TechForH2 Annual report 2023: Technologies and innovations for a future sustainable hydrogen economy

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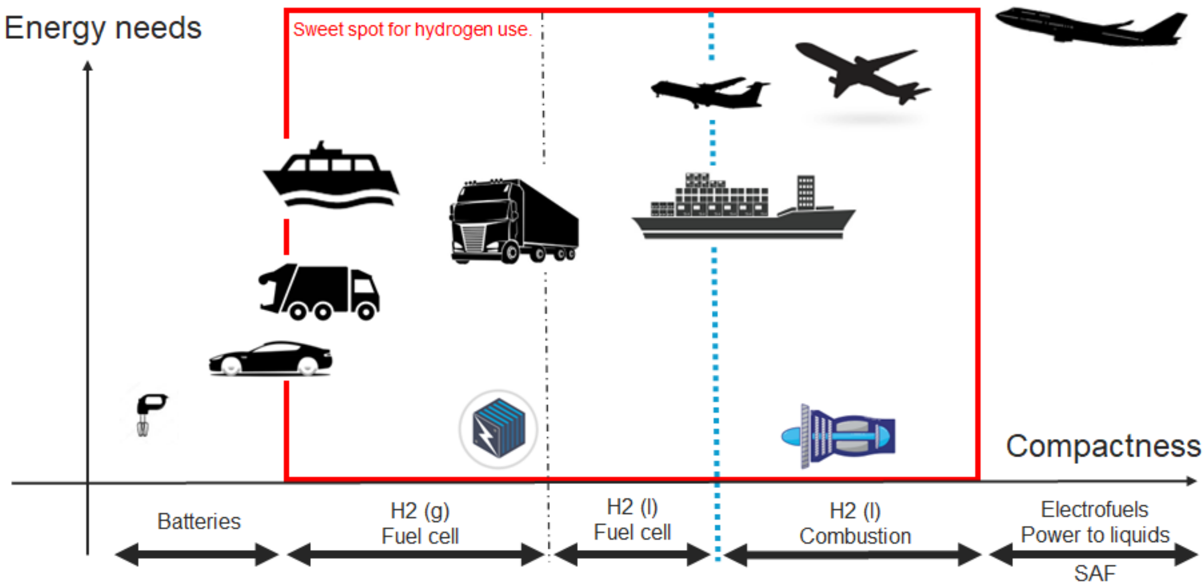
Annual report 2023: Technologies and innovations for a future sustainable hydrogen economy (TechForH2)



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

Revision history
2024-03-15 circulated to board for review
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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 later 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 and Insplorion.

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. All five arenas are now well up and running and eight Ph.D. research positions have been opened and launched. Although the core research activities revolve around the Ph.D. projects, Chalmers university is boosting the launch of TechForH2 by initiating seven post doc projects in the area of transport with a hydrogen focus.

The center was started in 2022 with most of the recruiting performed in the end of 2022 and the last planned additions in august 2023. Despite the recent launch of the center, the scientific reporting in most of the multidisciplinary research areas is already quite strong. This kick-start is to a great degree due to Chalmers commitment to fund the seven post docs to boost the launch of the center.

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 och Insplorion.

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. Alla fem arenorna är nu väl igång och åtta doktorandtjänster har öppnats och lanserats. Även om kärnverksamheten i centrat kretsar kring doktorandprojekten, så har Chalmers kick-startat lanseringen av TechForH2 genom att initiera och finansiera sju post doc-projekt inom transportområdet med vätgasfokus.

Centrat startades under 2022, med huvudparten av rekryteringen genomförd under slutet av 2022 men de sista planerade tilläggen i augusti 2023. Trots detta så har avsevärd rapportering från de flesta av de multidisciplinära områdena redan uppnåtts. Detta beror i stor uträckning på Chalmers post doc satsning som givit centrumet en flygande start.

TECHFORH2 ORGANIZATION

TechForH2 is today comprised of eleven 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

The TechForH2 board

Upon submitting this report, the TechForH2 board has had eight 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). Since the number of partners in TechForH2 is relatively moderate it is 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
Anders Lundbladh	GKN Aerospace
Pauline Leonárd	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
Mikael Larsson (avgående)	Johnson Matthey
Mikaela Wallin	Johnson Matthey
Per Wimby	Stena Rederi
Andreas Martsman	Oxeon
Florence Morerau	Oxeon
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 leaders full professor Leif Asp (lightweight composite materials and structures) and professor Martin Fagerström (computational fracture mechanics)
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 leaders Lucien Koopmans (full professor in combustion engineering) until April 2023 and 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 was 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.

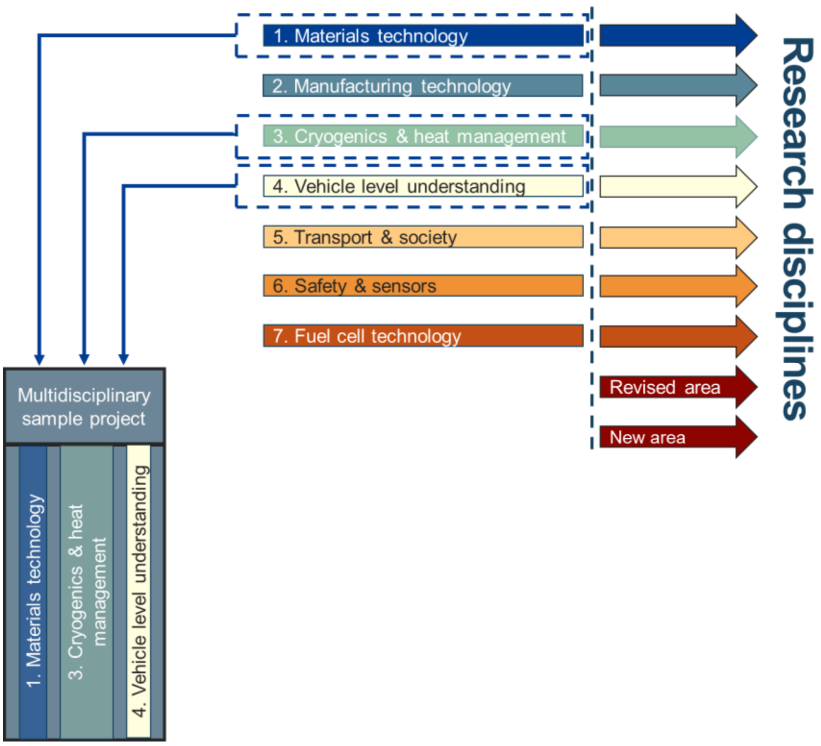

Figure 1: TechForH2 process for establishing new multidisciplinary research areas.

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
Leif Asp	Senior Lecturer, Soraia Pimenta, Imperial College London.
Fiona Schulz/Yu Cao	Full professor, Mariangela Lombardi, Politecnico di Torino.
Tomas Grönstedt	Associate professor Vishal Sethi (ENABLEH2 coordinator), Cranfield University, Arvind Rao, Delft university.
Anna Martinelli	Full professor, Luis M. Varela, USC Santiago.
David Sedarsky	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 . Professor of Technology, David Blekhman, Cal. State Univ, Los Angeles.
Christoph Langhammer	Prof. Bernard Dam, Delft University, Ass. Prof. Andrea Baldi, Vrije Universiteit, Amsterdam, Netherlands.

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

2023 highlights

- The TechForH2 recruitment of Ph.D. students is now completed.
    - From a gender perspective the recruitment was very successful reaching 40% female members out of an application rate of 20%.
- During the year 2023 a seminar series was launched that started with the TechForH2 Ph.D. students, and has now been widened to a collaboration with CH2ESS at LTU.
- The TechForH2 Ph.D. students have taken the initiative to a collaborative network that had their first workshop visiting SEEL and PowerCell. The network is used to explore joint publication opportunities and to develop the center from the PhD student perspective.
- A dedicated communicator to the center is now in place.
- A funding model is now proposed for the remaining funding as an output from a strategic workshop held by the center.

Figure 3: TechForH2 2nd annual meeting at Chalmerska huset.

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 where 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 the recruitment filling 6 out of the 9 Ph.D. positions. Hence the projects have been launched gradually during 2022. In 2023 the 9th Ph.D. was recruited, and the center has now finished the initially planned recruiting. In addition, an industrial Ph.D. has been added to the center (Volvo).

- Area1: Light weight composite storage solutions for cryogenic hydrogen. 2 Ph.D. students (Luis Fermando Gulfo Hernandez, Christian Svensson).
- Area2: Additive manufacturing for hydrogen fuel supply systems. 2 Ph.D. students (Vishnu Anilkumar, Erika Thuneskog)
- Area3: Nanoplasmonic hydrogen sensor maturation, 1 Ph.D. student (Athanasios Theodoridis)
- Area4: Fuel cell development and integration, 4 Ph.D. students (Christian Bosser, Mina Bahraminasab, Eva Dahlqvist, Gnana Lahari Kothala (industrial Ph.D.))
- Area5: The future of hydrogen – societal challenges. Hydrogen society, 1 Ph.D. student (Joel Löfving)

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.

Recruited post docs and joint research activities are now presented below, summarizing the activities within 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 two journal publications and one conference contribution has been published [1, 2, 3]:

- 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., 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 two journal articles [4, 5] as listed below, in addition these three conference contributions have been submitted of which one of the three articles was recommended to journal (ASME). Since these have not been published yet they are not listed herein.

- 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.

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. 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 his first paper:

- Svensson, C., Oliveira, A. A., Grönstedt, T. (2024). Hydrogen fuel cell aircraft for the Nordic market. International Journal of Hydrogen Energy, 61, 650-663.

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

RISE has also contributed working on three publications of which the article below has been accepted for publication in Applied Composite Materials [6]:

- Olsson R, Cameron C, Moreau F, Marklund E, Merzkirch M, Pettersson J (2023). Design, manufacture, and cryogenic testing of a linerless composite tank for liquid hydrogen.

The two other articles in progress are:

- Loukil MS, Xu J, Marklund E, Merzkirch M, Moreau F, Ohlsson F (2023). Thermal and mechanical cycling of thin-ply composites for cryogenic applications.
- Merzkirch M, Marklund E, Olsson R, Ramantani D (2023). Mechanical characterization at room and cryogenic temperature of thin-ply CFRP laminates manufactured by filament winding.

Summary of research achievements

- A conceptual aircraft design study targeting the 2045 Nordic aircraft market indicate 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 topics

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 will build on conceptual studies at Chalmers performed in the 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".

