FVV PRIMEMOVERS. TECHNOLOGIES.

The FVV Transfer + Networking Event | Autumn 2023

Knowledge and technology transfer | New research programme

Science for a
moving society

Knowledge and technology transfer

Decarbonising energy production and mobility is one of the most urgent tasks facing humanity worldwide to counteract climate change effectively. FVV's members invest significant resources and effort in developing future technologies for a climate-friendly and resource-efficient transformation.

FVV supports them in this by providing an international research network in which companies, research institutes and associations conduct pre-competitive collective research into solutions for accomplishing the energy, molecule and powertrain transition as quickly as possible, thereby laying the groundwork for the mobility of the future. These research projects cover the entire spectrum of possibilities offered by innovative energy converters and alternative energy carriers, whether battery electric powertrains, the use of hydrogen in fuel cells or thermal energy converters, or other alternative concepts. The ultimate measure is the solutions' potential in reaching the set goal reliably and as quickly as possible. In this context, hydrogen presents several advantages, emitting no CO_2 when used and being easy to store and transport.

FVV has been active in the field of hydrogen use since 2016 and has initiated a multitude of research projects that help further our understanding of the complexities of using this energy carrier.

Why? Because, in addition to mobility, hydrogen will also play a role in electricity and district heating generation in the future. To what extent depends on several factors: firstly, on the availability and cost of the fuel, and secondly, on the infrastructure such as pipelines and power grids. One thing is clear though: turbomachinery will continue to make an important contribution to the energy supply in years to come. In addition to hydrogen, companies and universities are researching other alternative energy carriers such as ammonia and methanol, each of which has its own advantages and disadvantages.

At the Transfer + Networking Event held in Würzburg in autumn 2023, FVV once again presented participants with an ambitious programme on Industrial Collective Research into future technologies and, as always, an opportunity to discover how current research projects are progressing, discuss and share results and expand their personal network.

An energy carrier of the future: hydrogen

// full project information from p. 17

PROJECT 1439 · Fuel Cell Compressor Design
FOCUS Development Tools **EXPERT GROUP** Turbo Machines
APPLICATION Road, Rail, Shipping

PROJECT 1406 · Energy Recovery in Fuel Cell Applications
FOCUS Materials **EXPERT GROUP** Fuel Cells
APPLICATION Road, Rail, Shipping, Aviation

PROJECT 1442 · Hydrogen Combustion and Comparison PFI/DI Concepts
FOCUS Fuels, Efficiency **EXPERT GROUP** Engines
APPLICATION Road (Commercial Vehicles)

PROJECT 1429 · CO_2-neutral Long-haul Heavy-duty Powertrains 2050 II
FOCUS Emissions, Efficiency **EXPERT GROUP** Sustainable Powertrain Systems
APPLICATION Road (Commercial Vehicles)

Hydrogen
– an energy carrier for climate-neutral mobility

The use of hydrogen in fuel cells or combustion engines does not produce any greenhouse gas emissions such as CO_2. If the energy used to generate it comes from renewable sources, it is »green« hydrogen and completely climate-neutral. As such, its use as an energy carrier is a key pillar of FVV's research strategy for future powertrain / energy conversion systems. Thanks to FVV's research projects, significant advancements have been made in energy converter technology for hydrogen. Key results from ongoing and completed projects were presented in three sessions at the FVV Transfer + Networking Event | Autumn 2023: development tools, fuels and materials in **SESSION 1**, orientation studies, emissions and efficiency in **SESSION 2** and turbomachinery in **SESSION 3**.

Fuel cell systems

The polymer electrolyte membrane fuel cell (PEM fuel cell) is a particular focus of development in the area of fuel cell applications for car powertrains. PEM fuel cells operate using hydrogen as the energy carrier for the electrochemical reaction occurring on the catalytic cell surfaces within the stack. The hydrogen is usually supplied from pressure tanks. The required oxygen is taken from the surrounding ambient air and delivered through the stack using an electrically driven compressor.

To maximise the system efficiency of the PEM fuel cell, the sizing and operating strategy of the stack and ancillary units must be perfectly attuned to one another. The electrically driven centrifugal compressors used for turbocharging are subject to high efficiency requirements. As the largest auxiliary electrical consumer, the cathode air compressor unit offers the greatest potential for optimisation. Increasing the operating pressure of the stack, or the hyper-stoichiometric supply of reaction gases reduces the losses during the reaction,

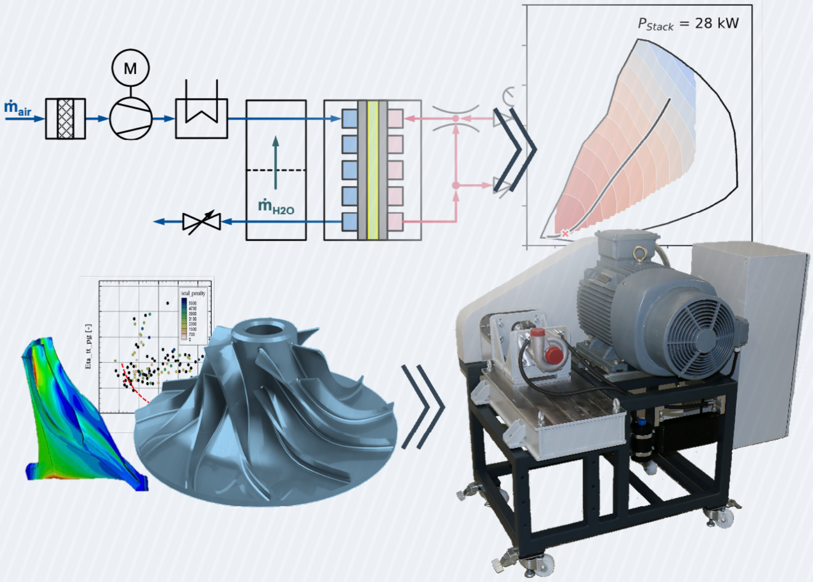


FIGURE 1

Schematic representation of the structure for the »Fuel Cell Compressor Design« project // RWTH Aachen University | TME

thereby raising the efficiency and power density of the stack. However, due to the low production volumes for PEM fuel cells, current concepts mostly use centrifugal compressors for cost reasons, even though they are not optimally matched to the requirements of PEM fuel cells. Differences arise primarily from the low speeds of the electrically driven compressor in fuel cell applications as well as the need for oil-free air bearings instead of conventional plain or rolling bearings for the compressor shaft. The results of the FVV project **»Fuel Cell Compressor Design«** funded by the German Federal Ministry for Economic Affairs and Climate Action are to serve as the basis for simplifying their design in the future. »In this project, we are devising a method to optimise centrifugal compressors for PEM fuel cells for the requirements of each application quickly and efficiently using a simulation tool,« explained project manager Thomas Hildebrandt, founder of the NUMECA engineering firm specialising in flow simulation in turbomachinery. The Chair of Thermodynamics of Mobile Energy Conversion Systems (TME) and the Institute of Jet Propulsion and Turbomachinery (IST) at RWTH Aachen University are involved in the research. »As the first step, the impact of the fuel cell system architecture on the requirements profile of the cathode air compressor unit was identified at TME. To do so, representative systems were simulated as a simple means to determine which operating strategy of the system and cathode air compressor unit offered the highest degree of efficiency. As a second step, an especially demanding use case was devised at the vehicle level,

