historical as well as present conditions. This complicates lifetime prediction of fuel cells and limits the utility of physical-model based prediction methods, while data-driven (or

hybrid) approaches which can be tailored more specifically to the stack hardware appear to be a promising way forward.

The PhD1 project is targeted to link the understanding of the causes and relative importance of degradation mechanisms in the membrane electrode assembly (MEA) to a vehicle configuration and control strategies which balance the need for agile stack response and durability. Empirical data from fuel cell testing will be used to develop a data-based stack model which will track probable deterioration and provide state-of-health information which can inform control of the vehicle. This model can then be applied to adjust the vehicle control strategy based on current state-of-health to further increase the lifetime of the stack.

The fragility of the perfluorinated polymer membranes used in PEM fuel cells is a significant drawback that contributes to the cost and reduced durability of PEMFC powertrains. Alternative fuel cell arrangements that replace the membrane with an ionic liquid offer huge opportunities for improving lifetime and reducing cost. The PhD4 project, led by Anna Martinelli aims to explore this approach and work is underway to produce membranes for testing. On a systemic level, the focus will be fuel cell stack design and optimization, including scaling aspects to larger fuel cell systems, maximizing power density, detection of poisoning agents, and close control of fuel and oxidant flows.

For now, stacks based on PEMFCs remain the most compelling choice for long-haul and regional transport, where the diminishing returns of increasing battery capacity severely impact the operational range, time in service, and payload capacity of battery electric powertrains. Fuel cell power systems based on PEMFCs rely on thin solid-state electrolytes for ion transport and their effective operating range is constrained to lower temperatures to maintain the water balance in the membrane. The heat generation and relatively strict temperature requirements of PEMFCs present difficulties for efficient thermal management,[1] but also some opportunities to repurpose waste heat for battery management and auxiliary use with a comprehensive temperature control strategy.

High-load operation of a PEMFC stack presents a number of challenges in balancing the heat dissipation and contrasting water management demands on the anode and cathode sides of the MEA unit cells, especially under more extreme environmental conditions. The power of the fuel cell stack for vehicle applications must be matched by the heat rejection capability of the powertrain. Here, the changes in power demand, time-varying stack response, and external temperature variation result in complex interactions that require adaptive control.

The PhD2 project targets development of a system model that combines the mass flow and heat dissipation of an active cooling system to the temperature dependent behavior of the PEMFC electrochemistry and heat transfer within a physics-based stack model. This approach is intended to enable closer, faster heat control which can drive efficiency savings in some conditions but also allow for better performance and a wider performance envelope for a given PEMFC system.

[1] Kandlikar, et al., Thermal management issues in PEMFC stack – a brief review of current status, *Applied Thermal Engineering*, **29** (7), 1276-1280, 2009.

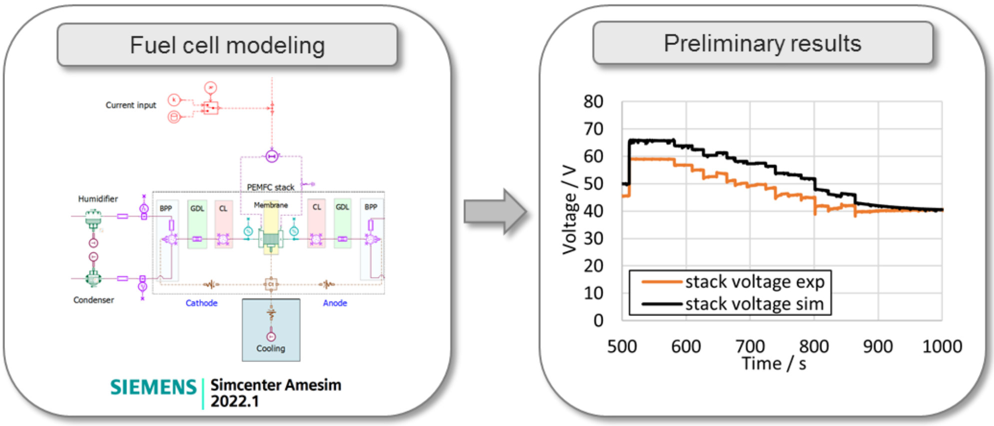
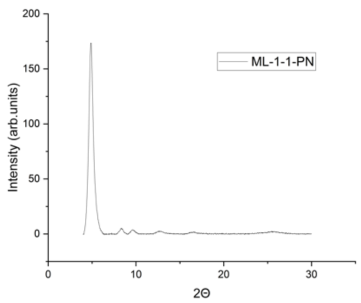
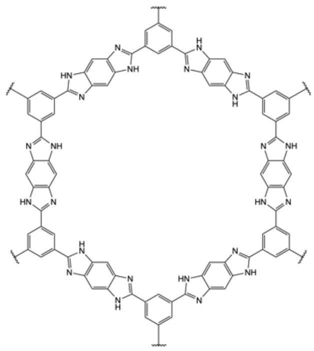
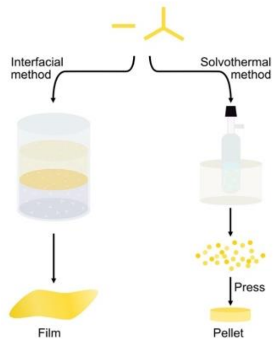


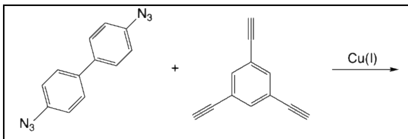
Figure 16: Preliminary model results, together with PEMFC experimental data (5 kW short stack).

A preliminary model with an idealized cooling setup has been implemented in Simcenter Amesim. Figure 16 shows a view of the PEMFC membrane electrode assembly from the simulation setup and a comparison of model results targeting a 5 kW test bench stack and experimental results measured from the 5 kW PEMFC stack.

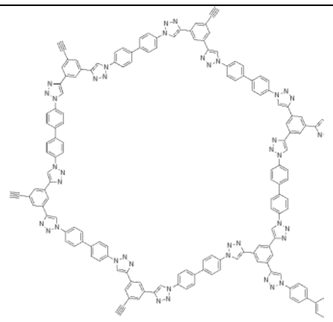
The PhD3 project aims to develop materials for proton conduction at Intermediate Temperatures. Since its launch the project has worked on several promising synthesis routes, of which two have been selected for further investigation. One route has been the synthesis of a pre-network of COF that can later be exchanged to obtain a structure with the desired functional groups. Below we show the powder XRD of the synthesized pre-network (a) and the chemical structure of the final COF (b). To note, that the linker in the imidazole-based COF is a benzimidazole (PBI) group already known to be functional in high-temperature phosphoric acid-based fuel cells. These COFs are hence very promising and will be filled with an acidic liquid compound able to interact with PBI and thus support proton conduction. The XRD to the left reveals a high crystallinity along with the formation of the expected rings (peak at 2q = 5°) and stacking of the rings (peak at 2q = 26°). These COFs have been synthesized by a solvothermal route (c).

Another important result is the realization of a thin film of COF synthesized by the interfacial route (c), a method that keeps the reagents and catalyst separated into two immiscible liquid phases while the reaction only occurs at the liquid/liquid interface. These thin films are currently being investigated by TEM while a bulk synthesis is also ongoing to provide thicker materials (possibly less ordered) and thus enable a larger number of characterization techniques.

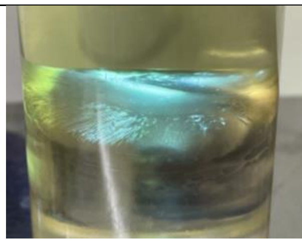
a)  Powder XRD of a COF pre-network	b)  Imidazole-COF network	c)  Interfacial and solvothermal routes
d)	e)	f)



Reagents for the click synthesis



COF network from click reaction



Thin film of COF formed at the interface

Figure 17: Work with synthesis of a pre-network of COFs

Once both these two routes have been set, larger amounts of COFs will be produced for a subsequent filling with a proton conducting phase. Here we consider both acidic water and protic ionic liquids. These filled materials, either in film form or pressed pellets will be assembled to a MEA and possibly tested in single cell fuel cell devices. This could be done in collaboration with PowerCell that is a partner of the center.
From a collaboration with colleagues at Santiago de Compostela (Prof Luis M Varela), we have also performed computational studies that among other things have generated a Raman spectrum for the imidazole-COF, see below. This will be compared to Raman spectra that we will measure experimentally, helping in understanding the chemistry of the realized COF and its orientation on the xyz plane.

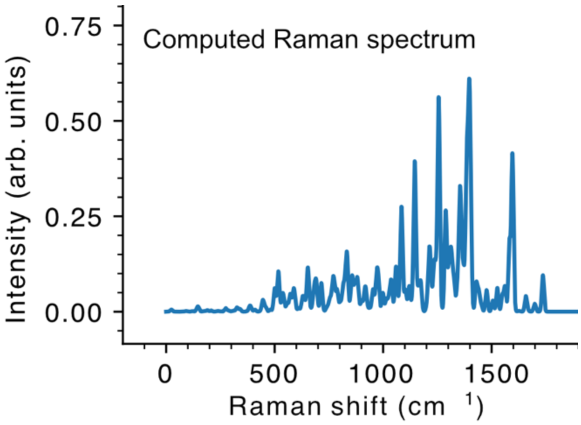


Figure 18: Raman spectrum for the imidazole-COF

The PhD4 project (Droas, Degradation Resistant Operation And Shutdown) aims to find ways to improving the durability and performance of PEM fuel cells, particularly under the demanding conditions of heavy-duty vehicle applications. Key activities include the development of a comprehensive fuel cell model that captures thermal, water, and molar balances, along with electrochemical behavior. A major challenge lies in accurately simulating the various loss mechanisms during cell operation, activation, ohmic, and mass transport losses, using advanced electrochemical equations such as the Butler-Volmer and Kulikovsky models (Figure 19 left). These simulations are implemented in AMESIM, where system-level models help understand performance degradation over time.

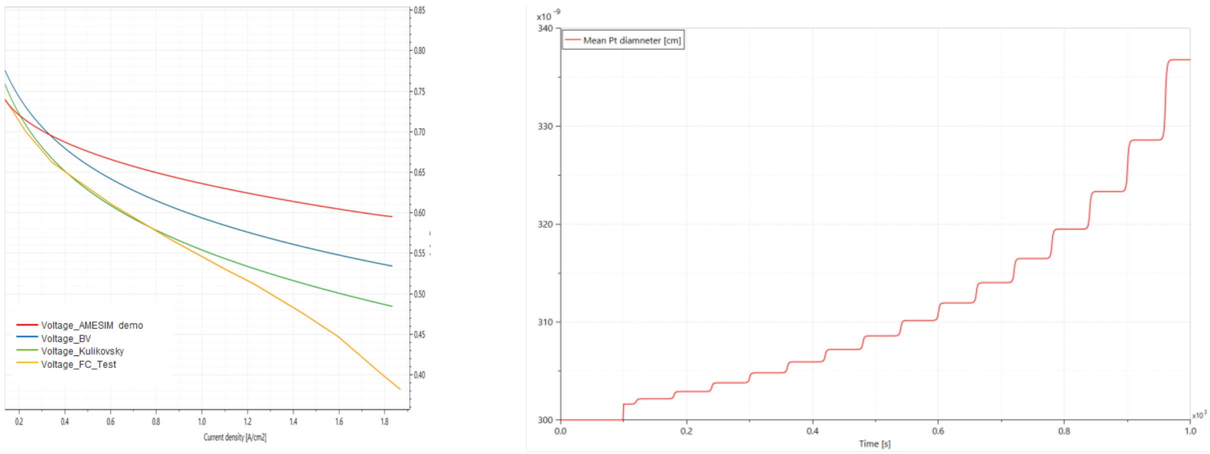


Figure 19: Fuel cell polarization curve modelled from models in literature, AMESIM and test (left) and Pt diameter increase over time.

One of the core components of DROAS is the modeling of catalyst layer degradation, which directly impacts cell efficiency and lifetime. The catalyst layer is particularly vulnerable to chemical and mechanical stress, and the model focuses on three critical zones: (1) platinum degradation through oxidation and dissolution, (2) carbon corrosion from repeated startup and shutdown cycles, and (3) Pt-carbon interactions leading to catalyst detachment. The degradation model accounts for phenomena such as Ostwald ripening—where Pt particles grow over time, reducing active surface area (ECSA)—as well as CO and CO_2 formation due to carbon corrosion (Figure 19 right). Validation with experimental data, including IL-TEM microscopy, confirms that the model reliably tracks both Pt particle growth and ECSA loss.