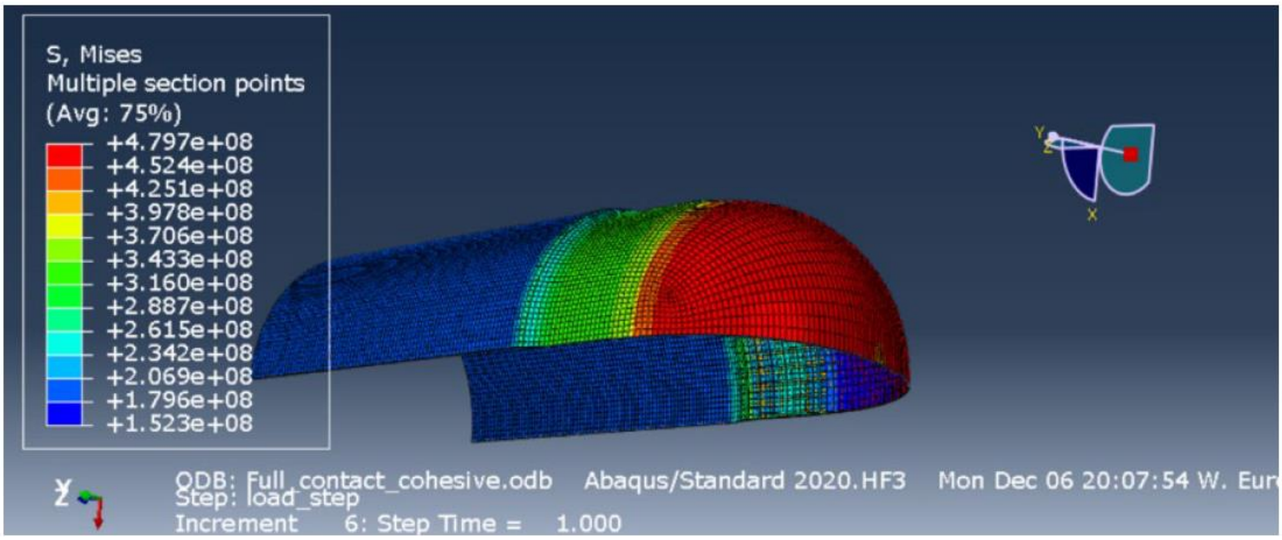

Figure 4: Stress analysis of a liner-less CFRP tank for liquid hydrogen storage, stresses in the overwrap. Results produced by Chalmers in the project LH2-Tanks.

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 [7].

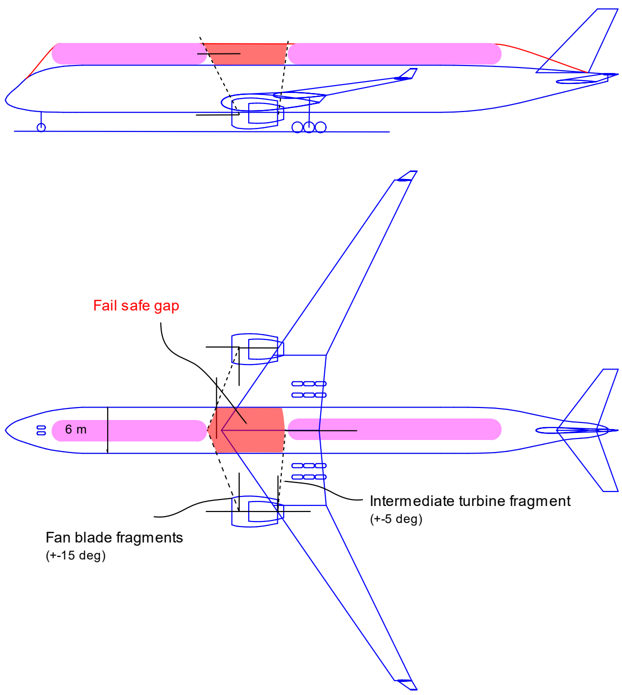

Figure 5: Conceptual design of hydrogen tank integration into tube-and-wing turbofan engine aircraft architecture [7]

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 [8], but to increase flexibility and make sharing of models easier another software, SUAVE [9], 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 [10, 11] and EnableH2 [12] have been inherited.

Progress in relation to project goals

(R1a): The projects aim to contribute to developing breakthrough ultra-low weight and low cost for hydrogen storage concepts. In [13] we show that fuel cell hydrogen aircraft can meet 97% of all intra-Nordic flight routes and 58% of all Nordic passenger volume by 2045. For longer distances 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. It is too early to quantify impact on cost and weight for pressurized and cryogenic concepts at this stage but a collaborative paper is being prepared to address these issues.

(R1b): In the line of model sharing and Swedish industry strengthening RISE conducted a workshop in 2023-12-14. This workshop was dedicated to defining critical research topics for the research area and better understand industry need. Having published the fuel cell aircraft model we can now share it within the center (for instance GKN, PowerCell, Oxeon, Scania, Insplorion).

(R1c): At the end of the first five-year term the projects should also have contributed to make TechForH2 visible as an international hub for light weight research. In the medium term this is planned to be ramped up with the international research network activities.

At the end of 2023 the aim is to achieve the milestone to have “design methods validated for pressurized and cryotanks” (Mile1). The cryotank-model is validated. There is still some work needed to have a corresponding pressurized tank model. The cryo-tank model delivers a better understanding of how the tanks are used in aviation service.

(I1a). Evaluation of the TeXtreme composite technology for tank design is a little bit further down the road but can now be addressed using our model.

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 Volvo 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
During 2022, two Ph.D. projects had been defined and two Ph.D. students were recruited. In addition, Chalmers has supported the project through Production AoA and Faculty funding. A postdoc project “Design for metal additive manufacturing” has been supported partly. Currently, this project area involves 3 men and 2 women, reaching a good gender balance.

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

- 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: Characterization and Post-treatment of Metal Component Produced by Additive Manufacturing for Hydrogen Application. 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 of engineering materials and competence in AM.

Saeed Khademzadeh was recruited as a post doc. starting from 2022-10-01. He has a background in additive manufacturing and Material science. In addition, the center funds efforts at RISE for spray testing and numerical modelling of various liquid hydrogen carrier fuels in fuel nozzle.

The research topics
The PhD1 project is targeting additive manufacturing (AM) as a means for high-performance metallic parts in the section of gas turbine and fuel cell with possible extension to internal combustion engine (under discussion). 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, Volvo) 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.

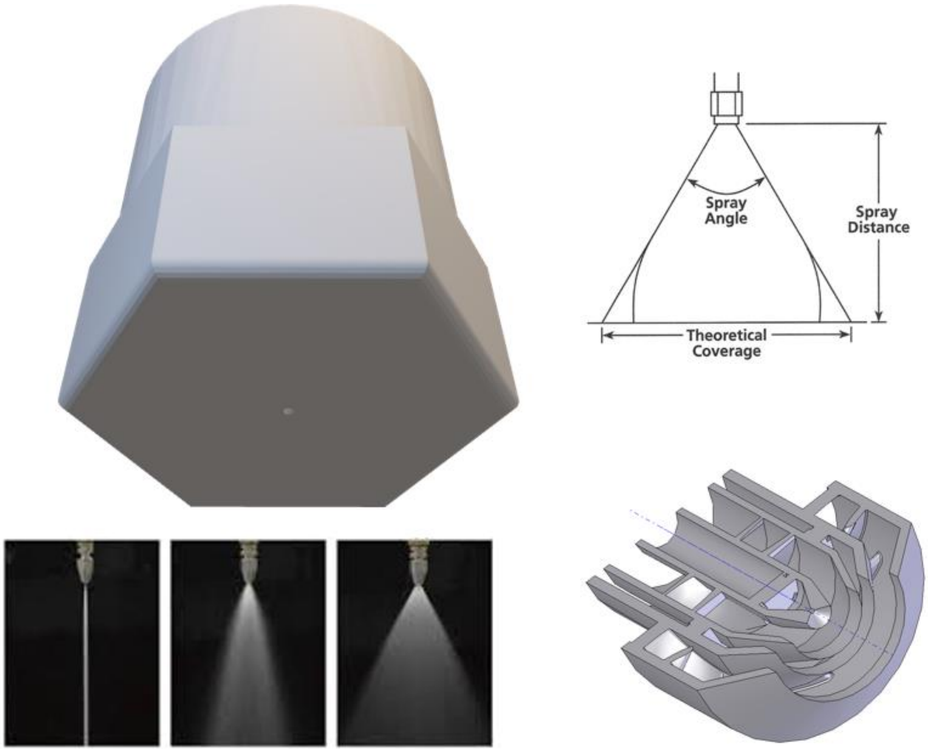

Figure 6: Hydrogen fuel nozzle and fuel spray

In PhD2 project, additive manufacturing (AM) is used as a means for high-performance metallic parts in the section of a gas turbine (possibly extended to the internal combustion engine) and fuel cell. The research focuses are **i)** Characterization of as-built and post processed components; ii) Environment impact which are relevant to the application condition of the metallic alloys, such as hydrogen embrittlement and oxidation/corrosion behaviour, iii) Surface engineering to improve material properties in hydrogen application. The goal is to gain improved understanding of material behaviour in hydrogen applications related to gas turbine and fuel cell usage; to establish efficient approaches for improving material properties in the conditions concerned; to build confidence to use additive manufacturing for high performance components that would benefit significantly from the design freedom of AM. 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.

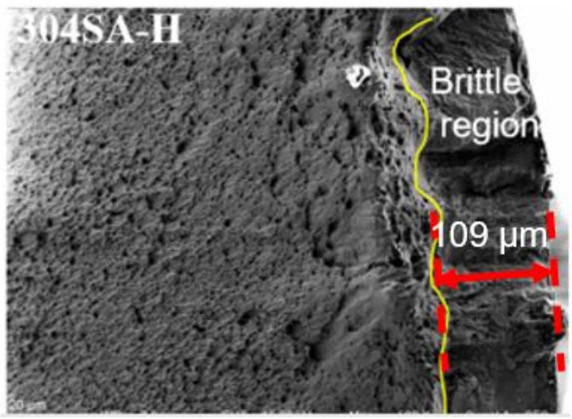

Figure 7: Brittle region formed due to hydrogen embrittlement

Activities since the start of TechForH2:

- Outlining a systematic literature review on issues associated with AM of spray nozzles including design concepts, nozzle performance, and surface integrity of internal complex channels made by AM.
- Systematic literature review on hydron embrittlement and material behavior when exposed to the hydrogen-related environment
- Design and additive manufacturing of a test model aiming at calibrating LPBF setup, printability assessment, and surface roughness investigation
- Evaluation of alternative AM processes
- Refining nozzle design for 1st test campaign at RISE in Piteå focusing on nozzle performance
- Setup of the test facility at RISE in Piteå has started, no exact timeline for when the test rig will be operational has been given but we estimate it will take between 3-6 months. The test setup will be calibrated by a 1st test campaign
- Production planning for the 1st test matrix is ongoing
- On-going characterization of samples exposed to ammonia
- Hydrogen embrittlement and corrosion resistance of 304 and 316L stainless steels
- The Chalmers funded post doc has so far mainly been involved in the activities commencing to work on the Siemens Energy AB use case, more specifically for the design and additive manufacturing of the spray nozzle

Progress in relation to project goals

The projects aim to manufacture nozzles that allows a gradual hydrogen introduction by additive manufacturing including postprocessing (R2a). Refining nozzle design and manufacturing planning is ongoing for the first test matrix. The first printing was performed. The roughness and outlet diameter were measured. Besides laser powder bed fusion, we also plan to use binder jetting for the production. It is too early to examine the effect at this stage. The project also aims for experimental validation of fuel nozzle at RISE in Piteå focusing on nozzle performance (R2b). Setup of the test facility has started, but this task is also premature. In the medium term, at the end of 2024, the first nozzle concept is supposed to be available (Miles 3). When the project is finalized, it should contribute to Swedish industry developing gas turbines usable for a range of future hydrogen scenarios (R2c). Another aim of the project is a more sustainable use of materials when using hydrogen as fuel for cleaner transportation in for instance fuel cell vehicles (R7a). As one type of commonly used material for bipolar plates, hydrogen embrittlement and corrosion resistance of 304 and 316L stainless steels have been tested. A better understanding of the material behavior has been obtained.