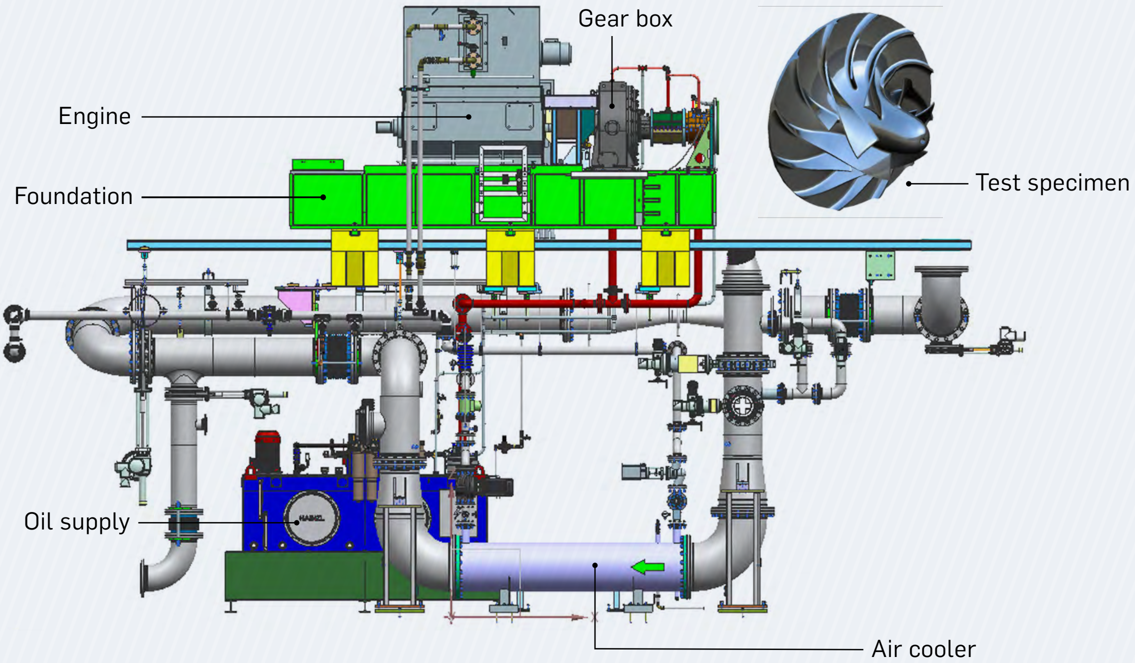


FIGURE 2

Test bench for testing centrifugal compressors // IST

and a requirements specification for compressor design was created based on the boundary conditions,« reported Julian Toussaint from TME in his talk held jointly with Janik Rajh from IST. Building on this, the aerodynamic design of the fuel cell centrifugal compressor was devised at IST as a third step. »Among other things, our research included determining the operating points for optimisation, defining the target function, parametrising the geometry, specifying the design space and building the numerical model for the optimisation process. In parallel with the aerodynamic optimisation process, structural-mechanical integrity was ensured through structural-mechanical simulations,« stated Rajh. Now that the system and component simulations have been successfully completed, the results of the research are currently being validated through prototype compressor testing on test benches. »As such, our method enables a cost-effective, purely computational compressor design solely, allowing even small series of fuel cell systems to be designed for high efficiency,« concluded Hildebrandt.

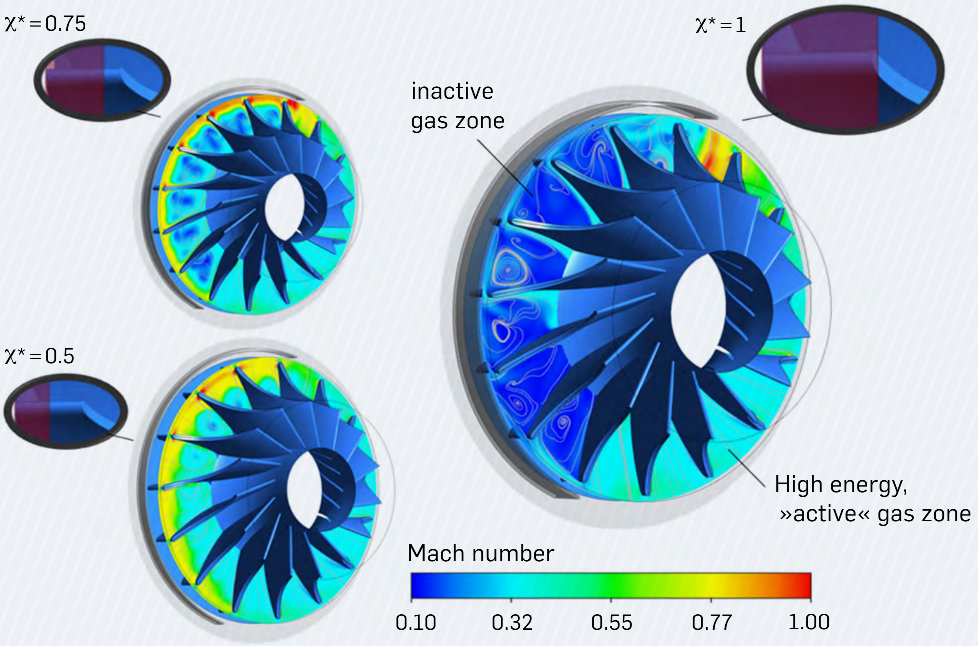


FIGURE 3

Flow simulation of the partial admission turbine with variable blockage // TFD

Further research in optimising the cathode gas path in PEM fuel cell systems was undertaken by the Institute of Turbomachinery and Fluid Dynamics (TFD) at Leibniz University in Hanover as part of the project **»Energy Recovery in Fuel Cell Applications«.** »During the course of our research, we have developed and compared concepts for improving the power density of the fuel cell system by integrating a downstream turbine with an active control mechanism,« explained Prof. Jörg Seume, Executive Director of TFD. The development of the recuperation system started with defining the requirements for a representative fuel cell system for vehicle applications and, on the basis of this, the demands on energy recovery. Different types of turbines with varying control mechanisms were then subjected to a conceptual analysis to assess their suitability based on the previously defined requirements. In addition to already established procedures such as a separate valve in the gas path, a wastegate turbine, a turbine with variable geometry (VTG) or less widespread concepts such as a »sliding nozzle turbine«, variable partial-admission turbines (VPATs) were developed for this purpose. As it turned out, blocking part of the inlet cross-section to the turbine using an axially adjustable control ring which encloses part of the turbine's circumference is a particularly mechanically robust and cost-efficient control mechanism. TFD analysed possible influencing factors for two example designs (180° and 360° ring) and calculated the thermodynamic potential. The implementation of the VPATs also entailed developing a numerical model for RANS and URANS simulations. This model was used to perform a sensitivity analysis