Accelerated Stress Tests (ASTs) are also vital tools within the DROAS framework, designed to simulate long-term fuel cell wear under compressed timelines. These tests replicate real-world conditions such as voltage cycling, dynamic load, high load, idling, and frequent start-stop operations, each contributing differently to catalyst and membrane degradation. For instance, start-stop events are especially harsh, leading to significant carbon corrosion and membrane wear, while dynamic loads mainly impact Pt dissolution. By identifying and quantifying these stressors, the DROAS team has developed a tailored algorithm to effectively simulate degradation for various operating conditions, aiding in the prediction and mitigation of long-term damage.

Fuel cell performance analysis under these stress scenarios reveals critical insights. Using the calibrated degradation model, DROAS simulates proportional drive cycles to assess voltage drop, Pt diameter changes, and ECSA reduction over time. Notably, the equivalent degradation that would typically take 72 hours in real conditions can be simulated in just 35 hours, enabling faster validation and development cycles. The project's outcomes support the advancement of PEM fuel cells in commercial heavy-duty vehicles by enhancing the understanding of degradation mechanisms and guiding the design of more robust operational strategies.

With respect to planned dissemination two additional conference contributions and four additional journal papers are underway for 2025 within the PhD1, PhD2 and PhD4 projects.

With regards to teaching impact (D6), both David Sedarsky and Anna Martinelli have contributed with invited lectures in a Chalmers course: TRA275, Fuel Cell Systems.

*

Current studies and publication plan
In 2022-08-01, Ahmed Zoukit was recruited as post doc in the project "Systematic control of PEM fuel cells for vehicle applications" and was working at Chalmers until 2023-09-30. Ahmed has a background in electrical engineering from Cadi Ayyad University, Morocco and experience with PEM fuel cell systems working at PSL University, France the following papers have been produced [35]:

- Zoukit, Ahmed, Issam Salhi, and David Sedarsky. "Takagi-Sugeno Fuzzy Approach for PEM fuel cell system modeling." European Fuel Cell Forum. 2023.

The PhD1 project was launched on 2023-05-01, with Mina Bahraminasab appointed to the position. The work is concentrated on the development of thermal control of high-performance fuel cells.

The PhD2 project was launched on 2022-10-10, the with Christian Bosser appointed to the position. Initial work in the project is focused on implementing and validating a simplified PEMFC stack model [36].

Senior work on system modelling of efficiency in electrified powertrains are reported in [36, 37]:
- Xu, Y., Kersten, A., Klacar, S., Ban, B., Hellsing, J., Sedarsky, D. (2023). Improved efficiency with adaptive front and rear axle independently driven powertrain and disconnect functionality. *Transportation Engineering*, *13*, 100192.
- Xu, Y., Kersten, A., Klacar, S., Sedarsky, D. (2023). Maximizing efficiency in smart adjustable dc link powertrains with igbts and sic mosfets via optimized dc-link voltage control. *Batteries*, *9*(6), 302.

Whereas work on fuel-cell hybrid vehicle use cases versus BEV and conventional vehicles is conducted in [38, 39]:

- Pipicelli, M., Sedarsky, D., Koopmans, L., Gimelli, A., & Di Blasio, G. (2023). Comparative Assessment of Zero CO2 Powertrain for Light Commercial Vehicles (No. 2023-24-0150). SAE Technical Paper.
- Xu, Y., Ingelström, P., Kersten, A., Andersson, A., Klacar, S., George, S., & Sedarsky, D. (2024). Improving powertrain efficiency through torque modulation techniques in single and dual motor electric vehicles. *Transportation Engineering*, 100289.

The PhD3 project was launched on 21st of August 2023, with the appointment of Eva Dahlqvist as a Ph.D. student. The project has generated the following publications [34] and two conference contributions.

- Dahlqvist, E., Morais, E. M., & Martinelli, A. (2024). Synthesis and characterization of new imidazolium based protic ionic liquids obtained by nitro-and cyano-functionalization. Journal of Molecular Liquids, 415, 126269.
- *Synthesis and characterization of new imidazolium based protic ionic liquids obtained by nitro- and cyano-functionalization*, Oral presentation, Materials, ILMAT2023, Porto, Portugal, November 22nd, 2023.
- *Synthesis of novel covalent organic frameworks for proton conduction*, International Symposium on Mesostructured Materials, Montpellier, France. IMMS, July 8th, 2024

Project area 5: The future of hydrogen – societal challenges

Industry stakeholders

This multidisciplinary research area is assessing the role of future hydrogen in society from a systems perspective. Volvo, Scania, Siemens Energy, PowerCell, GKN Aerospace, Johnson Matthey and Stena Rederi have all been involved in the initial phase of formulation this project and more intense collaboration was initialized during 2023.

Basic disciplines

The energy and environmental systems analysis discipline evaluates the role of different energy carriers in the energy system based on energy systems modelling and environmental systems analysis. Hydrogen can play an important role in a future sustainable low-carbon energy system. However, there are challenges to overcome during the transition period from today until used in large scale. Key factors are the amount of excess electricity, availability of infrastructure, capital cost of fuel cells and electrolysers, the lower round-trip efficiency compared to direct electrification, geopolitical and limitation risks connected to the use of scare metals, the relatively costly hydrogen distribution and storage and issues related to consumers' preferences. The role of hydrogen in the transport sector is in focus, but other parts of the energy system are also considered.

Key research challenges connected to the role of hydrogen in a future sustainable low-carbon energy system are to detect and model potential show-stoppers from for instance resource limitations, cost-competitiveness, environmental performance, social acceptance, synergies and competition with other energy sectors, the supply potential, localization and hydrogen infrastructure and storage demand, interlink transport hydrogen and future systems scenarios, predict and optimize policy and regulations of transport and society in general.

Joint projects and recruitments

During 2022 one Ph.D. project has been defined and one Ph.D. student has been recruited and started 1st of March, 2023. In addition, Chalmers has supported the project by two postdoc projects Hydrogen in transport – Global, European, and Nordic perspectives (Chalmers AoA Transport) and Systems assessment of hydrogen and electrofuels in transports (Chalmers Genie). The two postdocs are also engaged in the community of the competence center on catalysis (KCK). During 2024 the Genie-funded postdoc has finished his time at Chalmers and is now employed at RISE.

The Ph.D. project funded by the center is:

- PhD1: The future of hydrogen – societal challenges.

The PhD1 project has recruited PhD student Joel Löfving, a former Chalmers student with strong knowledge in environmental systems assessment and modelling. Joel started 2023-03-01. In addition to the centre funds this project will collaborate with Energiforsk's hydrogen program (Vätgasens roll i energi- och klimat-omställningen (VREK)) to increase knowledge transfer about the role of hydrogen in the energy system. The collaboration will first and foremost occur within an associated 3-year project funded by the Swedish Energy Agency with the long Swedish title: ”Vätgasens samlade påverkan på elsystemet och dess roll i energi- och klimatomställningen: En system- och syntesstudie om vätgas och elektrobränslens roll i framtidens sektorkopplade energisystem”. Project leader: Maria Grahn. Another project with close links is the Nordic roadmap for sustainable fuels for shipping (https://futurefuelsnordic.com/). It is a Nordic collaboration project centered around the establishment of a Nordic Cooperation platform to facilitate knowledge sharing, alongside the launch of pilot projects and studies that will build experience in new fuels, to establish "green corridors" and the enabling infrastructure, hydrogen is among the fuels investigated. Project leader at Chalmers: Selma Brynolf.

Developing a transnational network of hydrogen refuelling stations for trucks (HyTruck) is an EU Interreg (Baltic Sea Region) project coordinated from Germany. In WP1, GoA 1.2, Chalmers will lead the work on techno-economic assessments, energy economic modelling and life cycle environmental impact aiming to shed some light to questions as: Where does hydrogen come from? What is the environmental impact depending on the distance from the place of production to the point of refuelling, and for different outlines of hydrogen refuelling stations for trucks, e.g., compare 300 bar, 700 bar, or liquified H2? Under what circumstances (battery price, fuel cell price, hydrogen storage costs, fuel station cost, electrolyser cost, efficiencies, capacity factors etc) do the model show that hydrogen plays a dominating role in the fuel mix for trucks? WP1 leader: Maria Grahn.

Research production

Research production

During 2022-2024 work on a number of publications connected to the centre was initiated and progress in terms in of submission is reported below [40, 41, 42, 43, 44, 2, 45, 46]:

Published:

1. Grahn M, Malmgren E, Korberg AD, Taljegard M, Anderson JE, Brynolf S, Hansson J, Skov IR, Wallington TJ (2022). Review of electrofuel feasibility - Cost and environmental impact. Progress in Energy 4 (3), 032010. doi.org/10.1088/2516-1083/ac7937
2. Brynolf S, Hansson J, Anderson JE, Skov IR, Wallington TJ, Grahn M, Korberg AD, Malmgren E, Taljegård M (2022). Review of electrofuel feasibility - Prospects for road, ocean, and air transport. Progress in Energy, 4 (4), 042007.
3. Rennuit-Mortensen, A. W., Rasmussen, K. D., Grahn, M. (2023). How replacing fossil fuels with electrofuels could influence the demand for renewable energy and land area. *Smart Energy*, *10*, 100107.
4. Kanchiralla, F. M., Brynolf, S., Olsson, T., Ellis, J., Hansson, J., & Grahn, M. (2023). How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study. *Applied Energy*, *350*, 121773.
5. Malmgren, E., Styhre, L., Van Der Holst, J., Brynolf, S. (2023). Navigating unchartered waters: Overcoming barriers to low-emission fuels in Swedish maritime cargo transport. Energy Research and Social Science. *Energy Research & Social Science 106*, 103321
6. de Oliveira Laurin M, Selvakkumaran S, Ahlgren E.O, Grahn M (2024). Are decarbonization strategies municipality-dependent? Generating rural road transport pathways through an iterative process in the Swedish landscape. *Energy Research & Social Science 114*: 103570.
7. Kanchiralla F M, Brynolf S, Mjelde A (2024). Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations, *Energy & Environmental Science 17*, 6393. DOI: 10.1039/d4ee01641f
8. Brynolf S, Grahn M (2024). Liquid fuels: Flexibility with low environmental impact. News and Views. *Nature Energy 9*, 1179–1180. https://doi.org/10.1038/s41560-024-01637-0.

Under production:

1. de Oliveira Laurin M, Aryanpur V, Farabi-Asl H, Grahn M, Taljegard M, Vilén K (2025?). Road transport decarbonization: A comparison between urban and non-urban municipalities applying a participatory approach. *Nature Scientific Report.* Under revision.
2. Löfving, J., Brynolf, S., Grahn, M. (2025?). Geospatial distribution of hydrogen demand and refueling infrastructure for long-haul trucks in Europe. *Submitted to Int J of Hydrogen Energy* Under revision. .
3. Kanchiralla F. M., Grunditz E., Brynolf S., Wikner E., and Nordelöf A. (2025?), Environmental and economic assessment of electric ferries with different lithium-ion battery technologies. *Submitted to Energy & Environmental Science* (2024-11-24).
4. Velandia Vargas JE, Brynolf S, Grahn M, Rodriguez JF, Blekhman D (2025?). Technically-oriented, Sweden-inspired LCA: Hydrogen for long-haul trucks. *In preparation*.
5. Kanchiralla F. M., Brynolf S., Hansson J., Grahn M. (2025?) Shipping Fuel Choices and Well-to-Wake Environmental Impacts from an Integrated Energy System and Life Cycle Assessment Model under Decarbonization Policies. *In preparation*.
6. de Oliveira Laurin M, Johansson O, Brynolf S, Grahn M et al (2025?). Scenarios for an energy port in transition – the future role of hydrocarbon energy carriers. *In preparation*.

7. Kanchiralla FM, Grahn M et al (2025?). Under what circumstances are hydrogen a cost-effective fuel choice for heavy and medium duty trucks:Results from the global energy transition GET model. *In preparation*.
8. Löfving J et al (2025?). Hydrogen demand in Europe – bottom-up, geospatially distributed scenarios for transportation and industry. *In preparation*.
9. He Y, Song J, Brynolf S, Grahn M (2025?). Decarbonising hard-to-abate sectors with renewables: A comparative techno-economic analysis of power-to-hydrogen and electro-fuels pathways. *In preparation*.
10. He Y, Brynolf S, Grahn M (2025?). Cost-comparison of different hydrogen carrier options produced world-wide for distribution to Sweden. *In preparation*.