Current studies and publication plan

With respect to dissemination, several publications have prepared are in preparation. So far two a conference paper has been published [14]:

- Lindbäck, M., Frankolin, K., Tuneskog, E., Karlsson, B., & Wang, L. (2023, June). 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.

A list of planned / completed for 2024:

Accepted:

- Assessment of surface roughness in additively manufactured channels for fluid applications Erika Tuneskog, Lars Nyborg, Accepted by Euro PM2024 Congress & Exhibition, October 2024, Sweden
- Surface Roughness Effects on Spray Performance in Metal Additive Manufactured Spray Nozzles for Gas Turbine Applications, Erika Tuneskog, Lars Nyborg, Karl-Johan Nogenmyr & Daniel Moëll, Accepted by World PM2024 Congress & Exhibition, Oktober, 2024, Yokohama, Japan

- 3D-Printed Wideband Dual-Polarization Cryogenic Dichroic Filters, Leif Helldner, Denis Meledin, Saeed Khademzadeh, Yu Cao, Lars Nyborg, Igor Lapkin, Sven-Erik Ferm, Victor Belitsky and Vincent Desmaris

In progress:

- Impact of gaseous hydrogen on low cycle fatigue performance: Fractographic insights from surface analysis Vishnu Anilkumar, Lars Nyborg, Yu Cao, Submitted to ECASIA2024, European Association on Applications of Surface and Interface Analysis, Sweden
- Corrosion behavior of low-temperature carburised AISI 304 austenitic stainless steel after hydrogen uptake, Xiao Qin, Lars Nyborg, Huiqun Liu and Yu Cao
- Submitted to ECASIA2024, European Association on Applications of Surface and Interface Analysis, Sweden
- Assessing low cycle fatigue performance of metastable austenitic stainless steel: investigating the effect of cathodic and gaseous hydrogen charging, Vishnu Anilkumar, Lars Nyborg, Yu Cao, submitted to European Conference on Fracture 2024, Zagreb, Croatia
- Accepted by 33rd IEEE International Symposium on Space THz Technology, April 2024, Charlottesville, Virginia, USA
- Effect of low-temperature carburizing on hydrogen embrittlement of AISI 304 austenitic stainless steel, Xiao Qin, Lars Nyborg, Huiqun Liu, Alexandra Bauer, Yu Cao, Submitted to the journal", Corrosion Science"

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

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. Via the ties to materials technology, a collaboration with Oxeon AB is actively being explored.

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 in the sub-second range that can detect hydrogen concentrations in the low ppm/ppb range in air or in high pressure hydrogen environments, to develop stable sensor operation at widely varying relative humidity conditions, to facilitate long-term (years) stable sensor operation without significant deactivation/ageing/sensitivity loss, to provide reduced sensor cross-sensitivity to other molecular species.

Joint projects and recruitment

During 2022 one Ph.D. project have 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.

His main research directions during 2023 were 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, as well as H_2O, on the deactivation of plasmonic hydrogen sensors in collaboration with the group of Prof. Elad Gross at Hebrew University in Jerusalem.

The research production from the area

In terms of publications the multidisciplinary research area two very distinguished papers have already been published [15, 16]:

- 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.

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, where we also will collaborate with the Gross group to unravel the role of H_2O in sensor deactivation via in situ IR spectroscopy experiments and
- (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.

- A paper that uses machine learning ensemble models to accelerate hydrogen sensor response up to 50 times by predicting the sensor response (and the certainty of it) before the sensor physically reaches it. In this way we will be able to achieve ultrafast sensors in chemically challenging environments in a completely new way.

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.

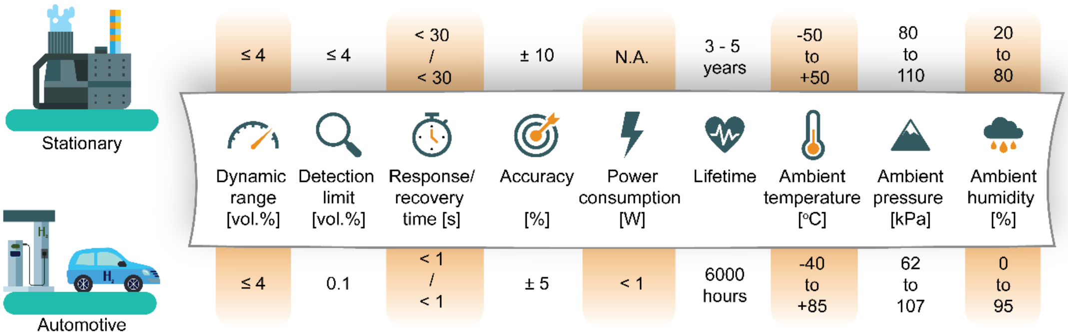

Figure 8: The DoE hydrogen safety sensor performance targets for stationary and mobile applications.

This PhD project is focusing primarily on developing nanoplasmonic hydrogen sensors that have the capability to operate in complex gas environments that, e.g., contain hydrocarbons, ammonia, O_2 and H_2O, by exploring a new generation of carbene-based H_2-transparent nanolayers to prevent competitive H_2O adsorption on and ageing of the plasmonic nanoparticles, and to spatially separate hydrogen dissociation from hydride formation and detection by developing catalytic adlayers based on Pt that will alleviate deactivation by water. Here, preliminary results generated in this PhD project and displayed in Figure 9 below show promising sensor response in up to 80 % RH when exploring the Pt-approach. The carbene-adlayers will be explored later during the project.

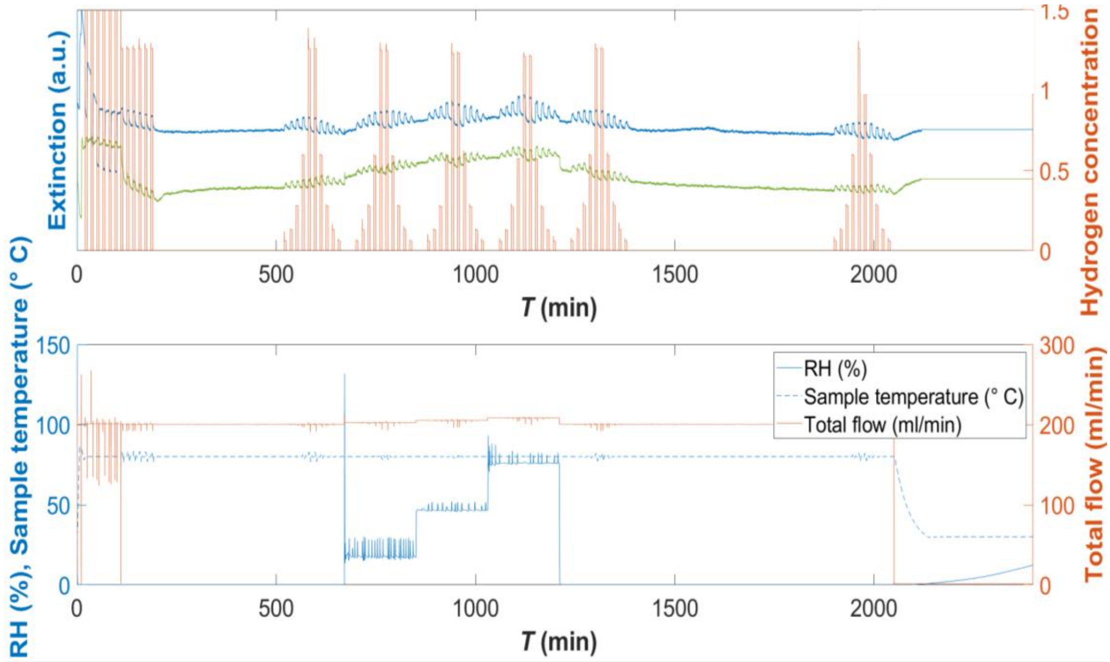

Figure 9: Preliminary results for a plasmonic hydrogen sensor with Pt co-catalyst operated in up to 80 %RH in air that demonstrates distinct response also at the highest humidity conditions.

As the second main aspect, this PhD project will focus 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 (see Figure 10below from Nature Communications 2022, 13 (1), 5737). This is a very strong foundation to further explore this concept using better sensing materials, such as our own PdAu alloys or PdTa alloys developed together with our collaborators at TU Delft.

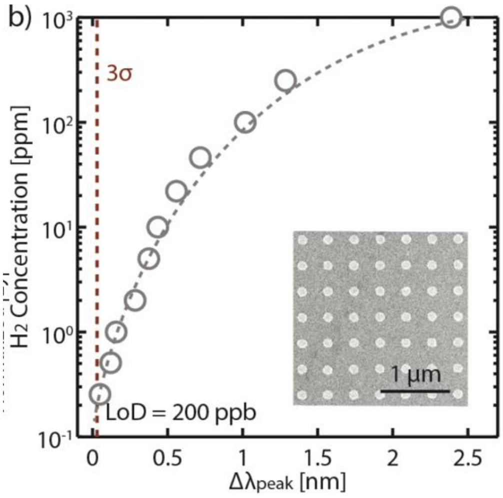

Figure 10: an SLR-based plasmonic hydrogen sensor with a limit of detection (LoD) of 200 ppb. Adopted from Nature Communications 2022, 13 (1), 5737

As further important aspect, the above main research efforts of this PhD project also tie into the Vinnova-funded project entitled “hAIdrogen sensors” that also is coordinated by the PI of this project area, C.L., and executed with Insplorion AB as industry partner. It explores deep learning methods for the treatment of data generated by plasmonic hydrogen sensors as an alternative and complementary means to materials engineering to improve limit of detection, response time and long-term stability. Here, we have recently demonstrated (see Figure 11 below) in a manuscript currently under peer-review that for a PdAu alloy plasmonic sensor a limit of detection of 200 ppm in highly humid air can be achieved (this exceeds the corresponding DoE target) and that the ISO 26142:2010 standard for sensor robustness can be met at 80 %RH. This an important breakthrough for the field that paves the way for further efforts in the direction of using machine learning techniques for the development of next generation hydrogen sensors.