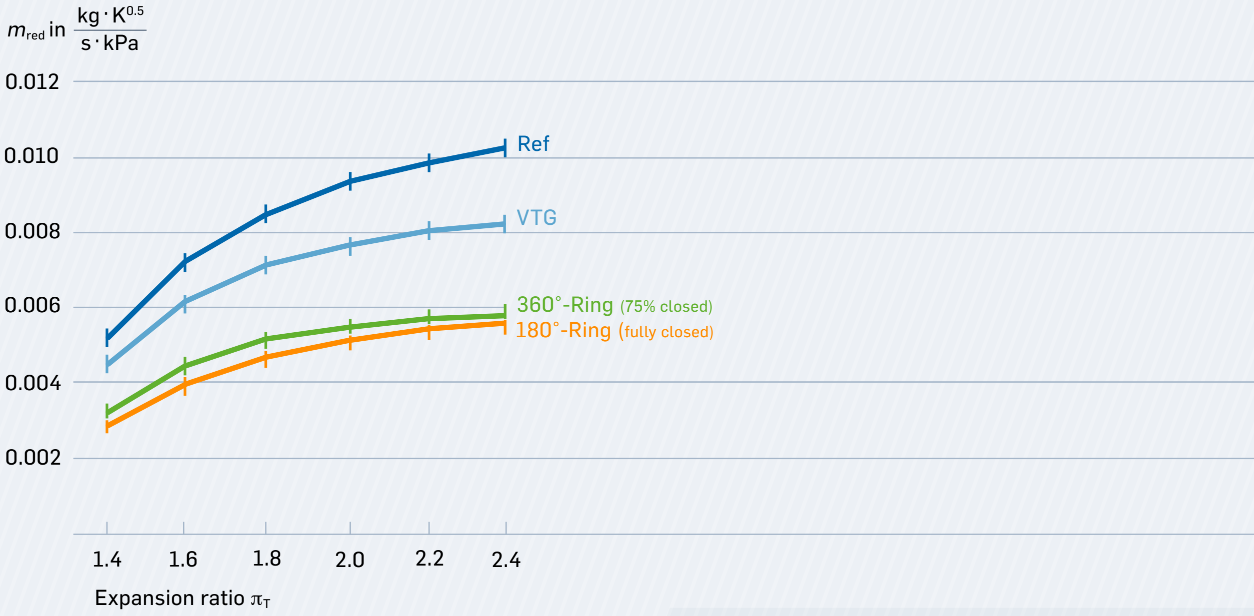


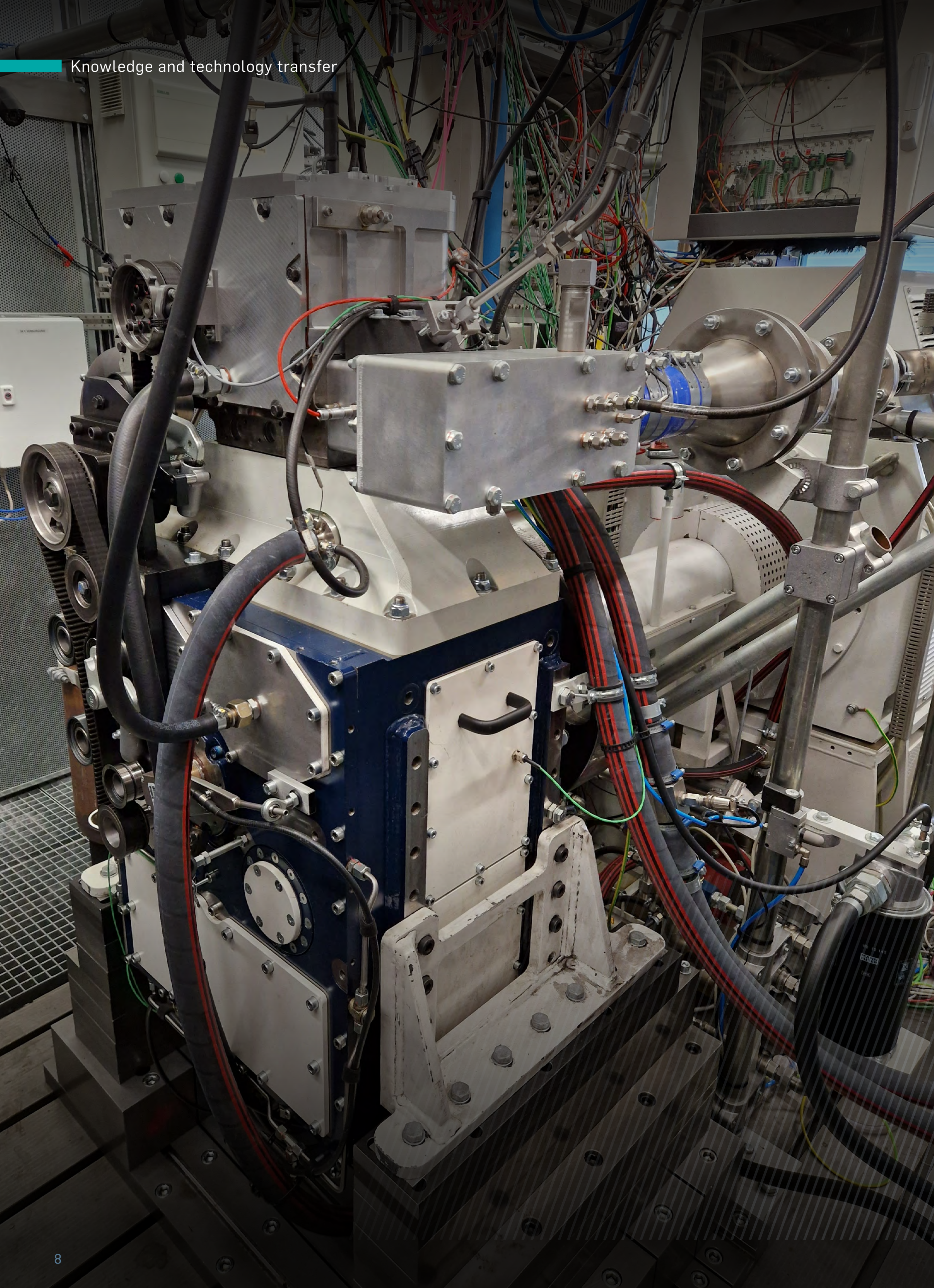
FIGURE 4

Exemplary turbine performance map with various control mechanisms // TFD

Read more:
Publication
»Centrifugal Compressors Research«
→ www.fvv-net.de

for evaluating the influence of the circumferential position of the control ring or the size of the gap between the front edge of the rotor and the control ring. »The VPAT concept turned out to be less efficient than other investigated turbine control mechanisms. If the development priorities are simplicity, cost efficiency and robustness, however, it offers advantages over established control mechanisms,« added Seume.

The chemical reaction on the fuel cell produces a large quantity of water on the cathode side. Accordingly, the components downstream of the fuel cell are exposed to very high relative humidity and must be resistant to water droplets in the flow. The radial turbine investigated in this project is positioned as close to the fuel cell as possible in order to utilise the maximum enthalpy gap. However, this also means that there is a relatively high risk of droplets hitting the impeller. To supplement the VPAT investigations, a droplet separator integrated directly in the turbine housing was examined, which offers the potential to further simplify the structure and complexity of the cathode circuit and thus make the system as a whole more affordable.



Hydrogen combustion engine

Alongside the use of hydrogen as an energy carrier in fuel cells, it is also prudent to use the element in spark-ignition combustion engines in order to decarbonise future vehicles. »Building on mature technology, hydrogen combustion engines can deliver a high power density, low operating costs, and form a reliable and robust powertrain solution, in particular for heavy commercial vehicles,« stated Prof. Thomas Koch, Head of the Institute of Internal Combustion Engines (IFKM) at the Karlsruhe Institute of Technology. However, hydrogen's physical and chemical properties differ from those of conventional fuels such as petrol or diesel, bringing both challenges and opportunities. In the FVV research project **»Hydrogen Combustion and Comparison PFI/DI Concepts«,** IFKM analysed the potential of different carburation concepts for hydrogen combustion engines in commercial vehicle applications. To this end, a single-cylinder commercial vehicle engine was equipped to run on hydrogen with port fuel injection (PFI) and direct injection and was driven on an engine test stand. At the same time, IFKM built a 3D CFD simulation model of the combustion chamber that provided detailed insights into the mixture formation and homogenisation. The design with PFI was used as a comparison basis for the various direct injection concepts with regard to the achievable performance, efficiency and emissions behaviour. One special focus of the investigations in this context was the combustion and emissions behaviour of PFI and DI as a result of variations in homogenisation within the combustion chamber. In addition, the experts analysed the extent to which jet forming caps for the injector improve carburation for direct injection. Two different cap geometries were designed to this end – one with a central hole for a compact jet, and one with four smaller individual holes for a more diffuse jet. Compared to direct injection, PFI showed better mixture homogenisation and much slower combustion, indicated by a higher burn delay and burn duration and lower pressure gradients, which is advantageous in terms of efficiency and nitrogen oxide emissions. Due to pre-ignitions, however, the achievable indicated mean pressure was limited to 18 bar at an absolute boost pressure of 3.4 bar. Direct injection with a four-hole cap enabled an indicated mean pressure of 19 bar, but accompanied by relatively high levels of nitrogen oxide emissions before pre-ignitions occurred here, too. In contrast, the system

FIGURE 5

Hydrogen engine on the test bench // IFKM

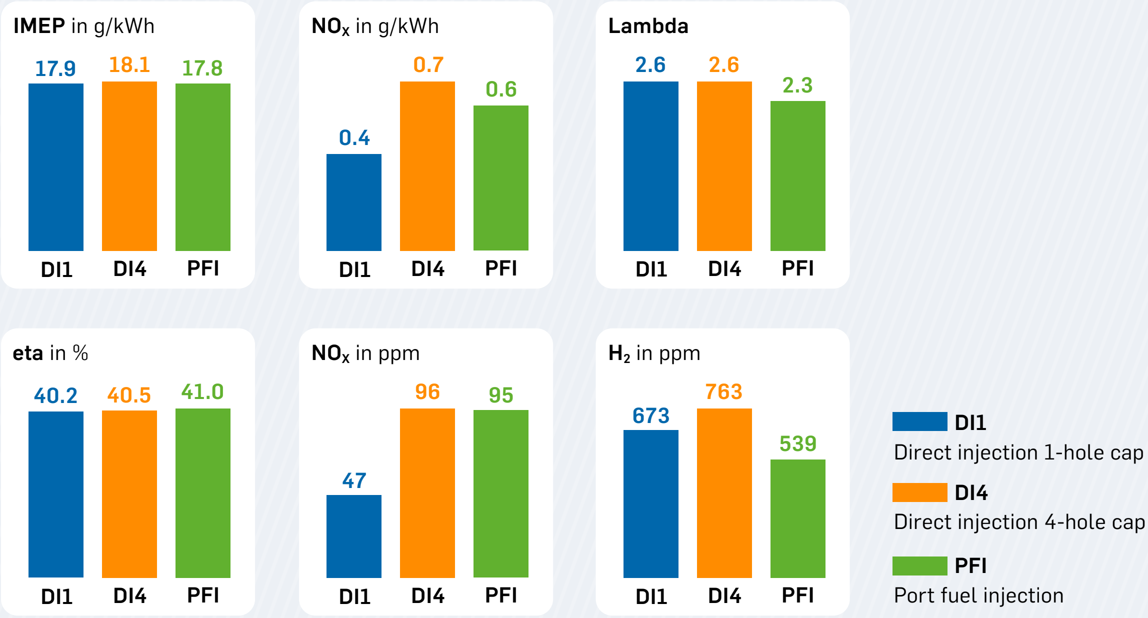


FIGURE 6

Efficiency and emissions of the hydrogen engine with the investigated injection systems at a mean pressure of 18 bar // IFKM

with the single-hole cap with a maximum indicated mean pressure of 20 bar demonstrated the greatest load capacity and was limited only by the maximum cylinder pressure of 180 bar in the investigated configuration. »All in all, we can conclude that port fuel injection offers advantages particularly at medium loads as a result of the more homogeneous carburation. Direct injection displays its strengths at higher loads, and also offers greater potential for optimisation in the system as a whole,« explained Koch. Current hydrogen engine concepts are generally based on modified diesel engines. The integration of PFI was therefore preferred to direct injection due to practicability and costs. »The results of the research now give engine and vehicle manufacturers a clear picture of both solutions' advantages and disadvantages. While a PFI concept is suitable for retrofitting, systems with direct injection are very promising for engines designed specifically for hydrogen,« explained PD Dr Reza Rezaei from IAV. »Hydrogen engines could be made more efficient in the future by combining them with intelligent functions for highly automated driving, through which the engine parameters are predictively adjusted based on environmental parameters«, he commented, looking ahead.