The research topics

The first phase of the PhD project *"The future of hydrogen – societal challenges"* (PhD student Joel Löfving started 1 March 2023) includes the development of a model for hydrogen production and distribution infrastructure in Europe based on demand scenarios for shipping, aviation, road transport and industry. The model will consider centralized and decentralized production in Europe as well as in other locations outside Europe with potentially even lower cost of producing renewable electricity, hydrogen and electrofuels, however with higher cost for fuel distribution, see Figure 14. The European model (initially named H2-Infra, now named SVENG) is developed from scratch for hydrogen production and distribution infrastructure considers different future hydrogen demand scenarios at NUTS3 site-specific level, for industries and transport offtakers across all of Europe. The model considers cost, efficiency, small scale versus large scale hydrogen production, amount, and scale of tank stations/bunker terminals etc. Results from SVENG will be used to analyze cost-effective implementation of hydrogen in Europe, as well as geospatially distribution of hydrogen refuelling stations. In addition to this, it will also be used as input data to existing models such as the Global Energy Transition (GET) model and the European energy systems model MULTINODE. The MULTINODE model can also generate valuable input data to the SVENG model as e.g., future electricity price scenarios for European regions. This data can also be used to investigate the incentives for different countries to implement the Alternative Fuel Infrastructure Regulation (AFIR).

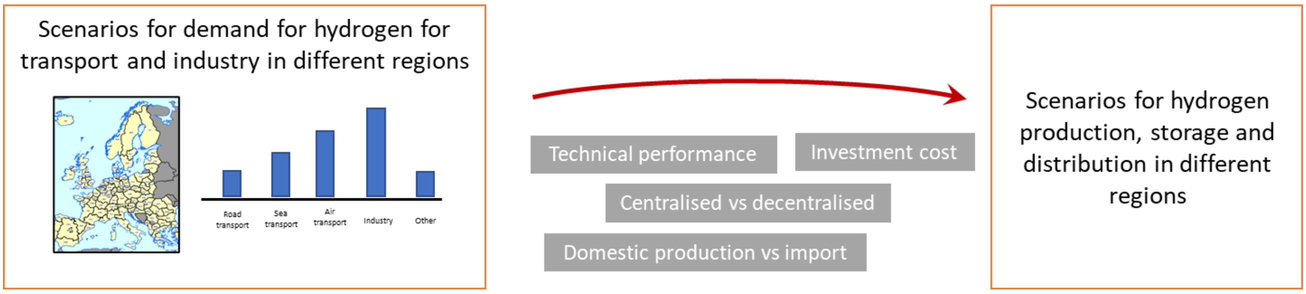


Figure 20: Overview of the main features that the developed European model SVENG considers.

The two postdocs, *Jorge Velandia and Hadi Farabi*, started their work in early autumn 2022. Below are summaries and status of Joel's, Jorge's and Hadi's ongoing work.

PhD student: Joel Löfving
Project: The future of hydrogen – societal challenges
Funder: Competence center TechForH2

Project summary and status: By the end of 2024, Joel has developed the SVENG model (see more above) and used it in two different studies. His licentiate exam is planned for 9 May 2025. In the first study, Joel uses the bottom-up, geographically detailed SVENG model for simulating energy demand from long-haul hydrogen trucks and determining locations and sizes of hydrogen refuelling stations (HRSs), across all of Europe under different scenarios in 2050. SVENG calculates weighted energy demand for network links, considering specific local conditions on each link along the route. These are used by a search algorithm for distributing demand along individual routes and simulate HRS locations and sizes. The model scales linearly, supporting large networks; for this study using 0.6 million rows of origin-destination cargo flow data on a network of 17,000 nodes. Joel shows that the model's novel functionality for calculating dynamic vehicle power requirements has a large impact on the distribution of fuel demand and required refuelling infrastructure. Results are compared to the Alternative Fuels Infrastructure Regulation (AFIR) for 2030, showing that AFIR may require too many HRSs in some countries unless vehicle sales increase rapidly. Other countries will need to deploy many times more capacity by 2050 even at lower rates of adoption. Figure 21 and Figure 22 are key figures from the manuscript.

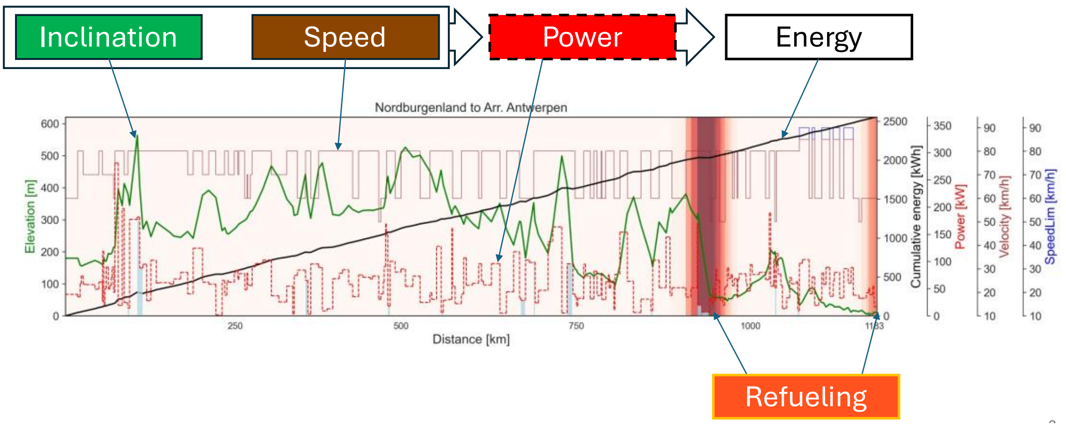


Figure 21: One simulated route. The x-axis represents distance driven along the route. Elevation (green) and velocity (brown) impacts power (red), which results in a total cumulative fuel demand (black). Where the power is accompanied by a light blue bar, the power needed (P_link) is negative and is utilized for regenerative braking, which in turn decreases the cumulative fuel demand. Refueling demand allocated to nodes along the route is depicted with vertical shaded areas. Speed limit (blue) is included to specify where the truck runs slower than the speed limit

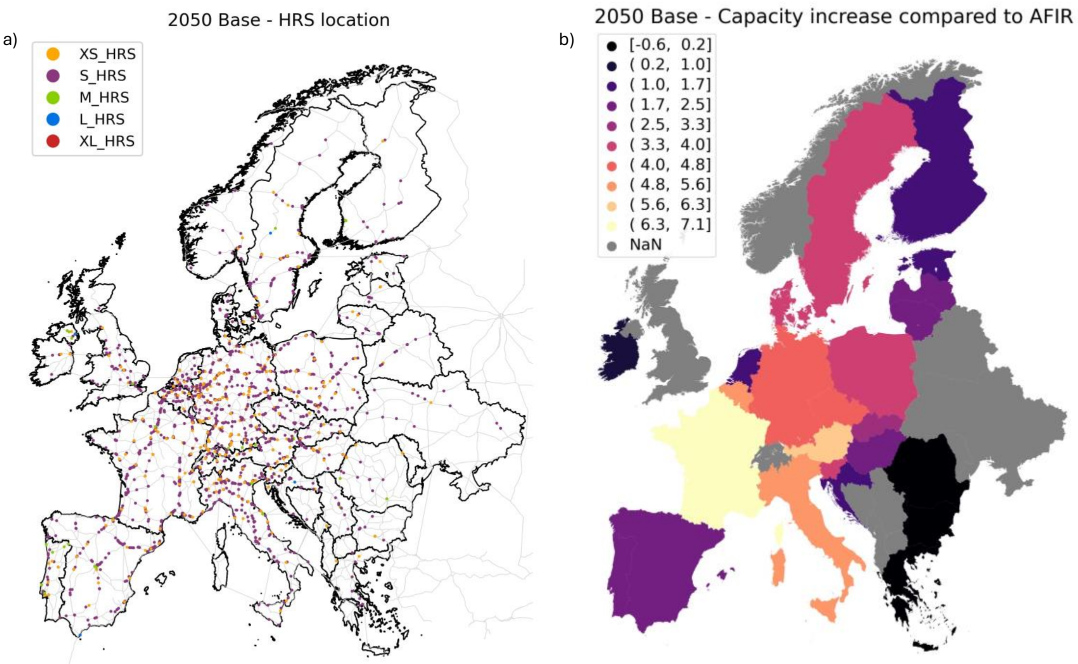


Figure 22: (a) Simulated location and size of discrete HRS, in Europe, and (b) additional HRSs needed until 2050, per country, compared to the numbers required by AFIR in 2030. Countries with grey Not a Number (NaN) values are not part of the EU and thus not covered by AFIR.

In Joel's second study, he broadens the scope to include all use of hydrogen demand including refuelling stations for road vehicles, hydrogen dispensing for ships and aircrafts in ports and airports, as well as hydrogen use for ammonia, steel, HVC, and renewable fuel production in the forms of biofuel and hydrocarbon based electrofuels for five scenarios: EU_policy_mix, Electrification focus, H2 focus, E-fuels focus, and Biofuels focus. Figure 23 shows the size, locations, and types of hydrogen use across Europe, in the scenario EU_policy_mix (a) and an example of a hydrogen supply chain optimization. The study will also analyze the impact the different scenarios may have on electricity prices, demand for land and freshwater.

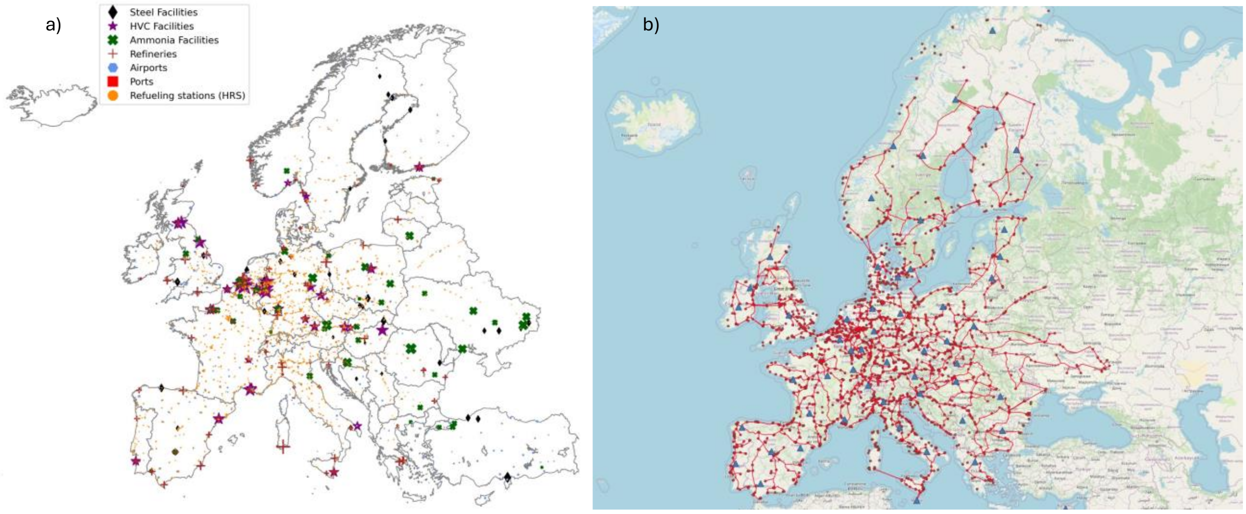


Figure 23: Early preliminary results on (a) geospatial hydrogen demand for 2050, and (b) hydrogen supply chain optimization.