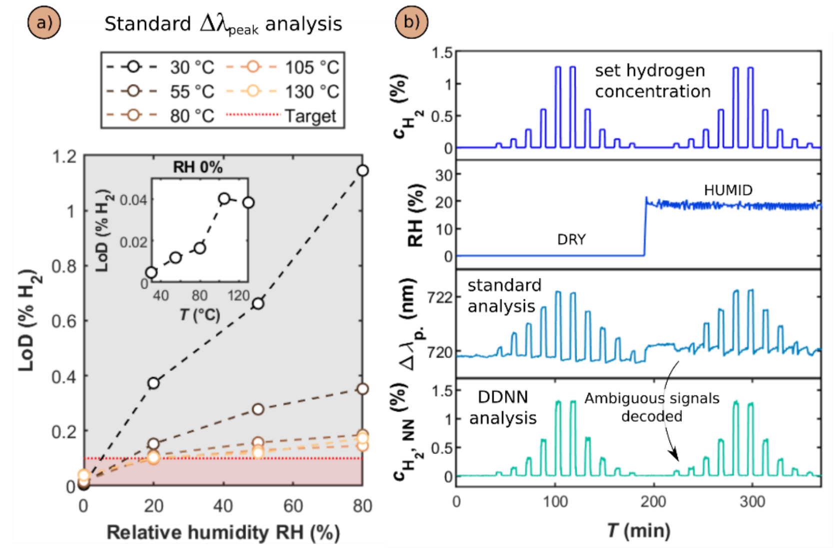

Figure 11: a) Sensor limit of detection (LoD) as obtained by the standard Δλpeak readout for different sensor operating temperatures and RH. Note that above 20% RH all sensors fall short on the US DoE target of LoD < 0.1% H2. b) Comparison of sensor response to c_{H_2} pulses at dry and 20% RH conditions 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 Tomecek et al [16].

Progress in relation to project goals

This PhD project addresses the *research goals*:

- R6a. Develop ultrafast sensor response technology in the sub-second range at hydrogen concentration in the low ppm/ppb range in air and air-starved environments. (M36)

Status: Using machine learning, or more specifically the *long short-term transformer ensemble model for accelerated sensing (LEMAS)* model that we have developed, we have been able to demonstrate that the response of an optical plasmonic hydrogen sensor can be accelerated by up to a factor of 40 and that its intrinsic pressure dependence in an environment emulating the inert gas encapsulation of large-scale hydrogen installations can be eliminated. This becomes possible by accurately predicting the sensor response value to a hydrogen concentration change before it is physically reached by the sensor hardware (Figure 12).

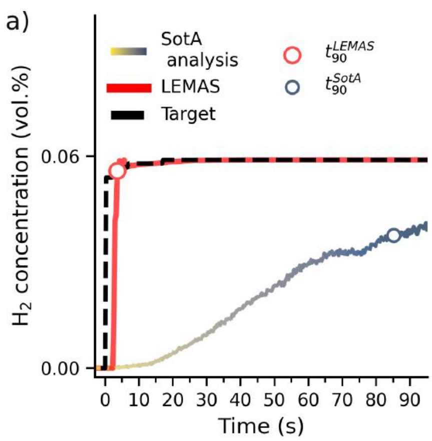

Figure 12: Comparison of the prediction of LEMAS and the SotA centroid analysis for a pulse of 0.06 vol.% H2 in inert Ar environment. By utilizing the full time-dependent spectrum of the measured sensor response LEMAS is able to accurately predict the final value H2 concentration before the sensor physically reaches its new state in equilibrium with the new H2 concentration level.

- R6b. Demonstrate reduced cross-sensitivity to other species present in the sensor environment. (M48)

We have demonstrated and published the first plasmonic hydrogen sensor (and to our knowledge the first in general) that can operate reliably in high humidity environments, which is regarded as the technically most challenging and most important chemically challenging environments (Nature Communications 2024, 15(1), 1-15). The technical importance stems from the fact that humidity is always present in ambient air and thus a concern for safety sensors in ambient conditions. We will now continue our efforts towards even more complex environments where we combine humidity with other species of concern that are present in air, such as CO, NOx, SOx and CO2.

- R6c. Survey and propose hydrogen sensor integration solutions for competing technology in collaboration with R1 (M60)

Not addressed yet.

- Mile8. First ultrafast sensor concept demonstrated.

Partly addressed by the first demonstration of the LEMAS concept (Figure 12). We will further develop this approach towards the truly ultrafast regime, which is sub-second resposnes.

This PhD project also addresses the following *innovation goals*:

- I2b. operation in high humidity (M36)

Fulfilled - (Nature Communications 2024, 15(1), 1-15).

- I2d. ultrawide dynamic range. (M60)

Have come a long way in the collaboration with the Bannenberg group in Delft, where we now are able to nanofabricate PdTA alloy nanoparticles that we have confirmed, using in situ XRD, to be in the same crystallographyic phase as the thin film systems demonstrated by Bannenberg et al. Implemented into a plasmonic H2 sensor they exhibit exceptionally large optical response to H2, which promises ultralow limits of detection and thereby also ultrawide dynamic range. What currently is limiting is the response time, which we have identified to be cause by some steps during the nanofabrication. We are currently working on resolving these issues.

- I2e. explore the plasmonic hydrogen sensor technology for application in hydrogen energy related process monitoring. (M60)

Not explicitly addressed yet but taken significant steps by Nature Communications 2024, 15(1), 1-15.

- Mile11. Demonstration in high humidity. (M24)

Demonstrated and published: Nature Communications 2024, 15(1), 1-15

In terms of *dissemination*:

- we have published a first paper in collaboration with VU Amsterdam [15].
- We have published a second paper on high humidity sensing [16].
  Insplorion AB collaborate actively with the Langhammer and the Bannenberg group on exploiting the PdTa- alloy nanoparticle systems for potential integration in a sensor device.

- Insplorion AB and the Langhammer group collaborate actively on exploring the practical implementation potential of the machine learning concepts we have developed to (i) enable sensing in high humidity and (ii) accelerate H2 sensing.
- We have presented our results at the Nanophotonics and Micro/Nano Optics International Conference 2023, Barcelona- Spain.
- we have included some of these results in the master level course TIF120 “Surface and Nanophysics” for which C.L. is examiner.

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 shaped the project goals and scope.

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 related concern is the need for finding non-volatile proton conducting electrolytes alternative to acidic water, 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 2023 three new Ph.D projects have been defined and new Ph.D. students have been recruited to work alongside the first Ph.D. student hired in 2022. These include an academic Ph.D. project focused on new advanced membrane materials for fuel cells, a project focused on PEMFC stack lifetime and durability, and a new industrial Ph.D. project (Volvo) on PEMFC stack operating conditions and consequences for degradation of fuel cell components. In addition, these projects are supported by work within the Chalmers-funded 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 (TRALA)
- PhD2: PEMFC temperature management for high performance (TMHP)
- PhD3: Materials for proton conduction at Intermediate Temperatures (MATITE)
- PhD4: Degradation resistant operation and shutdown (DROAS)

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 working with biological fuel cells.

The PhD2 project was launched on 2022-10-10, 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. She is a graduate of Chalmers with a background in Chemistry and a strong record of project work in Prof. Anna Martinelli’s research group.

The PhD4 project was launched on 1st of September 2023, with the appointment of Gnana Lahari Kothala, an industrial Ph.D. student recruited by Volvo. Lahari is a graduate of Andhra University, India with a degree in Chemical Engineering and previous experience in PEMFC testing.

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 12 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.

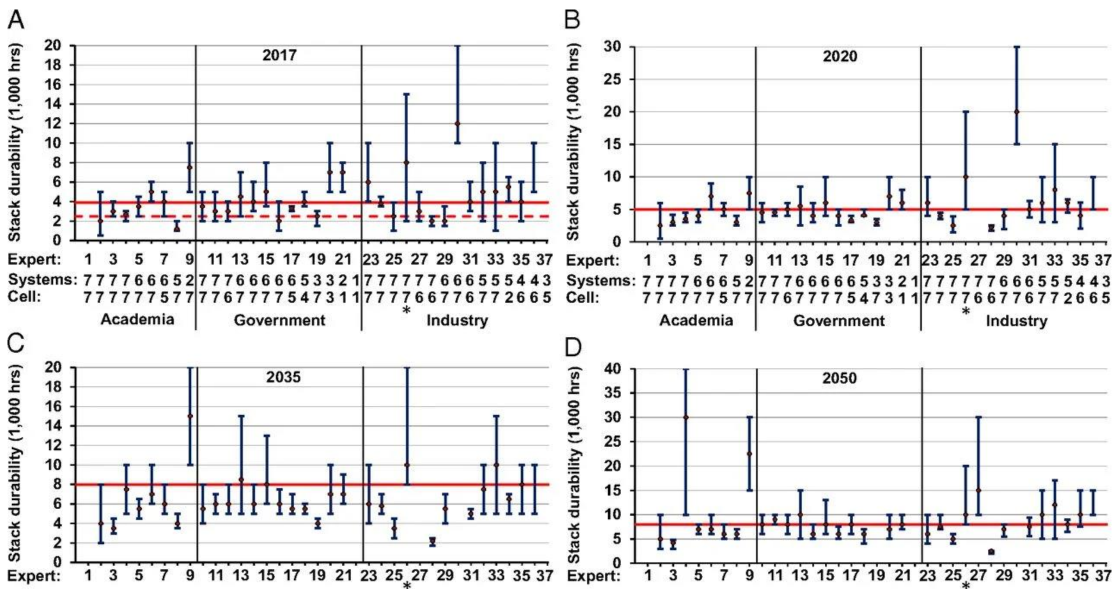

Figure 12: Assessment of PEMFC stack durability (A) 2017 values. (B) 2020 values. (C) 2035 estimate. (D) 2050 estimates. The solid lines represent DOE targets for stack durability. Courtesy of PNAS 2019, 116(11) 4899-4904.

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 (ECSA). However, the combined MEA (Membrane Electrode Assembly) 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 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.

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 but also some opportunities to repurpose waste heat for battery management and auxiliary use with a comprehensive temperature control strategy.