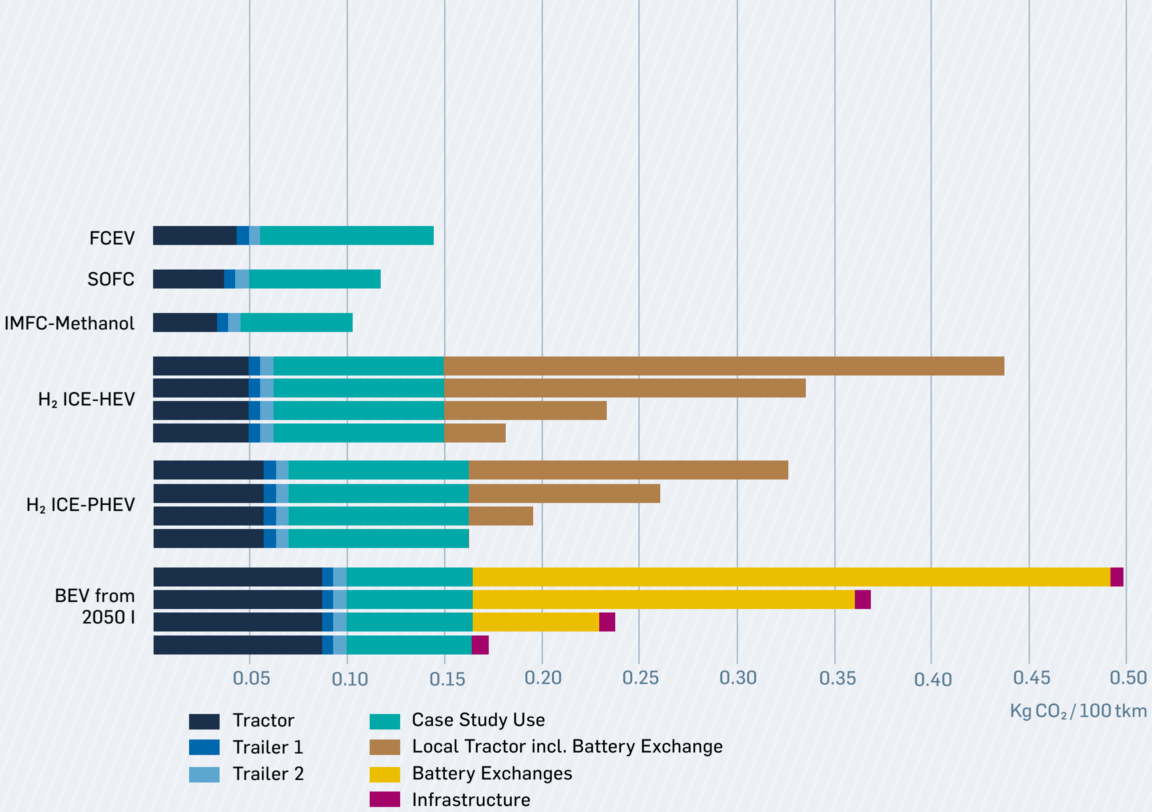


FIGURE 7

Life-cycle assessment including battery replacement for the respective powertrain variant with the best performance (for the »local tractor« of the H_2-ICE-HEV, the H_2-ICE-PHEV and the BEV, five, three, one and no battery replacements are incorporated over the lifespan in each case, from top to bottom) // IABP

Commercial vehicles in 2050

In the research project **»CO_2-neutral Long-haul Heavy-duty Powertrains 2050 II«**, the Institute for Acoustics and Building Physics (IABP) at the University of Stuttgart and IAV investigated possible powertrain concepts for future long-haul trucks and their environmental impact for the year 2050. The project builds on earlier investigations in which powertrain concepts for heavy-duty, long-haul trucks based on batteries, hydrogen, overhead cables and combustion engines were assessed from a technical and ecological perspective. The follow-up project concentrated on the use of hydrogen and methanol as energy carriers. The investigations focussed on fuel cell powertrains using the fuel variants LOHC (liquid organic hydrogen carrier), cryogenic liquid and compressed hydrogen, and hybrid hydrogen combustion engines, plug-in hybrid hydrogen combustion engines and battery electric powertrains for short-distance traffic. The objective of the research study was to provide reliable predictions on viable powertrain architectures for 2050 from a technical, ecological and economic standpoint. To this end, IAV conducted a vehicle simulation to evaluate power requirements and fuel consumption for the various powertrain configurations. »The key result of the calculations was that a truck fitted with a fuel cell system based on a solid oxide fuel cell (SOFC) combined with a 700-bar storage system has the lowest hydrogen consumption. In our observations, the use of LOHC tank systems would lower the overall efficiency

of the powertrain system,« commented Dr Dennis Jünemann from IAV. IABP's detailed life-cycle assessment (LCA) was based on the simulations. This considered all direct and indirect impacts at the different stages of the value chain when calculating the carbon footprint (cradle-to-wheel approach). For their calculations, the researchers assumed a German electricity mix for 2050 comprising a third each of hydro-electricity, photovoltaics and wind power, and resulting in CO_2 emissions of 11.5 g/KWh. In addition, they examined an electricity mix from the MENA region (Middle East and North Africa) for the production of the synthetic fuels, for which they assumed CO_2 emissions of 8.7 g/KWh. »Assuming that the climate goals for 2050 are achieved and that carbon-neutral technologies are available, the SOFC variant is the most expedient of the hydrogen-driven systems overall, as it releases low levels of greenhouse gas emissions in production and entails relatively low costs,« commented Andreas Geß from IABP. As demonstrated in a sensitivity analysis, the production of batteries makes the largest contribution to greenhouse gas emissions. »Under the assumptions made in the project, battery-driven vehicles are ecologically advantageous only when the battery does not need to be replaced during the forecast vehicle life of 1.5 million kilometres. This underlines the necessity to improve the range and lifespan of the batteries and, at the same time, minimise the costs,« explained the head of the research project, Herbert Schneider from Isuzu Motors. »With the results, we deliver a sound evaluation of the powertrain concepts currently being discussed. The industry can use this to determine which approaches are particularly conducive for their own long-term powertrain development,« added Schneider.

For this project, as in all LCAs, it was evident that the forecasts were highly dependent on the assumptions used as the basis for the simulations. In order to guarantee that the various study results are comparable by scientific standards, FVV therefore supports the standardisation of the boundary conditions and the methods used for LCAs on an EU level.

Read more:
Publication
»System efficiency«
→ www.fvv-net.de

FIGURE 8

Future study of a hydrogen-driven long-haul truck // IAV

Around 270 participants from industry and science joined in lively discussions

A total of 21 projects on scientific and technological foundations for climate neutrality and zero-impact emissions from sustainable energy conversion systems were presented

On 14 March 2024 we will meet again in Würzburg for the next FVV Transfer + Networking Event

Science for a
moving society

Keeping an open mind **for the future**

Around 270 attendees from companies, research bodies and associations came together in Würzburg to learn about the latest results of ongoing and recently completed FVV research projects. A multitude of informative presentations promoted the exchange of knowledge on future topics such as decarbonisation, alternative energy sources, fuel cell systems and new systems for the direct combustion of hydrogen (→ p. 17: research directory). The participants gained valuable support and a manifold stimuli for their own research and development activities.

In order to meet the demands of research in the future, too, FVV has restructured its research portfolio and research groups (→ p. 30: expert groups and fields of research (ToR)). The pre-competitive Industrial Collective Research organised by FVV thus provides the foundation for the development of even more environmentally friendly and resource-saving engines, hybrid powertrains, fuel cells, turbines, compressors and the corresponding energy carriers.

Live conferences are still a key medium for exchanging information and ideas and for expanding the scientific network. FVV's next transfer event is planned for 13 to 15 March 2024, and will once again take place in Würzburg.