Postdoc: Jorge Enrique Velandia Vargas
Project: Hydrogen in transport – Global, European, and Nordic perspectives
Funder: Chalmers Area of Advance Transport (Competence center TechForH2), and Swedish Energy Agency (FFI) project No 51458-1 "Reducering av emissioner från vätgasmotorer (HEER)
Partners: Chalmers University of Technology, Volvo Technology AB, Scania, Johnson Matthey

Project summary and status: The aim of this project is to quantify the environmental footprint of using green and blue hydrogen in fuel-cell trucks (FCT) and in internal combustion engine trucks (ICET), via life cycle assessment (LCA). As transport and distribution of hydrogen can potentially represent a significant share of the environmental burden, we evaluate both centralized and on-site production of hydrogen. The production on-site eliminates the need for transporting the hydrogen. In contrast, on-site production is not able to take advantage of the economies of scale of large centralized production facilities. In terms of data collection and computing time, it is usual practice to use LCA databases to model the so-called background processes. For the foreground processes, we build our own datasets for the trucks while for hydrogen production and transportation we appealed to the scientific literature. Figure 22 depicts the boundaries used in this study.

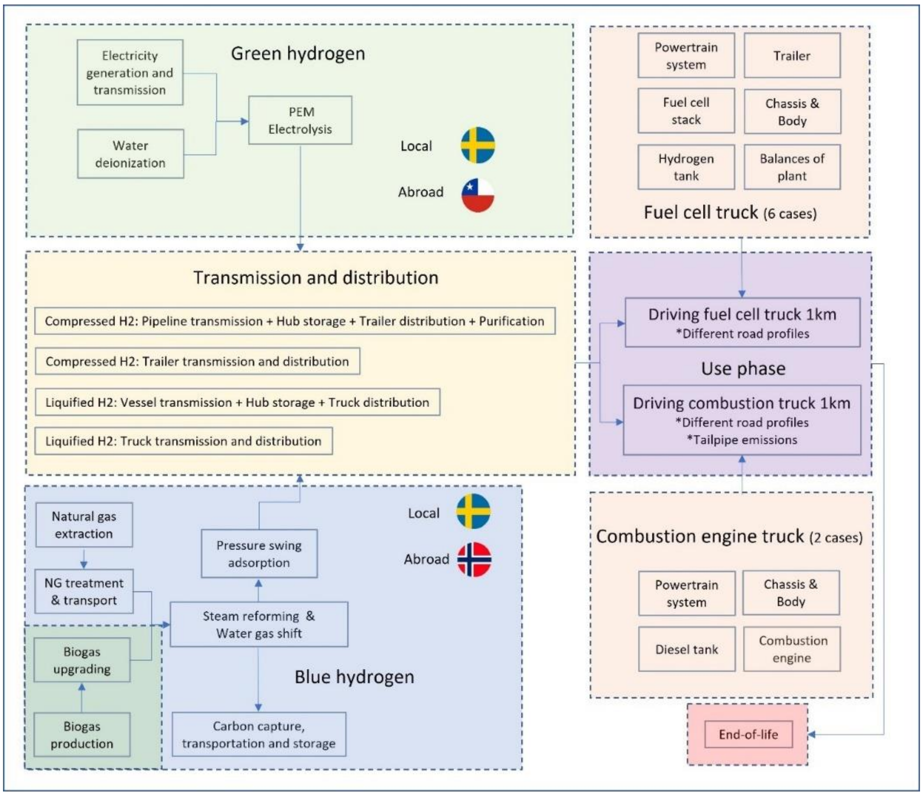


Figure 24: System boundaries hydrogen production, distribution and use in several combinations of pathways.

As of end of 2024, we have almost finished the study and is close to submit the manuscript to a high-ranked scientific journal. The partnerships have allowed us to obtain more accurate data, improving our model and decreasing uncertainties. Preliminary results on total LCA emissions in kg CO_{2eq} per ton-kilometer, based on a fully loaded 40-ton truck, are shown in Figure 25. The lowest carbon footprint is obtained in the cases where biomethane is used for the production of hydrogen and the released carbon is captured and permanently stored underground. If carbon is indeed captured and stored underground during steam reforming process, the entire production of hydrogen has potential to result in a net removal of carbon from the atmosphere.

Apart from the bio-based options, the lowest carbon footprint can be seen for the three options (1) Scenario B where hydrogen is large scale produced in central plants, and powered by green electricity, then liquefied and, distributed in trailers for 150 km, and used in fuel cell trucks having a stainless steel tank for liquid hydrogen, (2) Scenario “on-site” where hydrogen is produced from green electricity, at the refueling station, and used in fuel cell trucks having a 350 bar tank of carbon fibers, and (3) the same as (2) but a 700 bar storage tank also of carbon fibers. All three options at a total carbon footprint of around 0,01 $kgCO_{2eq}$ per tonkm. The highest carbon footprint is seen from all options assessing blue hydrogen around 0,03 $kgCO_{2eq}$ per tonkm. Slightly higher for the internal combustion engines compared to fuel cells, and slightly lower for the options assuming steel tank compared to a tank of carbon fiber.

A: Trailer-gas 1100 kg (500 bar) 150 km
B: Trailer-liquid 4300 kg (-253oC) 150 km
C: Pipeline-gas (70 bar) 150 km
D: Vessel run on biodiesel (-253oC) 14,600 km

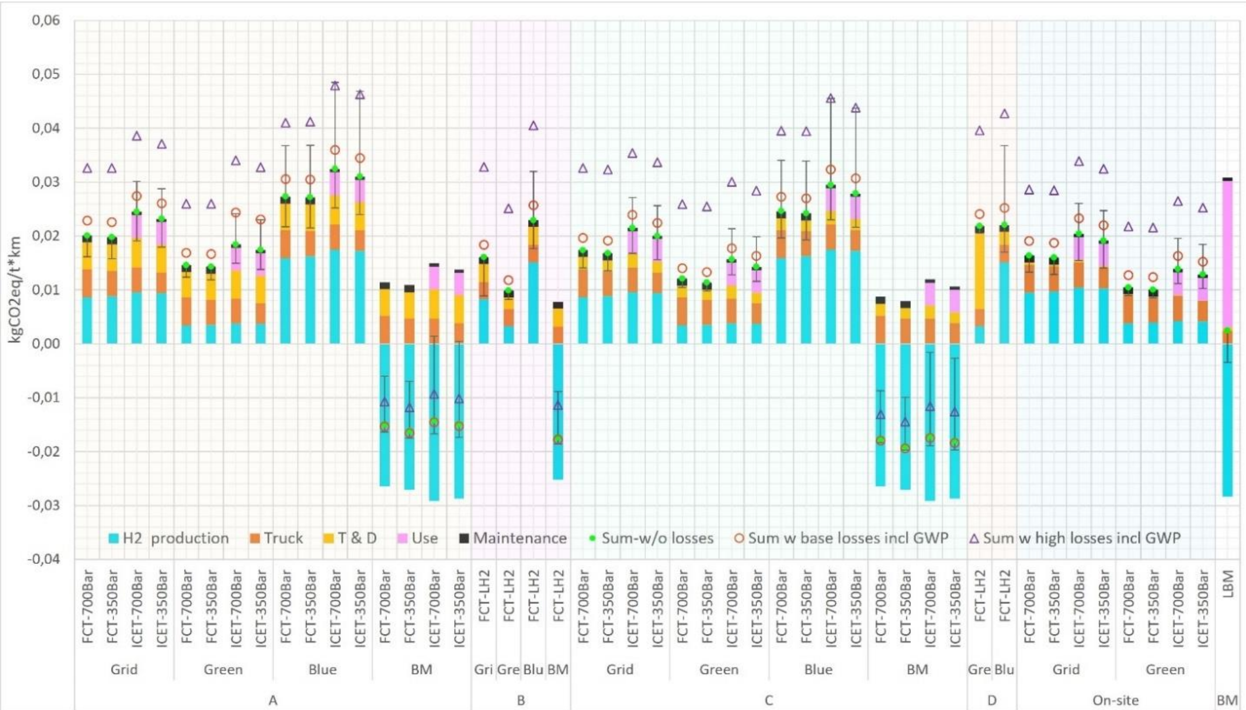


Figure 25 Life cycle impacts (GWP100) for transportation pathways and truck configurations, in kg CO2eq per ton*km, based on a fully loaded 40 ton truck. All presented FCTs correspond to a 200 kW fuel cell combined with a 40 kWh battery. For the liquefied biomethane (LBM) case included for comparison H2 production refers to biomethane production. Bars represent the cases included in the sensitivity analysis and were not added to the leakages. The estimated impact of hydrogen leakages for low and high estimations are calculated with respect to the initial sum of impacts without any leakages (green circle), low estimations consider a GWP100 of 8.8 while for high estimations it is 14.4. For on-site production the small contribution of Transport and Distribution (T&D) refers to compression at the hydrogen refueling station

Postdoc: Hadi Farabi
Project: Systems assessment of hydrogen and electrofuels in transports.
Funder: Chalmers Genie and European Union Interreg Baltic Sea Region program. Project title: Developing a transnational network of hydrogen refuelling stations for trucks (HyTruck). Grant number: C031. Coordinator: Ministry of Economics, Infrastructure, Tourism and Labour Mecklenburg-Vorpommern, Germany.
Partners: Chalmers University of Technology, and IVL Svenska Miljöinstitutet AB

Project summary and status: The aim of this project is twofold. (1) to assess the sustainability of different global policy instruments for reducing greenhouse gas emissions from shipping and their potential impact on cost-effective fuels and propulsion choices up to 2050, and (2) assess technoeconomic aspects of hydrogen refueling stations, for trucks, in the Baltic Sea region. A literature review of various policy instruments, potentially possible for the shipping sector has been carried out. In a next step, we assessed a selection of policy instruments considered interesting for the global shipping sector using global energy systems modeling. We have analyzed the impact of the selected policies on carbon budget, carbon prices, and cost-effective fuel and propulsion technology using the global energy transition (GET) model. GET is a cost-minimizing "bottom-up" systems engineering model of the global energy system set up as a linear programming problem in time steps of 10 years to minimize the discounted total energy system cost for the period under study while meeting both a specified energy demand and a carbon constraint.

Preliminary results for the ten different policy cases assessed are, e.g., that comparing Cases A (a global emission trading system covering several sectors without specific targets for shipping) and D (a moderate global marine carbon levy) shows that applying a carbon levy facilitates the introduction of hydrogen and earlier phase-out of heavy fuel oil. In 2050, the contribution of hydrogen in meeting shipping energy demand is 4% in Case A and 35% in Case D. A higher carbon levy (Case E) results in 65% hydrogen in the global fuel mix by 2050. Applying the marine ETS policy (Case B) resulted in meeting 55% of shipping energy demand by hydrogen by 2050. Implementing the fuel quota limitation (Case H) changes this value to 21% and also the share of bio- and electrofuels increased. The main insights so far include that for all scenarios analysed, the increase in total system cost (for the whole energy system, not just the shipping sector) is in the range of 0.4%-0.8%. Hadi has presented these results on the 12th Annual Swedish Transport Research Conference, STRC 2023, at KTH, Stockholm.

Regarding the work related to hydrogen refueling stations for trucks, Hadi has developed a model, in TRNSYS (Transient System Simulation), for the techno-economic assessment. TRNSYS is a flexible, graphically based software environment used for simulating the behavior of transient energy systems. It is widely utilized in the field of energy systems to model and analyze the performance of various thermal and electrical energy systems. The primary objective, in this study, was to estimate the cost of producing green hydrogen from electrolysis powered by solar or wind. The four different hydrogen production systems are shown in Figure 26.