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 disordered polymer membrane with a structured, covalently bonded network offer huge opportunities for improving lifetime and reducing cost. The PhD3 project, led by Anna Martinelli is planned to explore this approach. On a systemic level, the focus will be on consequence for 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.

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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.

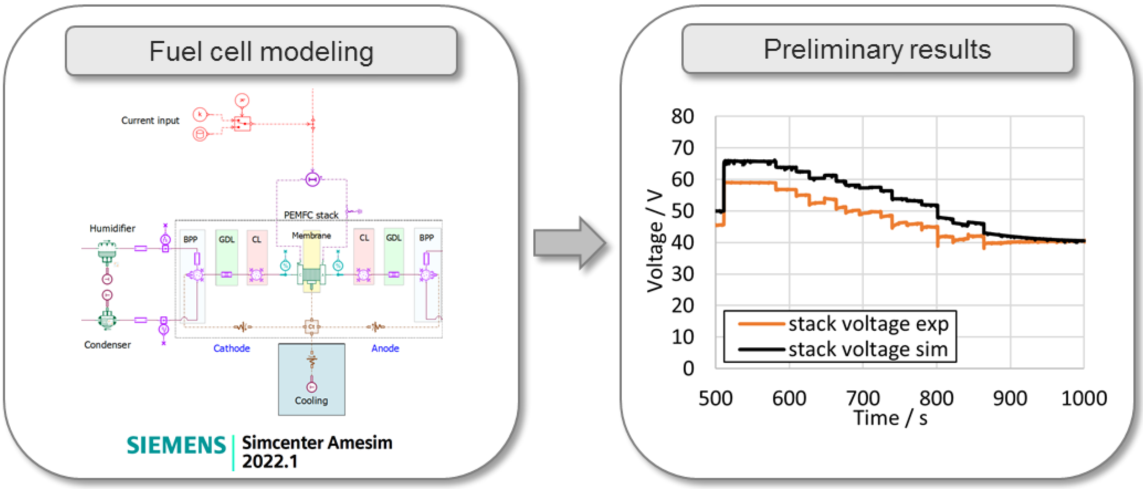

Figure 13: Preliminary model results, together with PEMFC experimental data (5 kW short stack).

A preliminary model with an idealized cooling setup has been implemented in Simcenter Amesim. Figure 13 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 widely varying power demands which are common in road transport give rise to transients which can severely impact the durability of PEMFC components. Likewise, frequent startup, idling, and shutdown conditions pose degradation challenges for PEMFC electrodes and membranes. These unsteady conditions promot imbalances in the chemistry, temperature, pressure, and humidity control which lead to miniscule material changes in the fuel cell stack which gradually contribute to performance degradation.

The PhD4 project focuses on identifying the main operational conditions which lead to performance degradation for the PEMFC stacks (2x, 150 kW) used in the Volvo AB fuel cell truck, with a focus on developing control strategies that optimize idling performance and robust shutdown capability. This entails investigation of high cathode potentials (>0.8V) and voltage cycling conditions and the resulting effects on MEA stability in a full-scale PEMFC stack. A hybrid truck system model will be developed to link operational parameters of the PEMFC stack and dynamic power demands which are relevant to real-world road transport applications. Accelerated stress testing (AST) of scaled fuel cell stacks will be used to validate system modeling results and inform control strategies for the hybrid powertrain.

Progress in relation to project goals

The projects aim to contribute to developing design methods for hydrogen driveline integration in powertrains relevant to road, air, and sea vehicles (R4a). Here, progress has been made in implementing simplified PEMFC stack models, including a Matlab/Simulink model with idealized cooling and boundary conditions, and a Simcenter Amesim model with a simple cooling loop. The Amesim PEMFC model has now been integrated with a custom balance-of-plant hardware model parameterized in cooperation with a number of OEM collaborations and supplemented with literature values.

A further aim is to develop quantitative models for usage vs. durability (R4b). This will be addressed in the PhD1 project which started in 2023-05-01. A simple PEMFC model has been developed in Amesim. For now, work here focuses on improving/replacing water transport used in the model and integrating submodels to track membrane stress, chemical activity, and hydration.

An important project aim is to demonstrate next generation fuel cell concepts (R7c and R4c). This should be addressed in the future fuel cell work led by Anna Martinelli and informed by PEMFC system modeling results from more advanced system models developed in year two or three of the PhD1 and PhD2 projects.

Another aim is to demonstrate concepts for more sustainable use of materials on the stack level (R7a, R7b and R4c). This goal requires the expansion of the fuel cell testing capabilities leveraged by TechForH2 at Chalmers. Implementation of the test-bench hardware is underway, with plans for installation of the chassis, cathode loop, and control system in the Nov/Dec. 2024. This aim also served by the upcoming work led by Anna Martinelli.

With respect to dissemination one conference contribution and one journal paper are underway for 2024. The projects are slightly behind due to delayed starts. Notice that the Ph.D. projects have run 39 months in total at the time of writing (plan for first year was 24 months).

With regard to teaching impact (D6), both David Sedarsky and Anna Martinelli have contributed with invited lectures in a Chalmers course: TRA105, 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”. Ahmed has a background in electrical engineering from Cadi Ayyad University, Morocco and experience with PEM fuel cell systems working at PSL University, France. Ahmed is currently on parental leave with plans to continue modeling work in 2025. The following papers have been produced [17]:

- 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 [18].

Senior work on system modelling of efficiency in electrified powertrains are reported in [18, 19]:

- 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 [20]:

- 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.

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 formulating this project and have during 2023 participated in different types of reference groups meetings.

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 during 2023 one Ph.D. student has been recruited. In addition, Chalmers has supported the project by two postdoc projects Hydrogen in transport – Global, European, and Nordic perspectives (Chalmers AoA Transport) (postdoc: Jorge Velandia) and Systems assessment of hydrogen and electrofuels in transports (Chalmers Genie) (postdoc: Hadi Farabi). The two postdocs are also engaged in the community of the competence center on catalysis (KCK).

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 and started 1st of March 2023.

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 350 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.

During 2023 the Horizon Europe project Advanced POwer conversion technologies based on onboard ammonia cracking through novel membrane reactors (APOLO) was granted and is starting from 2024. In this project environmental and cost assessments of ships using ammonia and hydrogen will be performed.

Research production

During 2022 and 2023 work on a number of publications connected to the centre was initiated and progress in terms in of submission is reported below [21, 22]:

- 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.
- 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.

Under production:

- LCA of multiple ways of producing and distributing hydrogen used in 7 trucks configurations (Velandia et al, Brynolf, Grahn and Blekhman co-authors),
- “Global policy instruments for a fossil free shipping sector and potential impacts on cost-effective fuel choices.” This paper assesses the effect on fuel mix for the marine sector depending on different CO_2 reduction policies, hydrogen is one of the alternatives in the fuel mix (Farabi et al, Brynolf co-author).
- “The future role of liquid fuels - Insights from global energy systems modeling and views from a Swedish local energy cluster in transition.” This article assesses global scenarios of future fuels including hydrogen for different transport modes (Johansson et al, Brynolf and Grahn co-authors).
- “Hydrogen for heavy-duty road transportation: How much and where? Modelling geospatial distribution of energy consumption in Europe” (Löfving et al, Brynolf and Grahn co-authors).
- Hydrogen demand in European heavy-duty transport – geospatially distributed scenarios for long-haul trucks, ships and aircrafts (Löfving et al, Brynolf and Grahn co-authors).

The research topics

To address the challenges with production and distribution of hydrogen on a societal scale across all of Europe, this project has during its first year focused on the creation of an energy demand distribution model. This is important in order to give more geographical detail in different scenarios for demand. Data generated by this model will, in the later stages of the project, feed into an energy systems optimization model (see Figure 14) that will be built to analyse suitable strategies to meet the future demand for hydrogen. The demand model combines national models for projections on future levels of transport work, with models for determining energy demand on truck-, shipping-, and aviation routes in Europe. Two papers are currently in progress, detailing the combined model (which we call SVENG – Simulating Vehicle Energy Needs Geospatially) and some results.

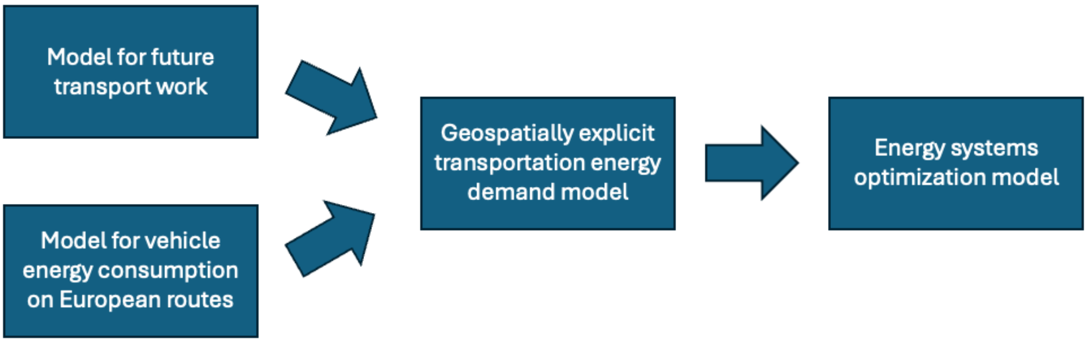

Figure 14: Illustration of models under development and how they relate to each other.

Some preliminary results from the demand model are shown in Figure 15. Possible distribution of hydrogen demand from trucks in 2050 is shown in the left and centre of Figure 15. A hydrogen refuelling station distribution algorithm has also been developed, to find places potentially suitable to build stations from a demand perspective. A preliminary result from this one is shown in Figure 15 to the right. One of the partners in the HyTruck project is the University of Tartu, Estonia, and they focus on developing hydrogen refuelling station locationing models with higher detail concerning the physical suitability of a location. We aim to explore a combination of our models later in the projects.

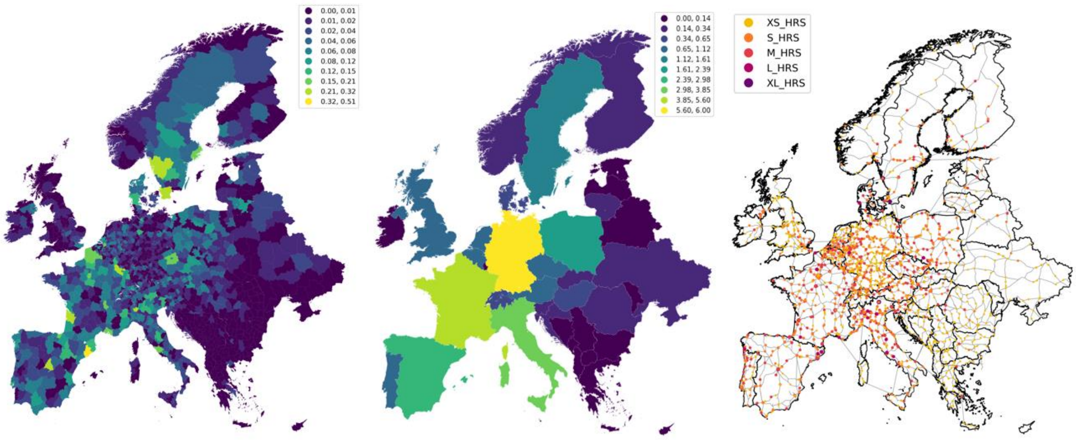

Figure 15: Illustration of models under development and how they relate to each other.