See also:
The FVV Transfer + Networking Event | Spring 2024
→ www.fvv-net.de

Proceedings R 606
The FVV Transfer + Networking Event | Autumn 2023

→ **www.themis-wissen.de**

NR	› TITLE › FUNDING ORGANISATION	› RTD PERFORMERS › PROJECT COORDINATION	› PROCEEDINGS › FINAL REPORT
1431	› **SACI Combustion System with Active Pre-Chamber:** Investigation of the CO_2 reduction potentials of a combustion system based on spark-assisted compression ignition (SACI) in combination with an active pre-chamber › FVV	› Prof. Dr. Stefan Pischinger (tme, RWTH Aachen University) Prof. Dr. André Casal Kulzer (IFS, University of Stuttgart) Prof. Dr. Alexander Heufer (PCFC, RWTH Aachen University) › Dr. Jonas Villforth (Dr. Ing. h.c. F. Porsche AG)	› R606 (pp. 5-46)
1435	› **Modelling of Turbulence III:** Quasi-dimensional modelling of the cycle-to-cycle variations of the in-cylinder flow field with focus on high-efficiency engines (long-stroke, high-turbulence, Miller / Atkinson) › FVV, BMWK/CORNET	› Prof. Dr. André Casal Kulzer (IFS, University of Stuttgart) Prof. Dr. Stefan Pischinger (tme, RWTH Aachen University) Prof. Dr. Kai Herrmann (ITFE, FHNW University of Applied Sciences and Arts Northwestern Switzerland) › Marinus Wieser (Bosch Engineering GmbH)	› R606 (pp. 47-87)
1442	› **Hydrogen Combustion and Comparison PFI/DI Concepts:** Study of hydrogen combustion characteristics and comparison between SI and CI combustion concepts for HD applications › FVV	› Prof. Dr. Thomas Koch (IFKM, KIT Karlsruhe) › PD Dr. Reza Rezaei (IAV GmbH)	› R606 (pp. 88-117)
1377	› **Shaft Bores:** Development of a method to increase torsion fatigue strength on bored shafts › BMWK/IGF	› Prof. Dr. Tobias Melz (Fraunhofer LBF) Prof. Dr. Thomas Bergs (WZL, RWTH Aachen University) › Stefan Roth (MAN Energy Solutions SE)	› R606 (pp. 118-133) › H1346 (2023)
1402	› **Exhaust Gas Effected Tribosystems:** Characterization of the wear mechanism of unlubricated tribological systems exposed to exhaust gases › BMWK/IGF	› Prof. Dr. Peter Gumbsch (Fraunhofer IWM) Prof. Dr. Martin Dienwiebel (IAM-ZM, KIT Karlsruhe) › Dr. Heiko Haase (Rolls-Royce Solutions GmbH)	› R606 (pp. 134-146)
1406	› **Energy Recovery in Fuel Cell Applications:** A comparison of architectures for energy recovery in fuel cell systems and corresponding turbine design › FVV	› Prof. Dr. Jörg Seume (TFD, Leibniz University of Hannover) › Dr. Dirk Jenssen (Volkswagen AG)	› R606 (pp. 147-182) › H1347 (2023)
1463	› **Future Mobility Dialogue:** Developing communication methods to achieve a credible and attention-catching science dialogue on tomorrow's mobility › FVV	› Prof. Dr. Andreas Welling (IWD, TH OWL Ostwestfalen-Lippe) › Prof. Dr. Thomas Garbe (Volkswagen AG)	› R606 (pp. 183-225)
1429	› **CO_2-neutral Long-haul Heavy-duty Powertrains 2050 II:** Study on CO_2-emissions, energy consumption and costs of long-haul heavy-duty trucks with SOFC, H_2-ICE, efficiency-optimised hybrid concept considering future energy supply for 2050 › FVV	› Prof. Dr. Philip Leistner (IABP-GaBi, University of Stuttgart) › Herbert Schneider (ISUZU MOTORS Germany GmbH)	› R606 (pp. 226-260) › H1344 (2023)

NR	› TITLE › FUNDING ORGANISATION	› RTD PERFORMERS › PROJECT COORDINATION	› PROCEEDINGS › FINAL REPORT
1457	› **Acoustics of Hydrogen Piston Engines:** Detection and evaluation of the combustion noise of the hydrogen piston engine › FVV	› Prof. Dr. Stefan Pischinger (tme, RWTH Aachen University) › Dr. Stefan Heuer (MAN Truck & Bus SE)	› R606 (pp. 261-290)
1382	› **Lubrication Large Bore Engines II:** Scientific deepening of the comprehension about particle emission formation traceable to lubricating oil consumption in medium speed marine engines › FVV	› Prof. Dr. Michael Thiemke (HS Flensburg) Prof. Dr. Gerhard Matz (IAM-Hamburg e.V.) Prof. Dr. Friedrich Wirz (ASM, TU Hamburg-Harburg) › Dr. Udo Schlemmer-Kelling (formerly FEV Europe GmbH) Dr. Tobias C. Wesnigk (formerly M. JÜRGENSEN GmbH & Co. KG)	› R606 (pp. 291-324)
1391	› **Cleaning Mechanisms in the Exhaust Path:** On-board removal of carbon-based deposits from the exhaust gas path of internal combustion engines › BMWK/IGF	› Prof. Dr. Sven Kureti (IEC-RT, TU Freiberg) Prof. Dr. Peter Eilts (ivb, TU Braunschweig) › Dr. Bernhard Lüers (FEV Europe GmbH) Raimund Vedder (formerly Atlanting GmbH)	› R606 (pp. 325-359)
1398	› **TWC Impact on Particulate Properties:** Investigation of the change in particulate emission characteristics of an Otto engine in a 3-way catalytic converter › BMWK/IGF	› Prof. Joachim Mayer (GFE, RWTH Aachen University) Prof. Dr. Stefan Pischinger (tme, RWTH Aachen University) › Dr. Julie Le Louvetel-Poilly (Toyota Motor Europe NV/SA)	› R606 (pp. 360-391) › H1345 (2023)
1424	› **Fill Factor Influence:** Improving the efficiency of fast running journal bearings by targeted use of partially filled gap and pocket areas using radial journal bearings as an example › BMWK/IGF	› Prof. Dr. Hubert Schwarze (ITR, TU Clausthal) Prof. Dr. Beate Bender (LPE, University of Bochum) › Dr. Christoph Weißbacher (GTW Gleitlagertechnik Weißbacher GmbH)	› R606 (pp. 392-412)
1437	› **Squeeze Film Dampers II:** Improved transient simulation of the non-linear dynamics of squeeze-film damper-mounted rotor systems by taking into account flow and friction effects in the area of the oil feed and the anti-rotation devices › BMWK/IGF	› Prof. Dr. Elmar Woschke (IFME, OVGU University of Magdeburg) › Dr. Oliver Alber (MAN Energy Solutions SE)	› R606 (pp. 413-446)
1375	› **Brush Seals – Statistical Approach:** Use of statistical methods to describe the rubbing and leakage behaviour of brush seals › FVV	› Prof. Dr. Hans-Jörg Bauer (ITS, KIT Karlsruhe) › Joris Versluis (MTU Aero Engines AG)	› R606 (pp. 447-470)
1453	› **Modelling of Primary Atomisation Using SPH:** Modelling of primary atomisaton processes of liquid fuel using Smoothed Particle Hydrodynamics (SPH) within complex industrial applications › FVV	› Prof. Dr. Hans-Jörg Bauer (ITS, KIT Karlsruhe) › Dr. Ruud L.G.M. Eggels (Rolls-Royce Deutschland Ltd & Co KG)	› R606 (pp. 471-493)

NR	› TITLE › FUNDING ORGANISATION	› RTD PERFORMERS › PROJECT COORDINATION	› PROCEEDINGS › FINAL REPORT
1390	**› Aluminum High Temperature Fatigue:** Analytical fatigue assessment of aluminum at highest service temperatures under consideration of influencing operation specific factors › BMWK/IGF	› Prof. Dr. Birgit Skrotzki (BAM Berlin) Prof. Peter Gumbsch (Fraunhofer IWM) › Dr. Reiner Böschen (Rolls-Royce Solutions GmbH)	› R606 (pp. 494-523) › H1341 (2023)
1443	**› Centrifugal Compressor in Flexible Operation:** Aerodynamic and acoustic investigations of the interaction between impeller, diffuser and volute casing at operating points remote from the design on a representative centrifugal compressor › FVV	› Prof. Dr. Peter Jeschke (IST, RWTH Aachen University) › Dr. Matthias Schleer (Howden Turbo GmbH)	› R606 (pp. 524-557)
1439	**› Fuel Cell Compressor Design:** System efficiency optimal compressor design for PEM fuel cells in mobile applications › BMWK/IGF	› Prof. Dr. Stefan Pischinger (tme, RWTH Aachen University) Prof. Dr. Peter Jeschke (IST, RWTH Aachen University › Dr. Thomas Hildebrandt (NUMECA Ingenieurbüro)	› R606 (pp. 558-592)
1388	**› Blade Forces and System Damping:** Investigation of the resonant excitation of turbomachinery rotors and of the influence of the total system damping on the resulting blade vibration amplitude › BMWK/IGF	› Prof. Dr. Damian Vogt (ITSM, University of Stuttgart) Prof. Dr. Manfred Wirsum (IKDG, RWTH Aachen University) Prof. Dr. Bernd Beirow (SMF, BTU Cottbus) › Dr. Thomas Hildebrandt (NUMECA Ingenieurbüro)	› R606 (pp. 593-635)
1389	**› Intentional Mistuning:** Forced response limitation of radial turbines by means of intentional mistuning › BMWK/IGF	› Prof. Dr. Damian Vogt (ITSM, University of Stuttgart) Prof. Dr. Manfred Wirsum (IKDG, RWTH Aachen University) Prof. Dr. Bernd Beirow (SMF, BTU Cottbus) › Thomas Winter (MAN Energy Solutions SE)	› R606 (pp. 636-674)

Technologies for generating energy: turbomachinery // full project information from p. 17

In his keynote speech, **Dr Benjamin Witzel,** Head of Fuel Flexibility, Hydrogen & Carbon Capture at Siemens Energy, outlined the role that gas turbines play in the energy transition, how to make a successful switch to using hydrogen and what challenges this entails.