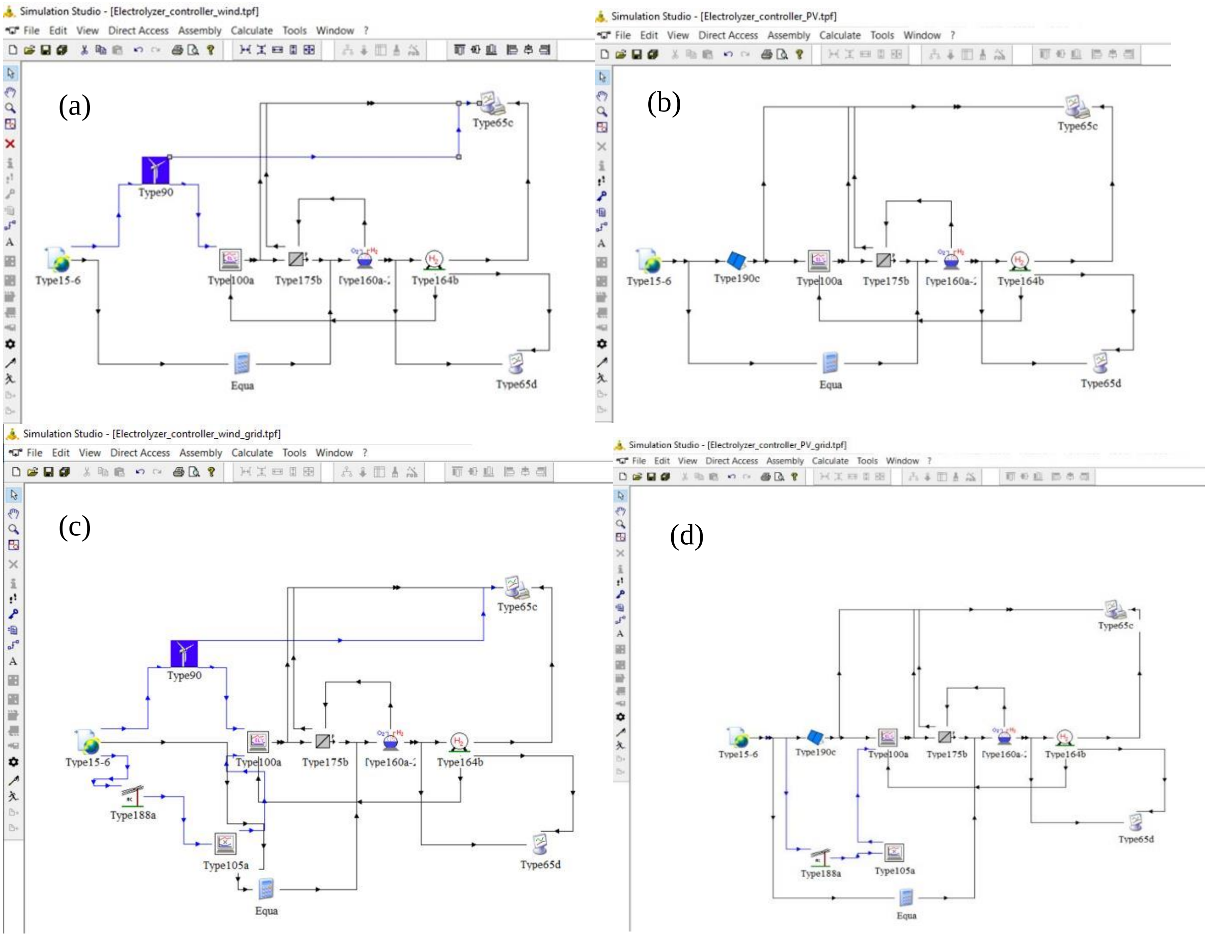


Figure 26: Hydrogen production cases in TRNSYS: (a) stand-alone wind, (b) stand-alone solar PV, (c) hybrid wind+grid, and (d) hybrid PV+grid.

In the hybrid cases, the electricity from the grid were used in the absence of power generation from the renewable source. Figure Y shows results on hydrogen production cost (€/kg) for grid-connected options for six selected countries with pilot regions in the HyTruck project, including Germany, Poland, Lithuania, Latvia, Estonia and Finland. The total cost is divided into three main parts of OPEX, CAPEX and Taxes. Results for the six countries show a hydrogen production cost for the stand-alone systems, in a range of 8-10 €/kg for PV and 6-8 €/kg for wind. The calculated cost is slightly higher in Germany. However, the cost does not vary significantly. In the stand-alone cases, CAPEX has a significant share in the total cost of the hydrogen production. In the grid-connected case, the cost of producing hydrogen shows a range of 4-11 €/kg. The production cost in Germany and Poland is higher than in other countries. The lowest cost is associated with Finland. CAPEX is similar between the countries and the driver of cost differences is OPEX and Tax categories, see Figure 27

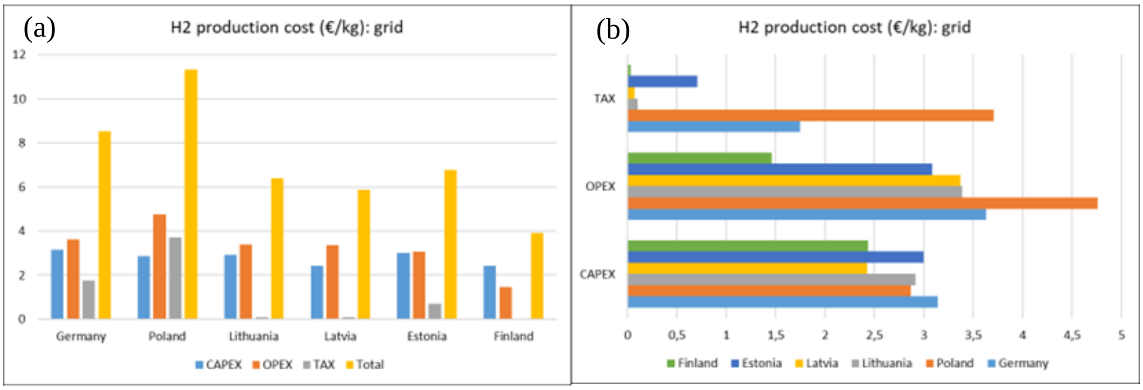


Figure 27: **Hydrogen production cost** for the **grid-connected** case (a) **by country and (b) by cost category.**

In grid-connected pathways, the cost variation between countries was higher compared to standalone systems, highlighting the impact of electricity prices.

Hadi is since November 2024 employed at RISE and the plan is that he will continue the work from there and submit a paper on this study.

DISSEMINATION AND COMMUNICATIONS EFFORT

Research publications achievements

For detailed publication achievements and plans see the presentations of the five multidisciplinary research areas above.

Public/popular science activities

The center tries to increase its visibility by becoming active in a wide range of public/popular science activities.

Output from the center has been publicly shared in the following events:

- Green Fly Way, Tomas Grönstedt, WP3 – focus area solar cells and hydrogen, 2022-04-13 [47].
- UK – Sweden Aerospace workshop, Tomas Grönstedt – 2022-05-16
- Energigas, Tomas Grönstedt, Interview, NR3, 2022-09-26 [48].
- Maria Grahn was invited as key-note speaker and panelist at Port of Ystad conference: "The goal is delivering sustainable fossil free transports". She presented the TechForH2 center and hydrogen related research results (2022-10-05).
- Maria Grahn was giving a speech at the maritime industrial network day arranged by Svensk Sjöfart in Helsinki, Finland. Maria presented the TechForH2 center and hydrogen related research results focusing on hydrogen as a marine fuel (2022-09-01)
- Maria Grahn was invited as plenary speaker at the International Workshop of the BEST project in Brussels. She presented the TechForH2 center and hydrogen related research results (2022-09-09)
- Maria Grahn was co-authoring a debate article, published in Göteborgsposten 2022-10-18 "Reduktionsplikten måste utvecklas – inte försämras" https://www.gp.se/debatt/reduktionsplikten-m%C3%A5ste-utvecklas-inte-f%C3%B6rs%C3%A4mras-1.82975045
- Vätgas Sverige – Seminar, Tomas Grönstedt – Ny flyger vätgas – 2022-10-26
- Yu Cao gave a speech on "Protection of austenitic stainless steel from hydrogen embrittlement by a surface engineering approach" was given in the 4th Swedish hydrogen seminar organized by Jernkontoret on 27th October 2022.
- Chalmers press release, 2022-12-01 [49].
- Chalmers press release on sensor research, 2022-12-01 [50]
- Selma Brynolf was invited as a panelist at "SamspEL Arena: Framtidens elbehov.". Selma presented the TechForH2 center and hydrogen related research at Chalmers (2022-12-08).
- P4 Göteborg, Maria Grahn, Interview – NYTT VÄTGASCENTRUM, 2022-12-10 [51]
- Maria Grahn was giving a speech at a meeting with Stena Teknik. She presented an overview of research topics carried out at Chalmers Team Brynolf& Grahn including the TechForH2 center (2022-12-12), (3)
- Maria Grahn was giving a speech at the industrial network day "f3 Innovationskluster för hållbara biodrivmedel", in Lund. She presented the TechForH2 center and hydrogen related research results (2023-02-01).
- Maria Grahn was interviewed by Tomas Augustsson at the newspaper Svenska Dagbladet about e-fuels. The article was published 24 Feb 2023 titled "Porsche och SAS satsar på e-bränsle", available here: https://www.svd.se/a/vendAl/e-bransle-kan-ersatta-fossilt-i-porsches-bilar-och-i-sas-plan
- Tomas Grönstedt gave a speech for industrirådet at Chalmers on the 2023-03-15 presenting TechForH2.
- Maria Grahn was interviewed in Swedish national radio P1, StudioEtt Vetenskapsradion Nyhetsfördjupning, about Germany's late reaction on banning combustion engines and the future role of hydrogen and e-fuels, 2023-03-17.
- Tomas Grönstedt gave a speech at flygtekniska föreningen, meeting 2023-04-30 med titeln "Vätgasteknik för framtida flygplan"
- Tomas Grönstedt gave a speech on "Hydrogen aircraft Technologies" at the SARC seminar series on the 17th of August 2023.

- Tomas Grönstedt gave a speech presenting the center on Jernkontorets meeting 2023-10-17
- Maria Grahn was interviewed by Mikael Törnwall from the newspaper Svenska Dagbladet 23 Oct 2023, about fossil free aviation.
- Tomas Grönstedt gave a speech for the EU-project HYTRUCK on 2023-11-03 presenting the TechForH2 research center.
- **"We shall not be afraid of taking risks"**, News article 30 Nov 2023 16:00 https://www.chalmers.se/en/current/news/m2-we-shall-not-be-afraid-of-taking-risks/
- Maria Grahn was interviewed by Carl Johan Liljegren about e-fuels, the article titled "Gryende marknad för elektrobränslen" was published in the magazine Tidningen Energi, 13 Nov 2023, available here: https://www.energi.se/artiklar/2023/november-2023/gryende-marknad-for-elektrobranslen/
- In National TV, SVT's Morgonstudion, Maria Grahn commented on the first flight across the Atlantic using only renewable aviation fuel, https://www.svtplay.se/video/jawzJNE/morgonstudion/idag-06-00?id=jawzJNE&position=660&highlight=london-new-york-med-100-procent-fornybart-flygbransle-forsta-fornybara-flygningen-over-atlanten-660. 2023-11-28
- Maria Grahn was invited as keynote speaker at the Biogas Solutions Research Center (BSRC) winter conference 7-8 of December 2023 in Linköping Konsert & Kongress. She presented TechForH2 and a selection of hydrogen-related research results.

- **Volvo Group invests in hydrogen research through PhD student at TechForH2** News article 15 Jan 2024 11:40, https://www.chalmers.se/en/current/news/volvo-group-invests-in-hydrogen-research-through-phd-student-at-techforh2/
- David Sedarsky and Tomas Grönstedt presented TechForH2 activities for AlfaLaval to screen for potential collaboration activities, 2024-01-16.
- Maria Grahn was interviewed by the newspaper Dagens Nyheter Ekonomi, about future aviation fuels, GKN and Trollhättan. The article was titled ”Okända flygsuccén – så gick Trollhättan vidare efter Saab”, available here: “https://www.dn.se/ekonomi/okanda-flygsuccen-sa-gick-trollhattan-vidare-efter-saab/, 2024-02-05
- *Results by Fayas Kanchiralla, Selma Brynolf and co-workers were published by several news-sites as a result of a press-release, for example in*
  - *Captain with the title: "Ammonia Marine Fuel Switch May Cause New Environmental Issues, Warns Study", available here: https://gcaptain.com/ammonia-marine-fuel-switch-may-cause-new-environmental-issues-warns-study/, 2024-02-05*
  - *TechXplore with the title "Ammonia attracts the shipping industry, but researchers warn of its risks", available here: https://techxplore.com/news/2024-02-ammonia-shipping-industry.html,*
  - *Extrakt with the title "Forskarna varnar sjöfarten för övergång till ammoniak", available here: https://www.extrakt.se/forskarna-varnar-sjofarten-for-overgang-till-ammoniak/?utm_campaign=unspecified&utm_content=unspecified&utm_medium=email&utm_source=apsis, 2024-02-09*
- *Selma Brynolf was interviewed in Swedish national radio P1, Vetenskapsradion, about future fuels for the shipping sector, available here: https://sverigesradio.se/avsnitt/2322460*, 2024-02-07
- Maria Grahn was interviewed by Anna-Karin Ivarsson at the Swedish national radio P1 Vetenskapsradion Klotet, about the hydrogen buses in Sandviken and the hydrogen refueling station in Borlänge, 2024-02-09
- **Future Nordic aviation needs could be met by hydrogen,** News article 12 Mar 2024 09:10 https://www.chalmers.se/en/current/news/future-nordic-aviation-needs-could-be-met-by-hydrogen/
- Christian Svensson popularly shared output from his research on 2024-03-12