Whereas demand modelling will be the focus of the work preceding Joel's licentiate, planned for submission in the first half of 2025, the energy systems optimization model will be the focus of the remainder of the project. Apart from using the data from the demand models, we plan to draw on the academic High Performance Computing (HPC) resources at Chalmers and nationally, through centres such as E-Commons, NAISS, and UPPMAX. This since a Europe-wide energy systems optimization model will be very computationally resource intensive to solve. In doing so, we aim to include a comprehensive set of features detailing the energy system and capture a high level of detail in both time, geography and different industries. Once we have some results on potentially suitable strategies for energy infrastructure to supply hydrogen for transportation, we aim to investigate further cost- and environmental aspects of these strategies.

The two postdocs, *Jorge Velandia and Hadi Farabi*, started their work in early autumn 2022 and below are summaries of their ongoing work:

Postdoc: Jorge Velandia
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

Introduction: Transport decarbonization has heavily relied on the deployment of battery-powered vehicles. In contrast, hydrogen has been considered as an alternative for decarbonizing other sectors, difficult to electrify. Long-haul transport is one of such sectors, in which some features render the use of batteries impractical. For instance, addressing range constraints would likely require heavy on-board batteries and fast charging infrastructure along the roads, creating large demands of power from the grid, while also negatively affecting the battery life expectancy. The aim of this project is to estimate the environmental burden of using green and blue hydrogen in fuel-cell trucks (FCT) and internal combustion engine trucks (ICET) via life cycle assessment (LCA). The geographical scope of the study includes the use of the vehicles in Sweden, but we explore the environmental consequences of hydrogen production in other geographies. Moreover, as transport and distribution of hydrogen is expected to represent a significant share of the environmental burden, we evaluate both centralized and on-site production of hydrogen. Furthermore, we evaluate several storage pressures on-board the trucks and two different configurations for batteries and fuel cells.

Method: We apply the LCA methodology which quantifies the impacts from the cradle to the grave of a product. In order to determine the final product system to be evaluated we first selected the pathways of transmission and distribution of hydrogen. We ended up including two cases of hydrogen production abroad which is then imported to Sweden, on liquid state, via tanker. It is important to highlight that our product system includes the creation of the so-called Gothenburg hydrogen hub; a logistic hub at the city gates where hydrogen is stored at large scale to guarantee supply for the future hydrogen economy. The time scope for our analysis is the decade between 2020 and 2030.

Results: As of March 2024, we have managed to complete the basic literature review which provides data for feeding the model in the OpenLCA software. However, as the technological advances and public policies for the hydrogen ecosystem remain changing on a daily basis, we keep on checking for new developments. The construction of the model for hydrogen production, both green and blue, has been completed based on the available literature. As an additional case we are including a pathway of hydrogen production using Swedish biomethane as feedstock. Furthermore, the modeling of the vehicles, FCTs and ICETs, has been concluded and we are validating our results with automotive industry specialists. Initially, we considered the modelling of only one FCT and one ICET; However, as new evidence appeared suggesting the environmental importance of vehicle design parameters, we decided to construct eight different models for the vehicles. Six of them are FCTs, four of which store hydrogen in gaseous form at 350 bar and 700 bar; in the other two FCTs hydrogen is stored on liquid state. Moreover, FCTs will face challenges when peak power is required on real-life driving conditions, thus it is still uncertain what would be the optimum balance between fuel cell capacity and battery capacity. Thus, to deal with the uncertainty, for each one of the hydrogen storage configurations we added two cases, one where the power needs are to be provided mainly by the batteries and another where the peak power requirements will be mainly faced by the fuel cell. Figure 16 depicts the preliminary results for carbon footprint for the 700 bar FCTs, based on the truck components (kgCO2eq). Finally, we have selected the final routes of transmission and distribution of the hydrogen. Furthermore, we are defining the energy consumption, potential leakages, and the infrastructure requirements for each one of the routes. After this process is finished, we will validate our results with David Blekhman, professor at Calstate LA, California, who has agreed to collaborate with us in the research paper being prepared. The research team has held discussions with experts along the entire supply chain, aiming to obtain feedback on the assumptions and preliminary results that have been obtained. The experts were part of the automotive industry, gas liquefaction and compression companies, fuel cell and battery researchers, oil refining companies and representatives from ports and gas transportation companies.

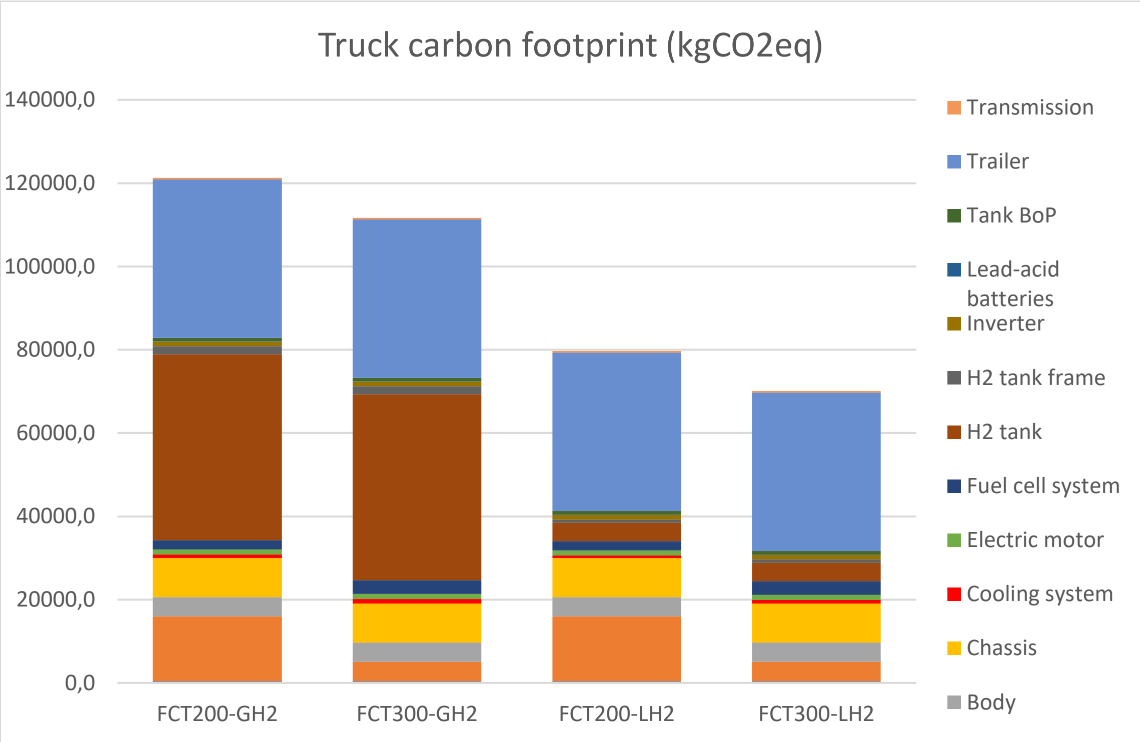

Figure 16: Preliminary carbon footprint results for 4 different versions of Fuel cell truck.

Postdoc: Hadi Farabi
Project: Systems assessment of hydrogen and electrofuels in transports.
Funder: Chalmers Genie.
Partners: Chalmers University of Technology, and IVL Svenska Miljöinstitutet AB (more to join).

Introduction and aim: Road freight transport accounts for almost one-fifth of the transport sector's GHG emissions in Europe. Considering the projections for the increase in road freight volume in the coming years (1% per year until 2050), the transition to zero-emission technologies in this sector must be accelerated. Alongside influential factors, such as improving efficiencies, shifting to less-emitting modes of transport, and avoiding increased transport activities, the application of policy framework has a key role in enabling and driving the transition to zero-emission road transport. Considering a whole-system approach, this study quantifies the long-term effect of applying market-based and regulatory policies on the future of road freight fuel mix and emissions.

Method: In this study, we assessed a selection of policy instruments for the decarbonization of road freight transport using global energy systems modeling. Global Energy Transition (GET) model was first developed by Azar and Lindgren. The geographical coverage of the GET model is global, in 10 regions. We followed a whole-system approach, covering the energy supply (including the trade between regions), energy conversion, energy demand, and a carbon cycle as part of the model. Our model considers carbon constraint and energy demand and minimizes the discounted total energy system cost (least-cost optimization) with a bottom-up approach in a linear programming problem. We have 10-year time steps in the model, and the study period is until 2100. The demand scenario in this study is based on the Shared Socioeconomic Pathways (SSP) scenarios (SSP2) from the IIASA SSP database. The propulsion technologies in the road freight transport sector of our model are internal combustion engines (ICE), fuel cell vehicles (FCV), hybrid, battery electric vehicles (BEV), and plug-in hybrid electric vehicles (PHEV). The available fuels are diesel, natural gas, liquid synfuel (here representing diesel or methanol from bio, electro, or natural gas production pathway), hydrogen, and electricity.

Results and discussion: Table 3 shows the assessed market-based and regulatory policy options. In all scenarios, including the Base case, there is a cap on commutative emissions of the whole energy system (905 Gt-CO2). Figure 1 shows the sample results on the choice of propulsion systems and fuel mixes to meet the demand (EJ). Comparing the results in the propulsion part shows that the large-scale application of new propulsion systems such as BEV and FCV have difficulties being cost-effective solutions until the mid-century, in the absence of extra policies. By applying policies, BEV and FCV could start playing roles in the near-term future with relatively high share and minimal share, respectively. In the fuel mix part, the share of hydrogen is zero by mid-century in the absence of added policies. Hydrogen's contribution starts with a minimal share in the near-term future by applying the policies and taking off the next time steps. Electricity is expected to play a considerable role in meeting the demand, even early time-steps. However, by reaching the end of the century, electricity loses the competition to hydrogen in most scenarios. The results in the emission section show that while approaching the end of the century, the emissions approach zero. However, the application of policies is necessary for a fast emission reduction and to achieve the zero-emission target in the earlier time steps.