How gas turbines can help decarbonise the energy sector

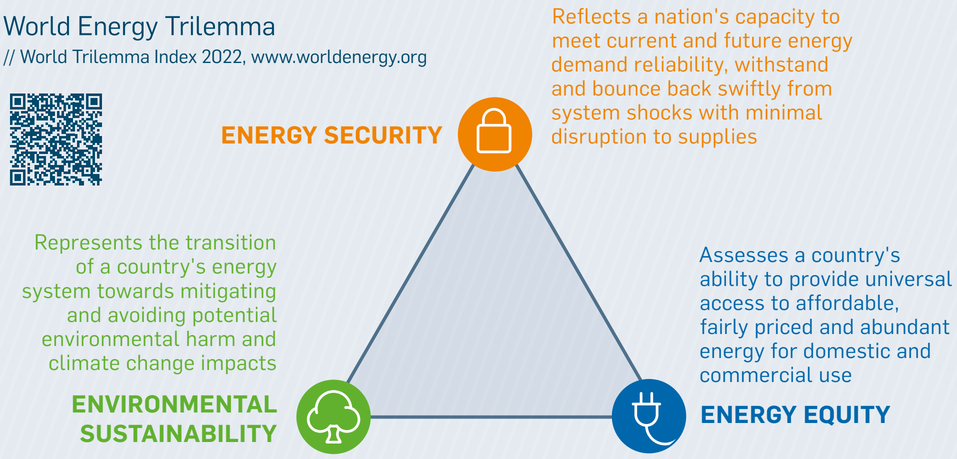
In a recent study, S&P Global assumes that over 50 billion tonnes of CO_2 equivalents will be released into the atmosphere in 2024 – with almost one third stemming from electric power and district heating. The good news is that this is predicted to be the peak of greenhouse gas emissions in both of the scenarios examined in the study and that levels will start to decline, primarily due to the expansion of renewable energy sources. Dr Benjamin Witzel, Head of Fuel Flexibility, Hydrogen & Carbon Capture at Siemens Energy, describes the hurdles that the energy transition faces as the **»energy trilemma«:** energy must remain affordable, there must be a reliable supply at all times, and it must be sustainable – i.e. ideally from renewable sources.

This presents a conundrum of contradicting objectives for which there is no easy answer. There are technical solutions for many challenges – even the reliability of the energy supply is an issue that can be resolved. The biggest issue today, however, lies in the costs: starting with the development of new technologies, carrying over to their production, and finally to their operation, which in the case of the latter are largely dependent on the price of fuel. This therefore requires a mix of different measures depending on the country, region and requirements. However, it is clear that turbomachinery will continue to play an essential role in all scenarios in the years to come.

FIGURE 9

World Energy Trilemma

// World Trilemma Index 2022, www.worldenergy.org



ENERGY SECURITY

Reflects a nation's capacity to meet current and future energy demand reliability, withstand and bounce back swiftly from system shocks with minimal disruption to supplies

ENVIRONMENTAL SUSTAINABILITY

Represents the transition of a country's energy system towards mitigating and avoiding potential environmental harm and climate change impacts

ENERGY EQUITY

Assesses a country's ability to provide universal access to affordable, fairly priced and abundant energy for domestic and commercial use

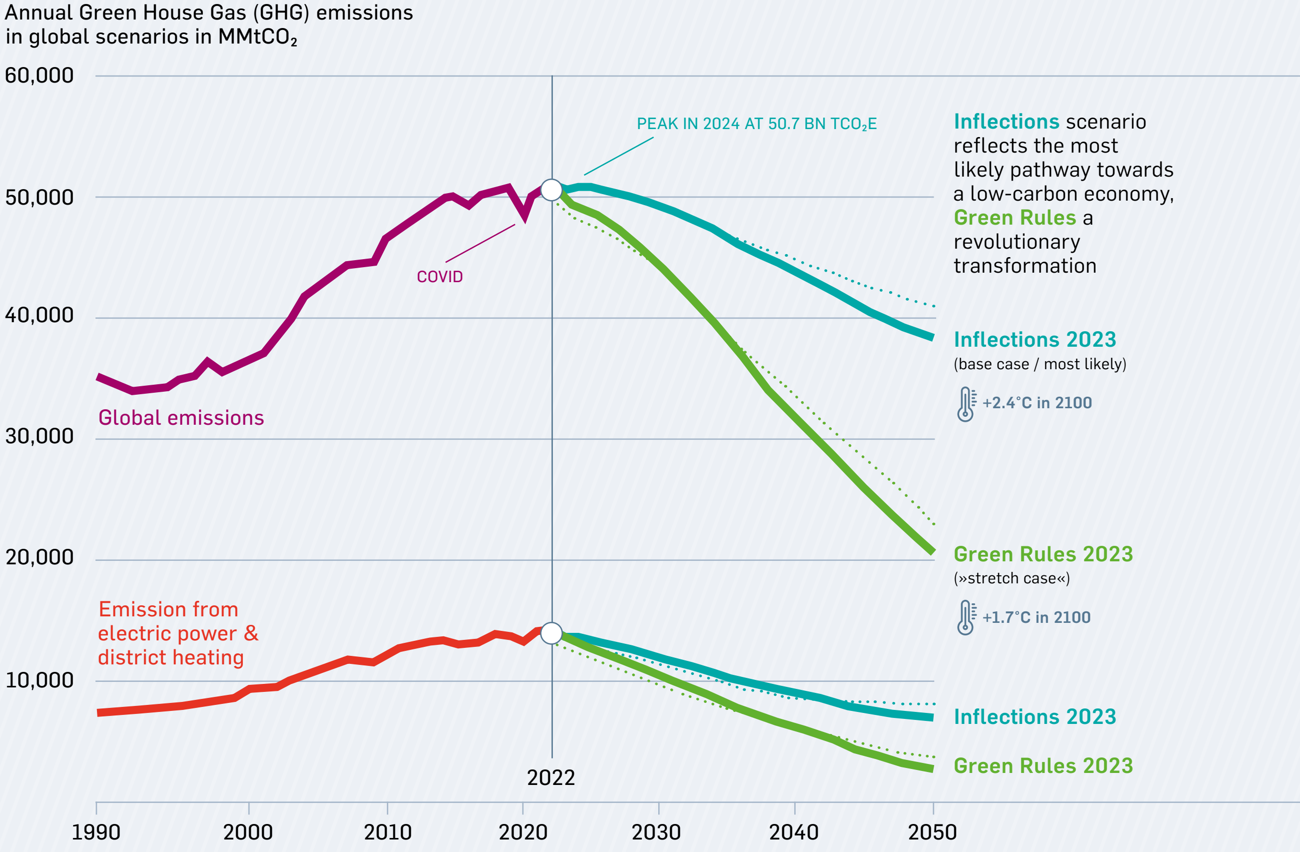


ABBILDUNG 10

Why Decarbonize? GHG Emissions need to be decreased to limit Global Warming

// S&P Global »Energy and Climate Scenarios – Energy outlook to 2050« (July 11, 2023), Siemens Energy 2023

Gas turbines are indispensable

Gas power plants will primarily serve to compensate for fluctuations in power supply, such as when renewable sources fail to deliver sufficient power during a period of low sunlight or wind. As such, gas turbines will be operated in a significantly more cyclic manner, e.g. no longer for 8,000 hours a year, but instead for just 1,000 hours with multiple system start-ups a day. Because the durability of certain materials and components is less limited by operating hours than by the number of cycles, however, material stress levels due to cyclic loading can increase despite fewer operating hours.