  - https://aktuellenergi.se/framtidens-nordiska-flygbehov-kan-motas-av-vatgas/
- Christian Svensson presented at the SHDC/TechForH2 co-arranged event (Vätgasflyg), 2024-04-10
- Tomas Grönstedt presented at the SHDC/TechForH2 co-arranged event (Vätgasflyg), 2024-04-10
- Anders Lundbladh presented (GKN) at the SHDC/TechForH2 co-arranged event (Vätgasflyg), 2024-04-10
- Andreas Boden (PowerCell) presented at the SHDC/TechForH2 co-arranged event (Vätgasflyg), 2024-04-10
- The center was presented at FTF, FlygTekniska Föreningen, Trollhättan, 2024-04-30
- **Safe hydrogen sensors the result of center collaboration,** News article 20 May 2024 13:20 https://www.chalmers.se/en/current/news/safe-hydrogen-sensors-the-result-of-center-collaboration/
- **Promising results for heat exchangers on hydrogen aircraft,** News article 30 May 2024 10:40 https://www.chalmers.se/en/current/news/m2-promising-results-for-heat-exchangers-on-hydrogen-aircraft/
- Tomas Grönstedt presented the TechForH2 cryogenics at an internal meeting at Scania 22th of May 2024.
- TechForH2 co-arranged the 30th May, Academic road trip, where Maria Grahn spoke on Hydrogen for future heavy-duty transport: Environmental performance and cost-competitiveness
- TechForH2 co-arranged the 30th May, Academic road trip, where Tomas Grönstedt spoke on Hydrogen for aviation
- **Hydrogen flight looks ready for take-off with new advances,** News article 11 Jul 2024 07:00 https://www.chalmers.se/en/current/news/hydrogen-flight-looks-ready-for-take-off-with-new-advances,c4011533/
- Maria Grahn was invited as speaker on the annual network conference, arranged by Hydrogen Sweden. She presented TechForH2 and a selection of ongoing hydrogen-related research projects (15 Oct 2024).
- Maria Grahn gave a key-note speech at the EUSBSR Annual Forum, session "Chicken & egg: Ramping-up of Hydrogen Refuelling Stations in the Baltic Sea Region"in Visby, Gotland (31 Oct 2024).
- Tomas Grönstedt presented the TechForH2 center at the Purdue (USA) Aviation Symposium, Nov. 13th, 2024.
- Tomas Grönstedt presented the TechForH2 cryogenics ambitions at a workshop in Florianopolis Brazil, Nov. 19th, 2024.
- Joel Löfving presented his research at Volvo Group 3rd of Feb 2025. The main aim of the workshop was to discuss how Volvo could contribute with more accurate input data regarding truck routes in Europe.

Web-based sharing:
- The https://www.chalmers.se/en/centres/techforh2/ home page is now up and running. It was launched already 2022 but now both the center director and the center communicator are regularly updating it.
- A linked-in channel has been launched: https://www.linkedin.com/company/101635746/admin/feed/posts/
  - At the time of writing we have over 300 followers. We actively post news from the center

To boost broader community visibility and demonstrate TechForH2's commitment to our vision, the center has produced a movie illustrating how we aim to work synergistically across a number of heavy transport solution areas. We plan to use it for LinkedIn, and show it at exhibitions and conferences, as a part of our general presentations and broader communities. The vehicle lineup in Figure 28 shows a snapshot from the movie. We plan to use it for linked in as well as other broader communities that have an interest in hydrogen.

Figure 28: Lineup of heavy transport hydrogen vehicles (snapshot of movie). Movie available at https://www.youtube.com/watch?v=oZbUwgvBoJc

In addition, TechForH2 has participated at internal meetings with a wider scope than the normal TechForH2 participants at Scania, Volvo, Goteborgs Energi and ABB and Johnson Matthey. This is intended to provide improved and detailed information about center activities at the companies. Recently, the H2society ambition was awarded funding for a pre-study.

The center has also committed to participate in the SHDC [52] as decided by the board on 2023-12-01. SHDC is a forum for hydrogen professionals addressing industrial needs and development. It is coordinated by RISE aiming to link industry innovation and research in the area of hydrogen development. Its scope is obviously broader than the current scope of TechForH2, but it is seen as an excellent platform to disseminate material and run activities through. See listing above on joint SHDC TechforH2 activities both 10th of April 2024 and 30th of May 2024.

To increase the center visibility TechForH2 has adopted an official acknowledgement for research output:

The Competence Centre for TechForH2 is hosted by Chalmers University of Technology and is financially supported by the Swedish Energy Agency (Project No. 52675-1) and the member companies Volvo, Scania, Siemens Energy, GKN Aerospace, PowerCell, Oxeon, RISE, Stena Rederi, Johnson Matthey, Insplorion and MannTek.

PhD student cross-collaboration initiative

A workshop was developed and held in Göteborg, 2024-01-23 in conjunction with company visits. Study visit at PowerCell and SEEL/Rise. Volvo was also planned but was cancelled due to the weather (snow). Workshop was held in the afternoon + dinner. Cross collaboration papers between research areas were planned by the students themselves under supervision discussions. Interpersonal contacts at the companies were developed.

TechForH2 co-arranging vätgaskonferensen

TechForH2 was part of the 2024 vätgaskonferensen planning and arranging committee. Apart from contributing to planning and arranging the program, TechForH2 also promoted the program at Chalmers. The Center had 5 speakers

- Tomas Grönstedt, Maria Grahn, Erika Tuneskog, David Nilebo (Insplorion), Andreas Bodén (PowerCell, frequently invited speaker to this conference), Simon Taylor (GKN, invited speaker through TechForH2).
- TechForH2s initiative led to that Chalmers for the first time contributed with the largest number of poster proposals of all universities in Sweden
- We developed a hydrogen aircraft mockup, it can be seen in the left corner of the photo in Figure 29, showcased the Insplorion hydrogen sensor, a TechForH2 backdrop and TechForH2 branded ice scrapers.

To develop a broader interest for the center we also contributed at the Exhibition.

Figure 29: TechForH2 contributing to Vätgaskonferensen exhibit

TechForH2 research seminars

To create knowledge exchange and boost interest in research questions TechForH2 has been running an internal seminar series. This is now done in collaboration with the LTU initiative CH2ESS and we try to allocate two to three 20-30 minute presentations with a generous amount of time for questions and discussions.

- 2025-02-10, 2024-12-16 (Christian Svensson Licentiate), 2024-11-04, 2024-09-23, 2024-09-23, 2024-06-17, 2024-04-08, 2024-02-05, 2023-12-18.

International network

A number of invited lectures have so far been conducted:

- Professor Bernard Dam (TU Delft), Collaboration with international network, invited talk, first annual meeting, 1st December, 2022.
- Professor Arvind Gangoli Rao (TU Delft), Hydrogen for hard to abate sectors, second half-annual meeting, Finspång, 2022-05-25
- A collaborative visit was spent in Cranfield University in February 2023 to discuss future collaborative projects. Collaborative presentations were given by Tomas Grönstedt and Vishal Sethi (International network, Cranfield) on past and future opportunities for hydrogen collaborations.
- Dr. Soraia Pimenta (Imperial College), Research activities at Imperial Collage and TechForH2 collaborative plans, second annual conference, 2023-11-27
  - Ioannis Katsivalis, research visit during autumn/winter 2023

- Professor David Blekhman, US Hydrogen Hubs and Hydrogen Workforce Training at California State University, second annual conference, 2023-11-27
- Joel Löfving made a research visit during 2024 and spent a week at David Blekhams group in 2024 California State University
- Joel Löfving plans a 6-month stay in California to work with Professor David Blekhman at California State University and at ITS Transportation Studies at UC Davis. TechForH2 pays Joels Löfvings salary (being a TechForH2 Ph.D. student) and has a granted additional support funding for the task.
- Juan Parajo (post doc) Participant in 2nd annual conference from Professor Luis Varela group
- Bobby Sethi, (International network, Cranfield University) gave a talk on challenges and opportunities for Hydrogen technology at the SHDC/TechForH2 co-arranged conference on the 10th of April 2024

Chalmers press release on hydrogen activities

On the 11th of July 2024 Chalmers University made a press release about potential game changers technology that can happen in the Hydrogen area including a mention of TechForH2 [53]. The press release was very successful and rendered in:

- 154 news articles. For instance:
    - Newsweek, USA [3]
    - MSN, USA [54]
    - Aftonbladet [55]
    - Artificially aware, Youtube (USA) [56]
    - Ny Teknik [57]
    - Net Ease (China), Oricon News (Japan), Mundo Deportivo (Spain),
- 542 million potential readers (according to Meltwater statistics database)

The same article that was singled out by Newsweek [4], main authorship by TechForH2 post doc Alexandre Capitao-Patrao, was lifted as IVAs 2024 Technology Advancements reports [58], for which only around 10 technical studies are singled out every year as noteworthy technical achievements in Sweden.

GOALS VISION AND THE CENTER DEVELOPMENT

Vision, strategy and goals

The TechForH2 vision is:

TechForH2 continues to contribute to the decarbonization of the energy and transport system by pursuing new innovations, stimulating enterprise sector investment and expands collaboration with the highly trained researchers and the engineers that continue to develop the hydrogen economy.

To accomplish this vision the center has a number of strategic commitments in the different research disciplines. These are:

- **Materials:** to create tailored, optimized, and sustainable material solutions to implement hydrogen propulsion across the transportation modes.
- **Production:** develop and experimentally verify novel manufacturing and product solutions for hydrogen use, required for manufacturability in terms of materials, geometrical capabilities, and product performance.
- **Cryo- and heat management:** to design and experimentally verify synergies between the cryogenic hydrogen storage and the fuel system and enable the use of cryogenic hydrogen across a number of transport modes.
- **Vehicle level research ambition:** to develop models and methods to understand, optimize and experimentally validate the impact of design choices and predict top-level vehicle performance for hydrogen propelled vehicles.
- **Transport & society research ambition:** to relate activities in TechForH2 with how to best introduce hydrogen and transit to a hydrogen economy by interacting and modelling larger societal activities including policies and regulation.
- **Safety & sensors:** to explore new classes of materials and develop their nanofabrication for hydrogen sensors with ultrawide dynamic range.

Strategic activities that are on a short list to support the above-mentioned technical ambitions are.

- Develop a visiting researchers' strategy through the international research collaboration network, preferably to further gender balance. Support mobility activities through Ph.D. students, post docs and senior researchers.

Strategic gender activities commitment:

TechForH2 is involved in a number of activities intended to advance gender balance, inclusion, and diversity:

- Genie will review the center's annual reports from a gender perspective.
- Initiate a dialogue with Genie (Chalmers Gender Initiative for Excellence) supporting the board and the director with advice on gender matters.
- The board, research leaders and key personnel will be offered a basic gender perspective course. This course is part of a sequence of courses being developed through the Genie initiative.
- TechForH2 may collaborate financially with Genie or independently take initiatives to stimulate mobility for female key researchers associated with the center.

The first two bullets have been achieved/will be achieved. There have been some delays due to that the Genie organization has been partly changed with new staffing between 2022/2023. This has been addressed by having a targeted education by Karin Matson (letstango) that will be held on the mid year board meeting in Södertälje, that is 2024-05-22 and with a follow up workshop with the Ph.D. students of the center.

The last bullet is still open, but could be managed by a joint student exchange that is now supported by the new funding form of TechForh2 (open activity).

Since the recruitment of Ph.D. students has been completed gender statistics can be accumulated and has been done so during 2023. Out of the total 503 applicants for the position 123 candidates where female, that is the center had a search frequency of around 20%. The center has hired 40% female researchers which must be viewed as very successful.

Tomas Grönstedt (director) has followed the seven full day course on Inclusive and Outstanding Research Environment resulting from a rector initiative to pursue inclusion policy and psychological safety.