Table 3: Analyzed policy instruments for the road freight transport sector.

Scenario	**Policy measures**
Base case	Without additional policy interventions
ETS	Emission trading scheme for the sector (a stepwise cap on the direct emissions of road freight transport)
Low levy	Global carbon levy for the sector (50 USD/ton-CO_2 from 2030 onwards)
Moderate levy	Global carbon levy for the sector (50, 100, 150 USD/ton-CO_2 for 2030, 2040, 2050-2100 rep.)
Fuel quota	Mandates for using alternative fuels in the sectors (15% in 2030 and adding 15% every decade)

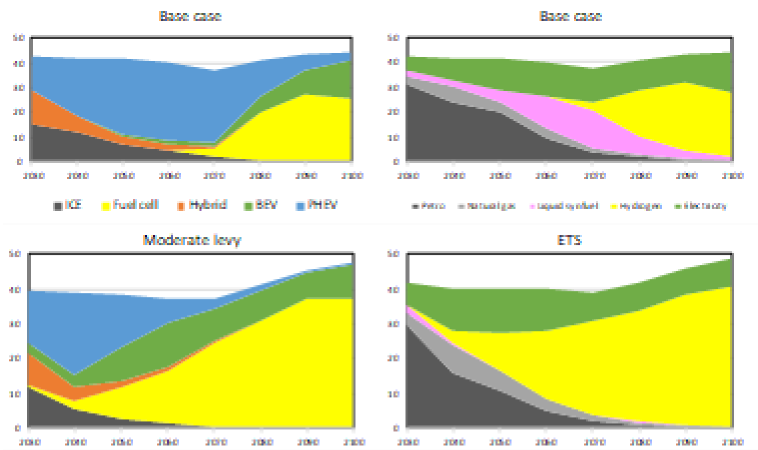

Figure 16: Sample results on propulsion systems (left), fuel mix (right).

Progress in relation to project goals

This project area 5: The future of hydrogen – societal challenges (initiated within the centers research discipline Transport and Society) have two main research goals: R5a. Develop comparative cost and sustainability methods for hydrogen use scenarios and its relation to transport and hydrogen society as a whole, and R5b. Interlink market needs and support innovation owners by surveying and trending technology usage in different hydrogen use fields. The work towards R5a started first of April, 2023, and R5b will be continuously worked on throughout the project. The milestone Mile6 with a first scenario defined by M12 is underway and will be published in forthcoming work. This project has no specific innovation goal, but the knowledge and insights generated from the project will support the industry including small and medium enterprises when taking decision about areas of innovation to focus on.

The project aims to contribute to all of the dissemination goals, what was accomplished during 2022 and 2023 can be seen in italic, below:

• D1a. The aim is to publish one paper per year in the project "The future of hydrogen – societal challenges". Additionally, we aim to publish about 10 collaborative papers during the five years of the project. In connection to the research collaboration network first and foremost together with the identified research group at Aalborg University and with David Blekhman at California State University. *See publication plan below*.

• D2a. Attend the centre's annual conference presenting results from the project. Project leader will further help out in organizing the conference including invite speakers. *Not applicable for 2022-2024.*

• D2b. Arrange at least one workshop at an industrial partner of the centre to ensure interaction across TechForH2. *No such workshop was arranged during 2022-2023* for this multidisciplinary research area.

• D3a. Co-publishing with the research collaboration network. Yes, two hydrogen-related papers were published in collaboration with Aalborg university during 2022, [23, 24],

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

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.

• D3b. Develop a visiting researchers' strategy through the international research collaboration network, where recruited Ph.D. student is encouraged to spend time at relevant international university. At least one postdoc, with a non-Swedish citizenship, will be connected to the project. *Jorge visited Cal State Los Angeles and David Blekhman during summer 2023. During Oct-Dec 2023, Joel made a research visit/internship at Lawrence Berkeley National Lab (LBNL), in Berkeley California. The purpose of the visit was to learn more about the developments in hydrogen technology for transportation in the area, policy instruments used to facilitate the process, modeling efforts and projections for the future, as well as networking with researchers, politicians, and industry in California. The trip was funded by Göran Wallberg memorial scholarship, A.H. Lindfors scholarship, and a travel grant from the department of M2. Apart from LBNL, Joel visited individual researchers as well as seminars and conferences at UC Berkeley, UC Davis, Stanford, and Cal State Los Angeles. The latter is a partner university to the center, and Joel continues a collaboration with Dr. David Blekhman there on curriculum development for courses in hydrogen technology. Among industry and political entities, Joel visited multiple public transport agencies using hydrogen in their vehicles, vehicle manufacturers, and legislative representatives. Other outcomes from the trip include contacts for future collaborations and knowledge sharing in Sweden about the market for hydrogen technology in California. In between these occasions, during September 2023, David Blekhman visited Chalmers and AB Volvo.*

• D4a. Contribute to at least 2 invited/panel talks *During 2022 we were invited to three panel talks: (1) 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). (2) 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) (3) Selma Brynolf was invited as a panelist at "SamspEL Arena: Framtidens elbehov.". She presented the TechForH2 center and hydrogen related research at Chalmers (2022-12-08). During 2023, Maria Grahn was invited as key-note speaker at the IEA Combustion TCP 45th TLM conference. System-level assessment of fuels for transportation, Hotel 11, Gothenburg (2023-06-21).*

• D5a. Meet experts at the Swedish transport administration, as well as the Swedish Energy Agency, to discuss the future of hydrogen in Sweden. *No such meeting was arranged by this multidisciplinary research area during 2022-2023.*

• D6a. Through the technology and innovation advisory group arrange at least 1 hydrogen related invited lecture at Chalmers courses. *No such lecture was arranged by this multidisciplinary research area during 2022*.

• D6b. Disseminate new knowledge through existing and new courses, e.g., the courses "TRA105: Fuel cell systems", "TEK: Sustainable transport", "SJO851: Towards Sustainable Shipping", and "MVKF25: Hydrogen, Batteries and Fuel Cells (in Lund)" *Maria Grahn, Selma Brynolf and Joel Löfving presented the aim of the TechForH2 center at all mentioned courses listed above during 2022 and 2023. A new course*

Modern Energy Technologies and Systems (TRA355) was launched Sept 2023 where Maria Grahn as well as Björn Wickman disseminated new hydrogen related knowledge. Joel has initiated two projects in collaboration with Swedavia, where four master's students (two of whom Joel is supervising) are investigating different aspects of the future implementation of hydrogen for aviation at Landvetter airport outside of Gothenburg. Joel continues a collaboration with David Blekhman there on curriculum development for courses in hydrogen technology.

• D7a. Disseminate research results and other relevant news from the project through Chalmers different media platforms, e.g., the newsletters of Area of Advance Energy and Area of Advance Transport. *No activities during 2022. During 2023, two dissemination activities was produced and spread through Chalmers media platforms (1) Maria Grahn was interviewed by the Chalmers' podcast Vera-podden, about hydrogen as a fuel for the transport sector: https://verapodden.podbean.com/e/maria-grahn/ (27 min) and (2). In November 2023 Chalmers also wrote an article about the annual TechForH2 meeting that was spread in different Newsletters, e.g., Area of Advance Transport and Department of Mechanics and Maritime Sciences: https://www.chalmers.se/aktuellt/nyheter/m2-vi-ska-inte-vara-radda-for-att-ta-risker/*

• D7b. Use the Chalmers Area of Advance as well as the linked-in platform to spread and discuss center activities such as recruitment and dissemination events. *The recruitment announcement for PhD student 2022 was spread through Area of Advance Energy's newsletter. A joint linked-in-post collecting five simultaneous applications was performed.*

• D7c. Publish at least 2 times in newspapers and/or popular science forums to increase public interest for project results and TechForH2 activities. Involved researchers in the project will at least 3 times speak about research results in local and/or national radio, as well as while being guest in different podcasts. *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. During 2023, Maria Grahn was interviewed eight times about the future of hydrogen in transport and society resulting in (1) the article "Porsche och SAS satsar på E-bränsle" published in SvD Näringsliv 2023-02-24 written by Tomas Augustsson (svd.se), (2) the radio P1 broadcast StudioEtt about the future of hydrogen and electrofuels. Interview by Camilla Widebeck 2023-03-17. (3) Interview by Nic Townsend at Spoon agency, on behalf of Volvo Group, about the overarching research results of future fuels for heavy duty vehicles, resulting in a film (2.16 min) and a text presented at https://www.volvotrucks.se/sv-se/news/magazine-online/2023/jun/olika-vagar-till-fossilfri-framtid-for-lastbilar.html (4) the article "Gamla bränslen på nytt sätt" written by Thomas Drakenfors, published in FKG (Fordonkomponentgruppens) newsletter 2023-05-24 https://fkg.se/gamla-branslen-pa-nytt-satt/ (5) a feature on the TV news (1 min), broadcasted by SVT Nyheter Blekinge, about hydrogen and electrofuels. Interview by Wivan-Kristina Sandberg, 2023-06-14* https://www.svt.se/nyheter/lokalt/blekinge/forskare-elektrobranslen-fyller-en-viktig-funktion-i-omstallningen-till-fossilfritt. *(6) the article "Gryende marknad för elektrobränslen" publicerad i tidningen Energi: ett magasin från Energiföretagen 2023-11-13. Interview by Carl-Johan Liljengren. https://www.energi.se/artiklar/2023/november-2023/gryende-marknad-for-elektrobranslen/ (7) the article "Första flygningen över Atlanten med förnybart bränsle" published in Göteborgs-Posten December 2023* https://www.gp.se/nyheter/varlden/forsta-flygningen-over-atlanten-med-fornybart-bransle-.4b5cf7b9-d7ce-457d-b91c-d2172240fbcd *(8) the TV-show SVT Morgonstudion 2023-11-28 (4 min) about future fuels for aviation: https://www.svtplay.se/video/jawzJNE/morgonstudion/idag-06-00?position=660&id=jawzJNE*