But as Benjamin Witzel explained, switching to the exclusive use of smaller turbines that can operate for longer periods is not an optimum solution either: »In this energy system, the gas turbine acts as a battery by reconverting chemically stored energy such as that in the form of green hydrogen. The requirement is then to deliver a high power output at a given moment, but also to an elevated degree of efficiency due to the high fuel costs. Therefore, the use of high-efficiency turbines of the 600 MW class will continue to have its merits.« He added that a gas turbine of this size requires significantly lower investment costs compared to, for example, ten 60 MW turbines. But those who depend on flexibility and who must operate the turbines in a very cyclic manner could benefit from smaller units.

In the future, he believes it will be essential to reconcile competing objectives more effectively: even today, flexibility is often more important than that last tenth of a percent of efficiency. »It's impossible to optimise everything at the same time. Some turbines are more efficient, whilst others can be used more flexibly. Our job is to get a sense of the where customer's needs overlap the most,« Witzel explained. Although requirements differ depending on the country, more and more customers are explicitly asking how much hydrogen they can admix to natural gas. »For some types this is 10 %, while for others it is 75 %,« he said. It will even be technically possible to switch to 100 % hydrogen in the future. But at the moment, very few customers are able to provide an uninterrupted supply of hydrogen in the quantities needed for operation.

Scaling up developments

By 2030, all new Siemens Energy gas turbines are planned to be »H_2-ready«, meaning that after replacing certain components such as the combustion system and auxiliary systems, up to 100 % hydrogen can be admixed with natural gas. Siemens Energy is currently operating approximately 20 different types of turbine worldwide, all of which were originally designed for burning natural gas. Evolutionary advancements for operation using 100 % hydrogen are not conducive as the flame speeds when burning hydrogen are too high, and the challenges related to the substances used (e.g. due to hydrogen embrittlement) or the reliable detection of potential flame flashback are too complex. The only way to tackle these challenges is with new developments.

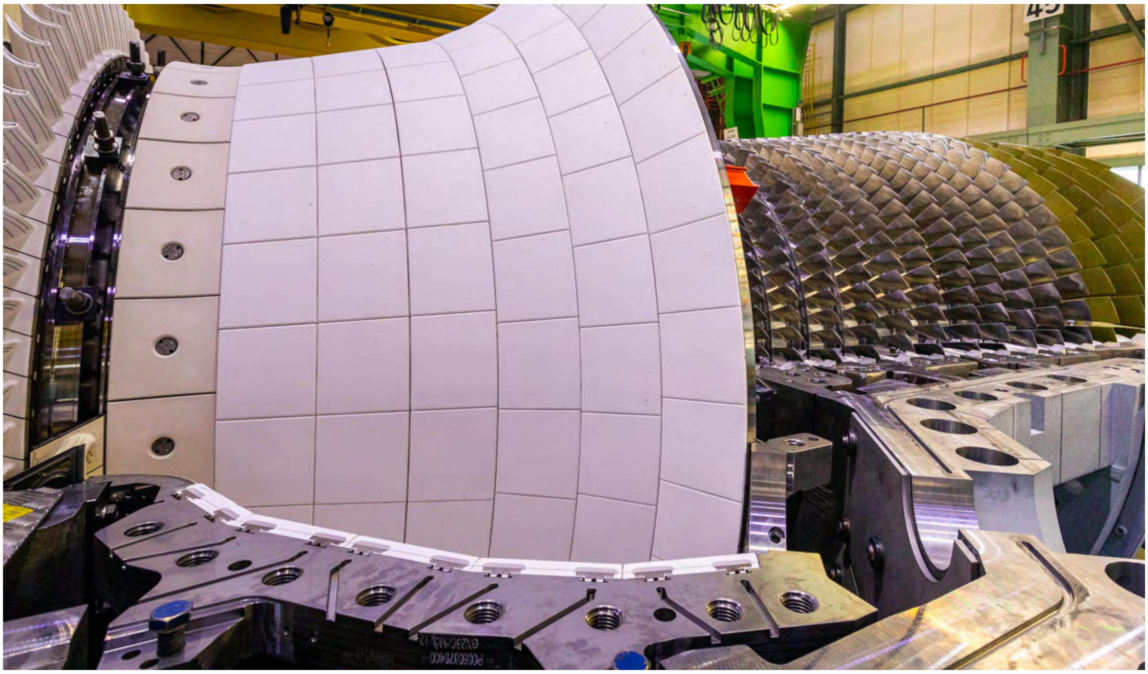
However, the broad portfolio of gas turbines cannot be switched to operating solely on hydrogen all in one go. For this reason, Siemens Energy is starting by developing base technologies such as the combustion system or ceramic materials on a smaller scale. Once a certain level of technological maturity is reached, the results can then be scaled to larger turbines. Smaller units such as the SGT-400 with an output of 13–15 MW are much cheaper to develop and test. For example, smaller burners can be produced using rapid prototyping methods such as selective laser melting. In addition, Siemens Energy requires less hydrogen for validating a 15 MW turbine than for a 600 MW turbine.

One challenge in developing new technologies for 100 % hydrogen combustion is the still limited availability of the fuel. This sometimes poses a significant problem as early as the development phase: for a single test on the complete machinery for an SGT-800 turbine, Siemens Energy's gas turbine facility in Finspång, Sweden, purchased almost all the available hydrogen in Northern Europe. Acquiring such large quantities of green hydrogen is not yet feasible. So where is the fuel to come from? Benjamin Witzel believes there will be practically no alternative to importing additional hydrogen from countries such as North Africa or Australia and shipping it to Europe, as the future domestic production capacities will be too low. All the same, six pipelines are planned in Europe by 2030 to enable the import and distribution of hydrogen. And by 2032, all power plants in Germany with a capacity of more than 100 MW are to have been integrated into the H_2 Start Net.

Methanol and ammonia as alternatives

One practical alternative for liquid fuel can be found in methanol derived from renewable or biological sources. »Dual-fuel«turbines use different fuel passages in order to utilise both liquid and gaseous fuels, such as hydrogen and methanol. While hydrogen serves as a substitute for natural gas, methanol is used as an alternative to liquid fuels such as heating oil. Existing turbines in lower power classes can be converted to run on methanol relatively easily, allowing Siemens Energy to offer customers a solution quickly. But more importantly, sufficient quantities of methanol will be available for smaller turbines.

While German and European policymakers currently favour hydrogen as a green energy source, turbines designed to burn gaseous or liquid ammonia are being developed in countries such as Japan. The advantage? Like hydrogen, ammonia can be produced from renewable energy sources, yet it offers significant advantages in terms of its transportation. This is an important factor for countries like Japan, which rely on energy imports due to their limited land surface area. As is the case with hydrogen, burning ammonia does not produce any CO_2. Nonetheless, Benjamin Witzel remains critical of the use of ammonia as the substance is



highly toxic – accordingly, alongside concerns about its general handling, the possible ammonia emissions produced due to incomplete combustion or start-up failures remain unresolved. Moreover, burning ammonia produces significantly higher nitrogen oxide emissions from the nitrogen bound in the fuel compared to current natural gas turbines. A further challenge when burning ammonia is its very low reactivity – unlike that for hydrogen. A system optimised for ammonia is unlikely to offer the flexibility of being able to use another fuel type in a dual-fuel turbine.

But regardless of which fuel is used in future: »There is no one single solution for the energy transition, but a mix of measures. We need to expand renewable energies, invest in infrastructure such as pipelines and power grids, develop new technologies and ensure reliable supply chains,« Benjamin Witzel concluded. And there is still much to be done when it comes to defining the corresponding standards and regulations. To overcome all these challenges, the industry must continue to collaborate closely with universities and research institutions – much like FVV and Siemens Energy are already doing.

Collective intelligence –
FVV members

→ **www.fvv-net.de/en/network/members**

Empowering a moving society –
Participating research and technology (RTD) performers

→ **www.fvv-net.de/en/network/rtd-performers**

New research programme

FVV’s innovation and transfer network is all about dynamism, future, responsibility and power. Pre-competitive fundamental research produces sustainable, environmentally friendly and climate-effective technology solutions.

Industrial Collective Research is pre-competitive, forward-looking and open to all topics. FVV’s pre-competitive research enables companies to solve shared technology problems and issues, such as on efficiency, life cycles, materials and the circular economy, at a systemic and component level on a sound scientific basis.

Unlike other transfer and technology platforms, FVV is a ›collaborative undertaking‹: industry-oriented research can only succeed where it is developed and designed together. That is why the expert groups come together on the second day of our transfer and networking event to determine their shared need for research and design projects accordingly, guided by experienced members.