Selected strategic commitments for 2025:

- Continue to develop the KPI-management plan
- Increase focus on international activities

References

[1] D. Tomeček, H. K. Moberg, S. Nilsson, A. Theodoridis, I. Darmadi, D. Midtvedt, G. Volpe, O. Andersson and C. Langhammer, "Neural network enabled nanoplasmonic hydrogen sensors with 100 ppm limit of detection in humid air," *Nature Communications,* vol. 15, 2024.

[2] S. Brynolf and M. Grahn, "Liquid fuels: Flexibility with low environmental impact. News and Views," *Nature Energy,* vol. 9, p. 1179–1180, 2024.

[3] S. McDonagh, "Newsweek," 26 July 2024. [Online]. Available: https://www.newsweek.com/fossil-fuel-free-flights-hydrogen-power-air-travel-1924613. [Accessed 16 February 2025].

[4] A. Capitao-Patrao, I. Johnsson, X. C., A. Lundbladh and G. T., "Compact heat exchangers for hydrogen-fueled aero engine intercooling and recuperation," *Applied Thermal Engineering,* vol. 243, 2024.

[5] I. Katsivalis, M. Persson, M. Johanssen, F. Moreau, E. Kullgren, M. Norrby, D. Zenkert, P. S. and L. E. Asp, "Strength analysis and failure prediction of thin tow-based discontinuous composites," *Composites Science and TechChology,,* vol. 245, 2024.

[6] I. Kativalis, F. Signorini, F. Ohlsson, M. Minelli and L. E. Asp, "Hydrogen diffusion through thin-ply composites," in *Proceedings of 11th International Conference on Composite Testing and Model Identification,* Girona, Spain, 2023.

[7] I. Katsivalis, M. Norrby, F. Moreau, E. Kullgren, S. Pimenta, D. Zenkert and L. E. Asp, "Fatigue performance and damage characterisation of ultra-thin tow-based discontinuous tape composites.," *Composites Part B: Engineering,* no. 111553., p. 281, 2024.

[8] I. Katsivalis, M. Signorini, F. Ohlsson, C. Langhammer, M. Minelli and L. E. Asp, "Hydrogen permeability of thin-ply composites after mechanical loading," *Composites Part A: Applied Science and Manufacturing,* vol. 176, 2024.

[9] A. Capitao-Patrao, I. Jonsson, X. C., A. Lundbladh, L. M. and G. T., "The heat transfer potential of compressor vanes on a hydrogen fueled turbofan engine," *Applied Thermal Engineering,* vol. 237, 2024.

[10] A. C. Capitao-Patrao, I. Jonsson and C. Xisto, "Compact Heat Exchangers with Curved Fins for Hydrogen Turbofan Intercooling,," *Journal of Engineering for Gas Turbines and Power,* vol. 146, no. 11, 2024.

[11] L. Gulfo, O. H. Nilsson, J. Sjöberg, I. Katsivalis, L. E. Asp and M. Fagerström, "A 3D voxel-based mesostructure generator for finite element modelling of tow-based discontinuous composites.," *Composites Part B: Engineering,,* vol. 278, 2024.

[12] C. Svensson, A. Oliveira and T. Grönstedt, "Hydrogen fuel cell aircraft for the Nordic market," *International Journal of Hydrogen energy,* vol. 61, pp. 650-663, 2024.

[13] C. P. M. a. T. G. Svensson, "Modelling Hydrogen Fuel Cell Aircraft in SUAVE," in *34th International Coundilc of the Auronautical Sciences*, Florence, Italy, 2024., ICAS Proceedings.

[14] C. Svensson, "Hydrogen Fuel Cell Aircraft for Regional Travel," Chalmers University of Technology, Göteborg, 2024.

[15] M. S. Loukil, J. Xu, E. Marklund, M. Merzkirch, F. Moreau and F. Ohlsson, "THERMAL AND MECHANICAL CYCLING OF THIN-PLY COMPOSITES FOR CRYOGENIC APPLICATIONS," in *34th Congress of the International Council of the Aeronautical Sciences, ICAS*, Florence, 2024 .

[16] R. Olsson, E. Marklund, M. Merzkirch and D. Ramantani, "Characterization of a filament wound thin-ply composite for a cryogenic tank for liquid hydrogen," in *11th International Conference on Composites Testing and Model Identification*, Girona, Italy, 2023.

[17] R. Olsson, C. Cameron, F. Moreau, E. Marklund, M. Merzkirch and J. Pettersson, "Design, Manufacture, and Cryogenic Testing of a Linerless Composite Tank for Liquid Hydrogen.," *Applied Composite Materials,* vol. 31, pp. 1131-1154, 2024.

[18] K. Dahal, S. Brynolf, C. H. J. Xisto, M. Grahn, T. Grönstedt and M. Lehtveer, "Techno-economic review of alternative fuels and propulsion systems for the aviation sector.," *Renewable and Sustainable Energy Reviews,* vol. 151, 2021.

[19] Pacelab Suite, "PACE," 20 02 2023. [Online]. Available: https://pace.txtgroup.com/products/preliminary-design/pacelab-suite/.

[20] E. Botero, C. M., R. Erhard, J. Smart and J. J. Alonso, "Aerodynamic Verification and Validation of SUAVE," in *AIAA SciTechForum*, San Diego, 2022.

[21] K. a. J. C. Amadori, "Towards Zero-Emission Transportation in Scandinavia," in *AIAA SciTech Forum*, 2023, 2023.

[22] C. Jouannet, T. Grönstedt, X. Zhao, P. Krus, A. Lundbladh and B. Nagel, "Sustainable Aviation for Sweden - Technology & Capability Asssessment Targeting 2045,," in *ICAS*, Stockholm, 2022.

[23] V. Sethi, X. Sun, D. Nalianda, A. Rolt, P. Holborn, C. Wijesinghe, C. Xisto, T. Grönstedt, J. Jonsson, A. Lundbladh, A. Isekverken, I. Williamson, T. Harrison and A. Yenokyan, "Enabling Cryogenic Hydrogen-Based CO2-Free Air Transport," *IEEE Electrification Magazine,* vol. 10, no. 2, pp. 69-81, 2022.

[24] H. Garg, G. Sahut, E. Tuneskog, N. K-J and F. C., "Large Eddy Simulations of Flow over Additively Manufactured Surface: Impact of Roughness and Skewness on Turbulent Heat Transfer," *Physics of Fluids,* vol. 35, 2023.

[25] L. Lindbäck, K. Frankolin, T. E. and B. Karlsson, "Development and Validation Under Engine Operation Environment of Additively Manufactured Hot Turbine Parts," in *ASME turboexpo*, Boston, USA, 2023.

[26] E. Tuneskog, L. Nyborg and K.-J. Nogenmyr, "Assessment Of Surface Roughness In Additively Manufactured Channels For Fluid Applications," in *European Power Metallurgy Association, EPMA*, Malmö, Sweden, 2024.

[27] E. Tuneskog, K.-J. Nogenmyr, D. Moëll, M. Gullberg and L. Nyborg, "Exploring Surface Roughness Effects on Spray Performance in Metal Additive Manufactured Spray Nozzles for Gas Turbine Applications, WorldPM2024 Conference Proceedings, Y," in *World PM2024*, Yokohama, Japan, October, 2024.

[28] V. Anilkumar, L. Nyborg and C. Y., "ASSESSING FRACTURE SURFACES AND MICROSTRUCTURES OF STAINLESS STEEL 321 TESTED IN HYDROGEN GAS," in *European Conference on Fracture*, Zagreb, August, 2024.

[29] X. Qin, L. Nyborg, H. Liu and Y. Cao, "Corrosion behaviour of low-temperature carburized AISI 304 austenitic stainless steel with hydrogen uptake," in *European Association on Applications of Surface and Interface Analysis*, ECASIA2024, Göteborg, Sweden, June 2024.

[30] V. Anilkumar, L. Nyborg and Y. Cao, "Impact of gaseous hydrogen on low cycle fatigue performance: Fractographic insights from surface analysis," in *ECASIA2024, European Association on Applications of Surface and Interface Analysis*, Göteborg, Sweden, June 2024.

[31] V. Anilkumar, "Hydrogen embrittlement in alloys used in gas turbines.," in *Swedish annual network meeting on fatigue, UTMIS25*, Husqvarna,, 2025.

[32] F. A. A. Nugroho, P. Bai, I. Darmadi, G. W. Castellanos, J. Fritzsche and C. .. a. B. A. Langhammer, "Inverse designed plasmonic metasurface with parts per billion optical hydrogen detection.," *Nature Communications, ,* vol. 13, no. 1, p. 5737., 2022 .

[33] V. Martvall, H. Klein Moberg, A. Theodoridis, D. Tomecek, P. Ekborg-Tanner, S. Nilsson, G. Volpe, P. Erhart and C. Langhammer, "Accelerating Plasmonic Hydrogen Sensors for Inert Gas Environments by Transformer-Based Deep Learning.," *ACS sensors.,* vol. 10, pp. 376-386, 2025.

[34] E. Dahlqvist, E. M. Morais and A. Martinelli, "Synthesis and characterization of new imidazolium based protic ionic liquids obtained by nitro-and cyano-functionalization.," *Journal of Molecular Liquids, Part B,* vol. 415, 2024.

[35] A. Zoukit, I. Salhi and D. Sedarsky, "Takagi-Sugeno Fuzzy Approach for PEM fuel cell system modeling," in *European Fuel Cell Forum*, Lucerne, Switzerland, 2023.

[36] Y. Xu, A. Kersten, S. Klacar, B. Ban, J. Hellsing and D. Sedarsky, "Improved efficiency with adaptive front and rear axle independently driven powertrain and disconnect functionality," *Transportation Engineering,* vol. 13, 2023.

[37] Y. Xu, A. Kersten, S. Klacar and D. Sedarsky, "Maximizing efficiency in smart adjustable dc link powertrains with igbts and sic mosfets via optimized dc-link voltage control," *Batteries,* 2023.

[38] M. Pipicelli, D. Sedarsky, L. Koopmans, A. Gimelli and B. d. G., "Comparative Assessment of Zero CO2 Powertrain for Light Commercial Vehicles," in *16th International Conference on Engines & Vehicles, Naples, Italy*, 2023.

[39] Y. Xu, P. Ingelström, A. Kersten, A. Andersson, S. Klacar, S. George and D. Sedarsky, "Improving powertrain efficiency through torque modulation techniques in single and dual motor electric vehicles.," *Transportation Engineering,* vol. 18, 2024.

[40] A. W. Rennuit-Mortensen, K. D. Rasmussen and M. Grahn, "How replacing fossil fuels with electrofuels could influence the demand for renewable energy and land area.," *Smart Energy,* 2023.

[41] F. M. Kanchiralla, S. Brynolf, T. Olsson, J. Ellis, J. Hansson and G. M., "How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study," *Applied Energy,* 2023.

[42] E. Malmgren, L. Styhre, J. Van Der Holst and S. Brynolf, "Navigating unchartered waters: Overcoming barriers to low-emission fuels in Swedish maritime cargo transport.," *Energy Research and Social Science. Energy Research & Social Science,* vol. 106, 2023.

[43] M. de Oliveira Laurin, S. Selvakkumaran, E. Ahlgren and M. Grahn, "Are decarbonization strategies municipality-dependent? Generating rural road transport pathways through an iterative process in the Swedish landscape," *Energy Research & Social Science,* no. 114, 2024.

[44] M. Kanchiralla F., S. Brynolf and A. Mjelde, "Role of biofuels, electro-fuels, and blue fuels for shipping: environmental and economic life cycle considerations," *Energy & Environmental Science,* vol. 17, pp. 6303-6418, 2024.

[45] M. Grahn, E. Malmgren, A. D. Korberg, M. Taljegard, E. Anderson J., S. Brynolf, J. Hansson, I. R. Skov and T. J. Wallington, "Review of electrofuel feasibility - Cost and environmental impact.," *Progress in Energy,* vol. 4, no. 3, 2022.

[46] S. Brynolf, J. Hansson, E. Anderson J., R. Skov I., T. J. Wallington, M. Grahn, D. Korberg A., E. Malmgren and M. Taljegård, "Review of electrofuel feasibility - Prospects for road, ocean, and air transport," *Progress in Energy,* vol. 4, no. 4, 2022.

[47] Green Flyway, 13 04 2022. [Online]. Available: https://www.greenflyway.se/.