• D7d. Involved researchers in the project will carry out at least 20 presentations at industry and/or society presenting the center and discussing project results. *During 2022 (1) Maria Grahn was giving a speech at the maritime industrial network day arranged by Svensk Sjöfart in Helsinki, Finland. She presented the TechForH2 center and hydrogen related research results focusing on hydrogen as a marine fuel (2022-09-01), (2) 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). (4) Selma Brynolf was invited to Johnson Matthey to present hydrogen research and the TechForH2 center (220908). (5) Maria Grahn and Selma Brynolf was invited to Volvo Penta to discuss Future fuels and* *energy carriers. The TechForH2 center and the potential role of hydrogen in shipping were discussed (220902). During 2023, Maria Grahn held nine presentations outside the academia about hydrogen and future fuels for heavy duty transport (1) the 12th of January she presented on-going e-fuel and hydrogen research, for ABB in Gothenburg (2) the 1st of February she presented the centre TechForH2 for an audience of mixed actors at the Industrial network day, f3 Innovationskluster för hållbara biodrivmedel, in Lund. (3) the 7th of February she presented on-going e-fuel and hydrogen research, for Siemens Energy in Finspång (4) the 1st of March she presented research results on e-fuels and hydrogen for Volvo's engine veterans, in Gothenburg (5) the 17th of April she presented on-going e-fuel and hydrogen research, for Stena Teknik, in Gothenburg (6) 12th of May she presented research results on hydrogen and e-fuels for the Preem Refinery, in Lysekil (7) the 2nd of June she presented research results on hydrogen and e-fuels for Handelskammaren, in Gothenburg (8) the 22nd of August she presented "Övergripande om elektrobränslen ur ett systemforskningsperspektiv: utmaningar och möjligheter" for a broad audience of mixed actors at a f3 webinar, and (9) the 11th of October she presented "Future fuels for transport: their cost-competitiveness and environmental performance" for Volvo Penta in Gothenburg. Joel Löfving presented his work and the center as a poster at the PhD course "Energy technology, policy and politics" at ETH Zürich 30th of August 2023.*

- D8a. Launch and examine 1 Ph.D. student within this project. *Joel Löfving started 1st of April 2023.*
- D8b. One licentiate thesis defense. *Not applicable for 2022-2023.*
- D8c. Develop common activities and arrange seminars for the postdocs involved in all the centre's suggested projects. *No such seminar was arranged during 2022. Postdocs are included in the TechForH2 PhD and Postdoc seminar series initiated during 2023.*
- D9a. Senior researchers involved in this project will constantly contribute to the discussions on how to involve potential new partners to TechForH2. *Yes, three potential new partners have presented themselves at board meetings.*

DISSEMINATION AND COMMUNICATIONS EFFORT

Research publications achievements

With respect to dissemination the projects are generally behind schedule, mostly due to delayed starts of the individual projects. Notice that the Ph.D. projects have, as a maximum, run a bit more than six months at the time of writing. This delay is expected to be improved upon by the collaboration of the post docs, but not to the originally planned extent. Collaborative publications are being planned with the international network.

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:

- Chalmers press release, 2022-12-01 [25].
- Chalmers press release on sensor research, 2022-12-01 [26]
- Energigas, Tomas Grönstedt, Interview, NR3, 2022 [27].
- Green Fly Way, Tomas Grönstedt, WP3 – focus area solar cells and hydrogen [28].
- P4 Göteborg, Maria Grahn, Interview – NYTT VÄTGASCENTRUM [29]
- UK – Sweden Aerospace workshop, Tomas Grönstedt – 2022-05-16
- Vätgas Sverige – Seminar, Tomas Grönstedt – Ny flyger vätgas – 2022-10-26
- 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 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)
- 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).
- 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
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- 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.
- Tomas Grönstedt gave a speech on "Hydrogen aircraft Technologies" at the SARC seminar series on the 17^{th} of August 2023.
- Tomas Grönstedt gave a speech at flygtekniska föreningen, meeting 2023-04-30 med titeln "Vätgasteknik för framtida flygplan"
- Tomas Grönstedt gave a speech for the EU-project HYTRUCK on 2023-11-03 presenting the TechForH2 research center.
- Tomas Grönstedt gave a speech for industrirådet at Chalmers on the 2023-03-15 presenting TechForH2.
- Tomas Grönstedt gave a speech presenting the center on Jernkontorets meeting 2023-10-17

- Christian Svensson popularly shared output from his research on [30, 31, 32, 33, 34].
  - https://aktuellenergi.se/framtidens-nordiska-flygbehov-kan-motas-av-vatgas/
  - https://www.energinyheter.se/20240312/30992/chalmers-dubbla-sfariska-tankar-ger-de-optimala-forutsattningarna-vatgas
  - https://www.dagensnaringsliv.se/20240312/267221/chalmers-dubbla-sfariska-tankar-ger-de-optimala-forutsattningarna-vatgas
  - https://www.transportochlogistik.se/20240312/18953/chalmers-dubbla-sfariska-tankar-ger-de-optimala-forutsattningarna-vatgas
  - https://www.travelnews.se/hallbarhet/vatgas-kan-klara-flyg-inom-norden/
- Joel Löfving presented his work and the center as a poster at the PhD course "Energy technology, policy and politics" at ETH Zürich 30th of August 2023
- *During 2023, Maria Grahn held nine presentations outside the academia about hydrogen and future fuels for heavy duty transport (1) the 12th of January she presented on-going e-fuel and hydrogen research, for ABB in Gothenburg (2) the 1st of February she presented the centre TechForH2 for an audience of mixed actors at the Industrial network day, f3 Innovationskluster för hållbara biodrivmedel, in Lund. (3) the 7th of February she presented on-going e-fuel and hydrogen research, for Siemens Energy in Finspång (4) the 1st of March she presented research results on e-fuels and hydrogen for Volvo's engine veterans, in Gothenburg (5) the 17th of April she presented on-going e-fuel and hydrogen research, for Stena Teknik, in Gothenburg (6) 12th of May she presented research results on hydrogen and e-fuels for the Preem Refinery, in Lysekil (7) the 2nd of June she presented research results on hydrogen and e-fuels for Handelskammaren, in Gothenburg (8) the 22nd of August she presented "Övergripande om elektrobränslen ur ett systemforskningsperspektiv: utmaningar och möjligheter" for a broad audience of mixed actors at a f3 webinar, and (9) the 11th of October she presented "Future fuels for transport: their cost-competitiveness and environmental performance" for Volvo Penta in Gothenburg.*
- Joel Löfving gave an oral conference presentation at Transportforum in Linköping 2024-01-18.

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/

In addition, TechForH2 has participated at internal meetings with a wider scope than the normal TechForH2 participants at Scania, Volvo, Göteborgs Energi and ABB and Johnson Matthey. This is intended to provide improved and detailed information about center activities at the companies.

The center has also committed to participate in the SHDC [35] 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.

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 and Insplorion.

The aim is also to share the center affiliation as part of publications.

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
- Dr. Soraia Pimenta (Imperial College), Research activities at Imperial Collage and TechForH2 collaborative plans, second annual conference, 2023-11-27
- Professor David Blekhman, US Hydrogen Hubs and Hydrogen Workforce Training at California State University, second annual conference, 2023-11-27
- Juan Parajo (post doc) Participant in 2nd annual conference from Professor Luis Varela group

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.

Selected strategic commitments for 2024:

- Formalize a plan for an internal review of the on-going research projects. This will be supported by the international network of TechForH2.
- Ramp up center visibility through TechForH2s communication plan and TechForH2 communicator Nadia Tahir.
- Develop a KPI-management plan

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TechForH2: who are we?

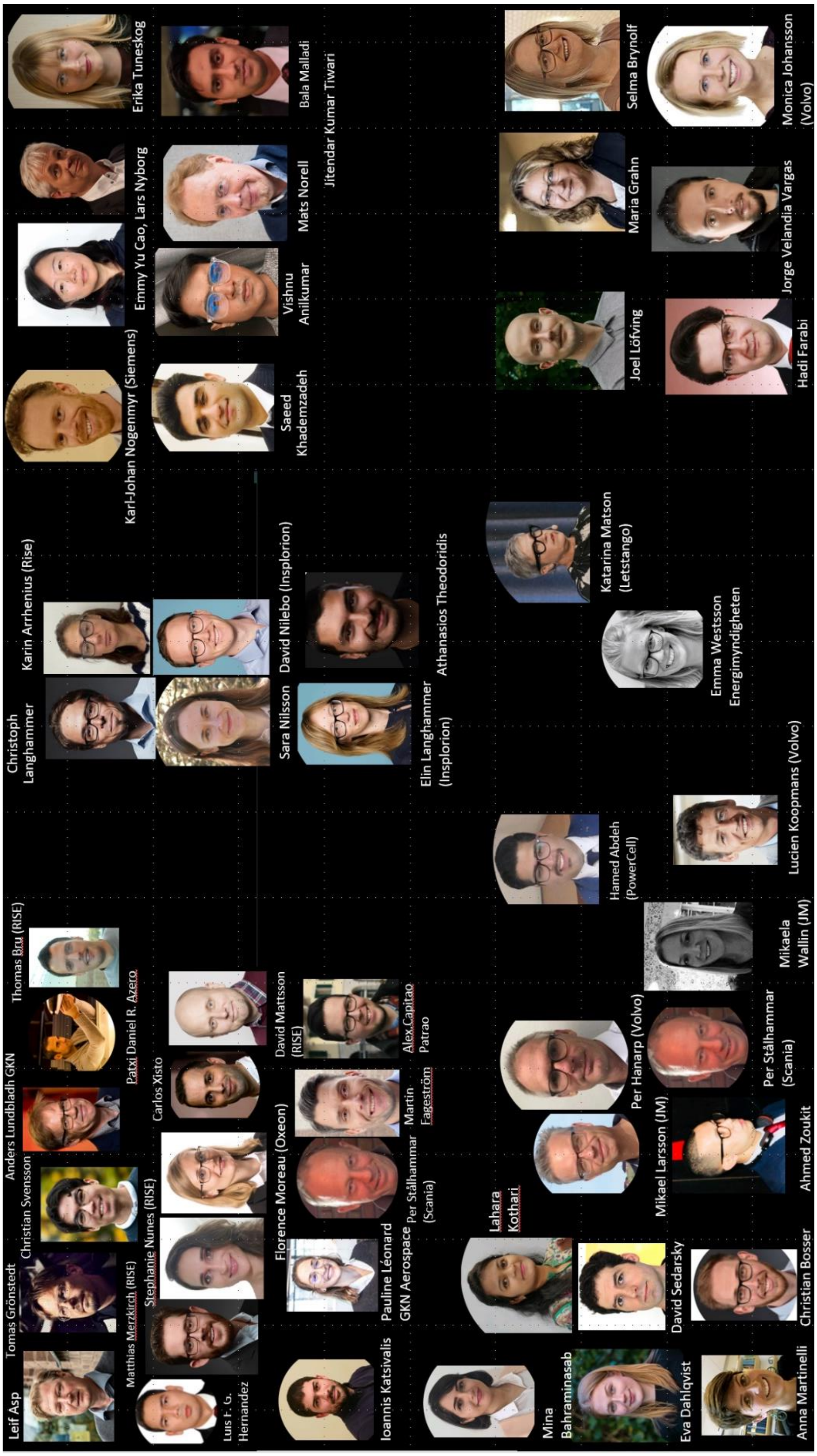

Figure 14: 2nd annual TechForH2 participants/involved personalities.