Planned and ongoing projects // Status: 01.11.2023

The pre-competitive project work of the FVV enables collaborative research to be performed on fundamental questions, thus allowing the ever stricter requirements regarding materials, fuel efficiency and environmental friendliness to be met. In doing so, the FVV research programme also contributes to enhancing the competitiveness of its member companies.

Members of the FVV innovation network can find a list of all planned and ongoing projects in the FVV research programme in THEMIS:
→ see p. 35

126
planned projects

113
ongoing projects

239
projects in Q4/2023

79 %
financed through external funds
BMWK/IGF
DFG, CORNET, …

21 %
financed through **own funds**

13
startet in Q3/2023 to Q4/2023

56 %
financed through external funds
BMWK/IGF
DFG, CORNET, …

44 %
financed through **own funds**

New project proposals and ideas // Status: 06.10.2023

In autumn 2023, a total of 23 new project ideas and 12 project proposals were up for discussion in the expert groups' face-to-face meetings in Würzburg and in the written silence procedure. The following package, with a planned funding volume of €15.4 million, was submitted to the FVV Board for final approval.

31 %
financed through
own funds

69 %
financed through
external funds
BMWK/IGF, DFG, CORNET, …

30 %
financed through
own funds

70 %
financed through
external funds
BMWK/IGF, DFG, CORNET, …

Planned
funding volume

Proposals	**5,819,606 EURO**
Own funds	1,780,142 EURO
External funds	4,039,464 EURO
Ideas	**9,583,000 EURO**
Own funds	2,904,000 EURO
External funds	6,679,000 EURO
	15,402,606 EURO

Scientific coordination

Together we develop ideas for the future. Experts from member companies meet in the groups to identify common research needs and design projects accordingly. The Scientific Advisory Committee of the FVV appoints chairpersons for each group to lead the scientific work.

SYSTEM

Energy Infrastructure and Storage

N.N.

Sustainable Powertrain Systems

Thorsten Oberpenning, Rolls-Royce Solutions

SUBSYSTEMS

Energy Conversion Systems

- → **Engines** | Dr. Christian Weiskirch, MAN Truck & Bus
- → **Electric Motors** | Carsten Weber, Ford-Werke
- → **Fuel Cells** | N.N.
- → **Turbo Machines** | Heinz Knittel, MTU Aero Engines
- → **Zero-impact Emissions** | Dr. Frank Bunar, IAV

COMPONENTS

Materials Science and Recycling

Dr. Dieter Eppinger, SEG Automotive Germany

See also:
»Make it new – Science for a moving society« (ToR)
→ **www.fvv-net.de/en/**

Terms of references (ToR)

The assignment of research topics to the expert groups, which replace the former planning groups, is made along the system cascade of the V-model.

SYSTEM

Energy Infrastructure and Storage

Interaction of energy sources and system components, energy infrastructure and external storage

→ Chemical energy carriers and alternative fuels beyond application
→ Standardisation → Life cycle analyses

+ General issues related to demand and availability of energy sources / carriers
+ Production, quality, distribution and availability of hydrogen, electricity-based and alternative fuels
+ Standardisation topics on future energy carriers and related issues such as infrastructure and storage
+ Life cycle assessment (LCA)
+ Development of collaboration projects with other institutions to serve the interests of FVV members (e. g. workshop with the fuel / energy industry, …)

Sustainable Powertrain Systems

Road / rail vehicles: classic powertrains (ICEV), hybrid / electrified powertrains (PHEV, BEV, FCEV), aircraft engines, marine propulsion, mobile machinery, power systems

→ Energy storage within the application
→ System efficiency → Air pollution, global warming, noise, sound, radiation
→ E-machine combined with battery

+ Questions on energy storage in the aforementioned applications
+ System efficiency of energy conversion processes e. g. charging, system control / regulation, sensor technologies, …
+ Thermal management
+ Zero-impact emissions, greenhouse gas emissions (e. g. CO_2), noise, sound, electromagnetic compatibility (EMC)
+ E-machine combined with battery / ICE [interface to E-MOTIVE platform]
+ Impact of legal, social and political requirements onto powertrain systems, circularity
+ Development / engineering of tools for i. e. the system architecture and interaction of powertrain assemblies

Energy Conversion Systems

Innovative and / or optimised energy conversion systems minimising environmental impact and maximising process efficiency and engine performance

SUBSYSTEMS

→ Engines

- \+ All conventional engine development topics
- \+ Optimisation and development of new energy conversion processes focusing on e. g. increasing process efficiency of future varieties of fuels (including use of hydrogen)
- \+ Reducing the environmental impact
- \+ Process-focused adaptation of related components and (sub-) assemblies
- \+ Effects of increasing electrification to the ›engine‹ subsystem and its aggregates
- \+ Digitalisation
- \+ Development and improvement of related development / engineering tools based on changing and adopting application / subsystem requirements

→ Electric Motors [interface to E-MOTIVE platform]

- \+ Improvement of electrical motor properties in mobile applications
- \+ Electrical energy storage systems (battery)
- \+ Power electronics of the electrical motor and electrical energy storage system
- \+ Application-focused adaptation of related components and (sub-) assemblies
- \+ Development and improvement of related development tools e. g. simulation tools, measurement and testing methods

Energy Conversion Systems

Innovative and / or optimised energy conversion systems minimising environmental impact and maximising process efficiency and engine performance

SUBSYSTEMS

→ **Fuel Cells** [interface to E-MOTIVE platform]

+ Air and hydrogen system path, media conditioning and purification
+ Thermal management of the fuel cell stack
+ Optimisation of fuel cell specific components and (sub-) assemblies e. g. ion exchanger, compressors, …
+ Research on materials at fuel cell specific conditions and effects, e. g. on bipolar plates, membranes, sealings concerning stack performance, loading characteristics, ageing (durability, degradation), humidification, …
+ Stack performance / efficiency improvements e. g. performance effects of component and assembly tolerances
+ Safety requirements and definitions
+ Development of defined evaluation methods towards industry standards (generic, ›best practice‹)
+ Technology comparison PEM, High-temperature PEM, SOFC
+ Development and improvement of fuel cell specific development tools e. g. simulation tools, measurement methods (e. g. impedance analysis)

→ **Turbo Machines**

+ All conventional turbomachinery development topics
+ Optimisation of aerodynamics
+ Optimisation of turbomachinery specific components and (sub-) assemblies
+ Research on materials of turbomachinery specific conditions and effects; e. g. high-temperature, loading characteristics, ageing, resonances, use of hydrogen
+ Development and improvement of turbomachinery specific development tools

Energy Conversion Systems

Innovative and / or optimised energy conversion systems minimising environmental impact and maximising process efficiency and engine performance

SUBSYSTEMS

→ Zero-impact Emissions

+ Exhaust aftertreatment concepts, systems and components
+ Alternative aftertreatment system technologies and approaches
+ Effects of the use of alternative fuels and operating liquids
+ Interactions of exhaust components, primary and secondary exhaust species
+ Non-exhaust emission evaluation of all mobile applications (incl. electrified), e. g. brake dust, tyre abrasion, …
+ Interaction emission and immission / air quality
+ Carbon capture approaches and technologies
+ Development and improvement of related development tools, e. g. simulation tools, measurement and evaluation methods

Materials Science and Recycling

All conventional topics on materials research in connection with new energy sources, production methods and recycled materials

COMPONENTS

→ Strength → Tribology → Recycling

+ Tribology, strength, fatigue models and improvements
+ Properties, strength and fatigue characteristics of materials for electric powertrains (e. g. copper)
+ Durability and robustness of electrically isolating materials (e. g. aspect of partial discharge, …)
+ Impacts and interactions on components and (sub-) assemblies caused by novel energy types (e. g. hydrogen, e-fuels, methanol, …)
+ Components made by additive manufacturing, their properties and related method approaches
+ Material properties impact of recycled materials
+ Energy footprint of components and assemblies depending on material and manufacturing process, circularity
+ Development and improvement of group related development tools e. g. simulation tools, measurement and evaluation methods

THEMIS Database

Members of the FVV innovation network can find a list of all planned and ongoing projects in the FVV research programme and dates for the discussion groups, workshops and project user committees in THEMIS.

Project list

Status: 01.11.2023

Meeting dates

Status: always up-to-date

Research programme

Status: always up-to-date

Science for a
moving society

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Transfer // Industrial Collective Research (IGF) empowers companies to solve joint research and technology problems on a science-based approach. It provides access to a continuous stream of new knowledge they can use to create their own products, processes and services. Industrial research and development benefits from the fact-/field-based collaboration with the science community, universities and non-profit research institutions, on the future of technology. This creates innovative power in industry and excellence in research, teaching and learning.

Networking // The research implemented by the FVV is based on a long-term cooperation between the partners. In spring and autumn, around 300 experts meet regularly at the FVV Transfer + Networking Events. This report from the science series FVV Prime**Movers.** Technologies. summarises the main results.

FVV e V

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