[48] "Tidningen Energigas," NR3 2022. [Online]. Available: https://www.energigas.se/publikationer/tidningen-energigas/energigas-nr-3-2022-tema-tunga-transporter/.

[49] Chalmers University, "TechForH2 paves the way for future hydrogen technology," 01 12 2022. [Online]. Available: https://www.chalmers.se/en/current/news/m2-techforh2-paves-the-way-for-future-hydrogen-technology/.

[50] Chalmers University, "Ultra-sensitive optical sensor can reduce hydrogen's risks," 01 12 2022. [Online]. Available: https://www.chalmers.se/en/current/news/f-ultra-sensitive-optical-sensor-can-reduce-hydrogen-s-risks/.

[51] P4 Göteborg, "Elpriserna och kriget ritar om energikartan - Ökat intresse för fossilfritt," P4 Göteborg, 10 12 2022. [Online]. Available: https://sverigesradio.se/artikel/elpriserna-och-kriget-ritar-om-energikartan-okar-intresset-for-fossilfritt.

[52] "SHDC," 16 02 2023. [Online]. Available: https://www.ri.se/sv/vad-vi-gor/projekt/swedish-hydrogen-development-center.

[53] "Chalmers," 11 July 2024. [Online]. Available: https://www.chalmers.se/aktuellt/nyheter/framstegen-som-ger-vatgasflyget-medvind,c4011325/. [Accessed 17 February 2025].

[54] "Subhangi Dua," MSN, 11 July 2024. [Online]. Available: https://www.msn.com/en-us/travel/news/all-travel-within-750-miles-could-be-made-with-hydrogen-planes-by-2045-study/ar-BB1pP6F0. [Accessed 18 02 2025].

[55] TT, "Aftonbladet," 11 July 2024. [Online]. Available: https://www.aftonbladet.se/nyheter/a/XjbK9g/resor-med-vatgasflyg-snart-i-sverige. [Accessed 18 02 2025].

[56] A. Aware, "Youtube," 19 July 2024. [Online]. Available: https://www.youtube.com/watch?v=g9QeUAGaEmQ&t=5s. [Accessed 18 02 2024].

[57] B. Burrau, "Ny Teknik," 11 July 2024. [Online]. Available: https://www.nyteknik.se/farkost/chalmersforskarnas-losning-ska-fa-vatgasplanen-att-flyga/4276188. [Accessed 18 02 2025].

[58] IVAs Högtidssammankomst, "Youtube," 28 October 2024. [Online]. Available: https://www.youtube.com/watch?v=56eDKBGJZTs&t=4543s. [Accessed 18 02 2025].

[59] E. Commission, "https://ec.europa.eu/research-and-innovation/en/projects/success-stories," [Online]. [Accessed 10 April 2021].

[60] I. J. J. Jonsson, G. Debarshee, C. Xisto and T. Grönstedt, "Design of Chalmers new low-pressure compressor test facility for low-speed testing," in *14th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics*, 2021.

[61] J. Wendel, K. S. Manchili, E. Hryha and L. Nyborg, "Reduction of surface oxide layers on water-atomized iron and steel powder in hydrogen: Effect of alloying elements and initial powder state," *Thermochimica Acta,* vol. 692, 2000.

[62] L. Koopmans, H. Ström, S. Lundgren, O. Backlund and I. Denbratt, "Demonstrating a SI-HCCI-SI mode change on a Volvo 5-cylinder electronic valve control engine," in *SAE Technical Paper*.

[63] I. Östergren, A. M. Pourrahimi, a. et and L. Langhammer, "Highly Permeable Flourinated Polymer Nanocomposites for Plasmonic Hydrogen Sensing," *ACS Applied Meteriasl & Interfaces,* 2021.

[64] O. Danyliv and A. Martinelli, "Nafion/Protic Ionic Liquid Blends: Nanoscale Organization and Transport Properites," *J. Phys. Chem,* vol. 123, no. 23, pp. 14813-14824, 2019.

[65] D. Wilhelmsson, D. Rikemansson, T. Bru and L. E. Asp, "Compressive strength assessment of a CFRP aero-engine component – An approach based on measured fibre misalignment angles,," *Composite Structures.,* vol. Vol. 233, 2020.

[66] F. A. A. Nugroho, et al. and C. Langhammer, "Metal-Polymer Hydbrid Nanomaterials for Plasmonic Ultrafast Hydrogen Detection," *Nature Materials,* vol. 18, pp. 489-495, 2019.

[67] V. Grewe, A. G. Rao, T. Grönstedt, C. Xisto, L. F., J. Middel, B. Ohlenforst, S. Blakey, S. Christie, M. S. and K. Dahlmann, "Valuating the climate impact of aviation emission scenarios towards the Paris Agreement including COVID-19 effects," *Nature communications, accepted,* 2021.

[68] P. Rompokos, D. Rolt, A. T. Nalianda, A. Isekveren, C. Senne and T. Grönstedt, "Synergistic technology combinations for future aircraft using liquid hydrogen," *Journal of Engineering for Gas Turbines and Power,* vol. 143, no. 7, 2021.

[69] M. Alves, D. Carlstedt, S. Pimenta, L. E. Asp and F. Ohlsson, "Ultra-thin and stiff randomly-oriented discontinuous composites," in *Proc. of ASC2019, Am. Soc. for Composites,* Atlanta, GA, USA., September 2019.

[70] S. Alekseeva, et al. and C. Langhammer, "Grain boundary mediated hydriding phase transformations in individual polycrystalline metal nanoparticles," *Nature Communications,* vol. 1048, no. 8, 2017.

[71] M. Alves, C. Carlstedt, F. Ohlsson, L. E. Asp and S. Pimenta, "Ultra-strong and stiff randomly-oriented discontinuous composites: closing the gap to quasi-isotropic continuous-fibre laminates," *Composites Part A,* vol. Vol. 132, 2020.

[72] A. D. Korberg, S. Brynolf, M. Grahn and I. Skov, "Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships," *Ren. and Sust. Eng. Reviews,*, vol. 142, 2021.

[73] S. Brynolf, M. Taljegard, M. Grahn and J. Hansson, "Electrofuels for the transport sector: A review of production costs," *Ren. and Sust. Eng. Reviews,* vol. 81, no. 2, pp. 1887-1905, 2018.

[74] N. G. Mounesha, V. Dracopoulos, et al and A. Martinelli, "A long-chain protic ionic liquid inside silica nanopores: enhanced proton mobility due to efficeint self-assembly and decoupled proton transport," *Royal Society of Chemistry,* vol. 12337, p. 10, 2018.

[75] M. Lehtveer, S. Brynolf and M. Grahn, "What Future for Electrofuels in Transport? Analysis of Cost Competitiveness in Global Climate Mitigation," *Environ. Sci. Tech.,* vol. 53 (3), 2019.

[76] I. Darmadi, et al. and C. Langhammer, "Bulk-Processed Pd Nanocube-Poly(methylmethacrylat) Nanocomposites as Plasmonic Plastics for Hydrogen Sensing," *ACS Applied Nanomaterials,* vol. 8, 2020 (3).

[77] B. Zhang, Z. Zhan, Y. Cao and H. Gulan, "Metallic 3-D printed antennas for millimeter-and submillimeter wave applications," *IEEE Trans. on Terahertz Science and Tech.,* vol. 6 (4), 2016.

[78] T. Rogers, P. Petersen, L. Koopmans, P. Lappas and A. Boretti, "Structural characteristics of hydrogen and compressed natural gas fuel jets," *Int. J. of Hydrogen Energy,* vol. 40 (3), 2015.

[79] S. Bengtsson and Å. Palmqvist A. and Valadi, "C2022-0444, Beslut om inrättande av centrumbildningen Teknologier och innovationer för en framtida hållbar vätgasekonomi (TechForH2)," 2022.

[80] "Dagens Industri," 10 12 2022. [Online]. Available: https://www.di.se/nyheter/lastbilsrivaler-samarbetar-om-vatgasforskning/.

[81] "TechForH2 home," Chalmers, 06 February 2023. [Online]. Available: https://www.chalmers.se/centrum/techforh2/.

[82] N. Tahir, "Akutell Energi," 12 03 2024. [Online]. Available: https://aktuellenergi.se/framtidens-nordiska-flygbehov-kan-motas-av-vatgas/. [Accessed 15 03 2024].

[83] Newsweek, "Better Planet," 2024 July 19. [Online]. Available: https://www.newsweek.com/fossil-fuel-free-flights-hydrogen-power-air-travel-1924613. [Accessed 18 02 2025].

TechForH2 personalities

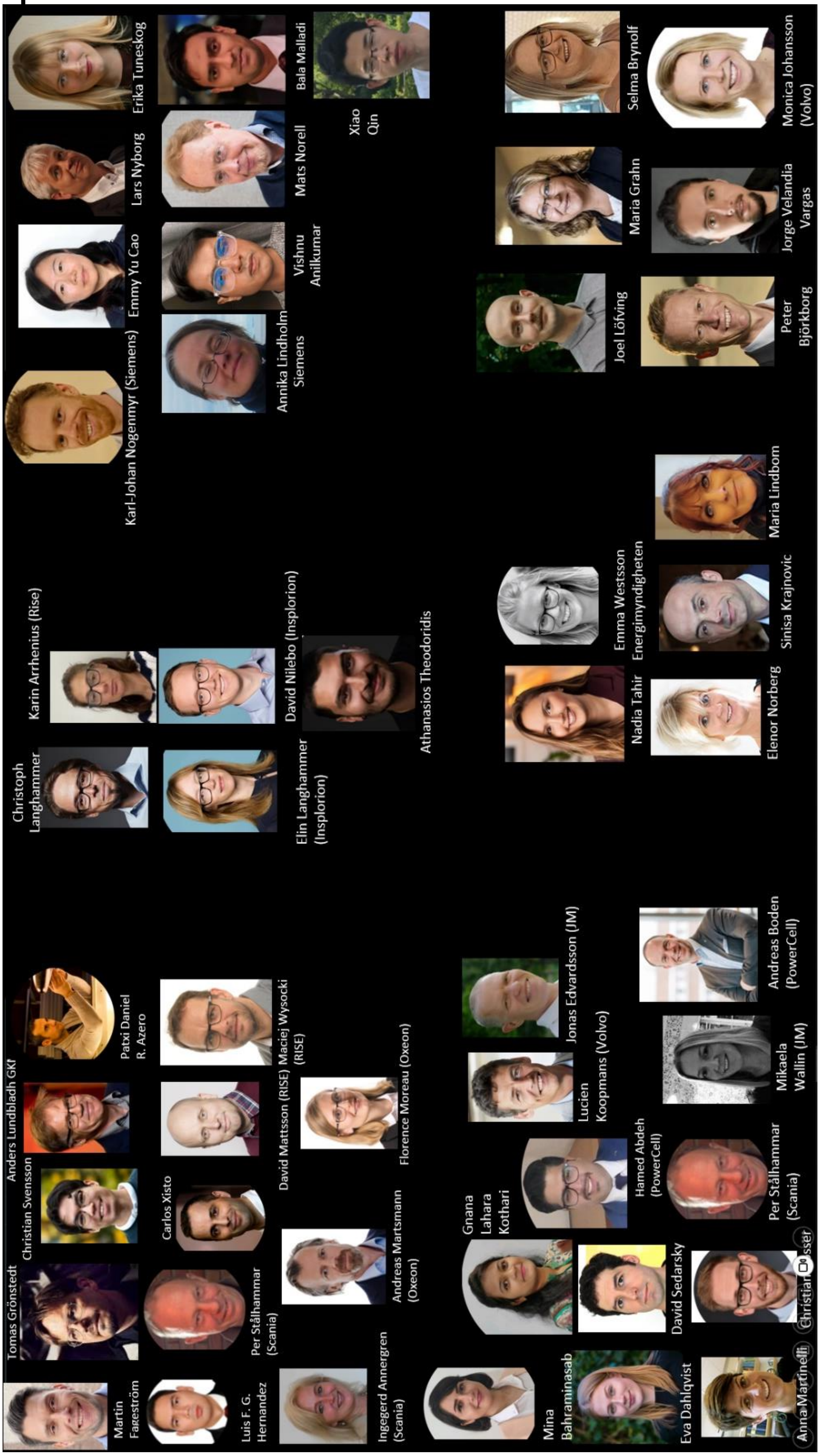


Figure 30: 3rd annual TechForH2 participants/involved personalities.