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Project acronym	FELICITAS
Project full title	Fuel cell power trains and clustering in heavy-duty transports

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Thematic Priority	PRIORITY [1.1.6] [Sustainable development, global change, and ecosystems]

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Acronyms

AC	Alternating Current
AHP	Absorption Heat Pump
APU	Auxiliary Power Unit
ATR	Auto-thermal Reforming
CFD	Computational Fluid Dynamics
CPOX	Catalytic Partial Oxidation
DC	Direct Current
DGPS	Differential Global Positioning System
FC	Fuel Cell
FESS	Flywheel Energy Storage System
GPS	Global Positioning System
GT	Gas Turbine
HD	Heavy Duty
HT	High Temperature
HVAC	Heating Ventilation Air Condition
ICE	Internal Combustion Engine
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LT	Low Temperature
PEFC	Polymer Electrolyte Fuel Cell
PEM	Proton Exchange Membrane
PES	Primary Energy Source
POX	Partial Oxidation
SOFC	Solid Oxide Fuel Cell
SEM	Scanning Electron Microscope
SP	Subproject
THC	Total Hydrocarbon
WGS	Water Gas Shift
WHSV	Weight Hourly Space Velocity
WP	Work Package

SI units and symbols for chemical elements or compounds are not listed.

1 Executive summary

The FELICITAS project – Fuel Cell Power Trains and Clustering in Heavy-Duty Transport – has been focused on developing Fuel Cell (FC) technologies capable of meeting the demands of Heavy-Duty Transport for road, rail and marine applications. FELICITAS was an Integrated Project executed between April 2005 and March 2008 within the scope of the 6^{th} European Research Framework.
FELICITAS has been concentrated on two FC technologies most suitable for Heavy-Duty Transport applications: Polymer Electrolyte Fuel Cells (PEFC) and Solid Oxide Fuel Cells (SOFC).

During the FELICITAS project further developments have been made in both SOFC and PEFC technologies, but in neither case can these developments be described as ground breaking.

Regarding the results of FELICITAS in the field of high power PEFC technologies most of the original objectives, like

- High efficiency, above 60%,
- High power density,
- Powerful units of 200kW plus,
- High durability, robustness and reliability

have been achieved. Caused by physical restrictions the energy efficiency of PEFC systems is limited below 50%.

The intention of FELICITAS was to recuperate kinetic energy in mobile applications by means of hybridised PEFC clusters. For that purpose two or more high power PEFC systems were combined with high performance energy storage technologies. Operating in such hybrid environment a PEFC twin cluster could be established which offers

- 160kW FC power plus 70kW available from the dual energy storage (Li-Ion battery and super-cap storage),
- An energy efficiency of 53% including recuperated energy (18% on the test field)
- A high power density (0.32kW/kg) using FC technologies designed for automotive applications,
- Remarkable life time extensions of the PEFC systems by means of highly sophisticated power control in the hybrid environment, and
- Highly reliable system performance by means of in-situ diagnosis functions.

FELICITAS results envisaged for PEFC technologies were demonstrated both on a test rig and on a large test vehicle. Thereby the outage of a flywheel based energy storage system had to be overcome. Nevertheless, the investigations of the running PEFC twin cluster at the test vehicle were completed few months after finishing the FELICITAS project.

The contribution of FELICITAS to SOFC technologies for heavy-duty transport applications has to be assessed differently. Low power density and restricted maturity of some core components set still strong limitations for instant migrations from stationary to mobile SOFC applications. Especially the harsh conditions of the marine environment were a great challenge for all SOFC developments done in FELICITAS.

The consortium has undertaken a mix of basic and applied research with some demonstration activities, to adapt and improve existing fuel cells and investigate other technologies, including gas turbines, diesel and LPG reforming as well as energy storages and FC power trains.

Powerful simulation tools, highly advanced energy management functions and dedicated methods for in-situ diagnostic of the FC health status have also resulted from the FELICITAS project. These can be usefully applied for the design and operation of hybrid FC power trains and other propulsion concepts.

The build-up of a running SOFC demonstrator in a high power range (> 200kW) was not foreseen in the FELICITAS project. The results of FELICITAS are mainly focused on an improvement of the SOFC component behaviour, basic electrochemical and thermoelectric investigations as well as demonstrations on test rigs.

The work on the marinization issues for stationary fuel cells has substantially improved the understanding of the various challenges, and these results will feed into future route maps for marine based fuel cells. A substantial improvement of on-board reforming technologies has been demonstrated in form of a diesel reformer applicable as part of an APU system for heavy-duty trucks, whilst LPG reforming for high power, and high efficiency SOFC APU systems for ships have also been developed.

The 15 partners within FELICITAS were engaged in quite different fields of engineering sciences, and the basic, applied and demonstration results of this work have substantially advanced the understanding of fuel cell drive trains for heavy-duty transport applications. A number of the initial objectives were achieved for example in the application of PEFC units to the AutoTram test vehicle, but due to technical complexity and resource constraints not all the objectives were met, for example the operation of a marinized SOFC unit. Nonetheless the learning experience has significantly improved the European knowledge base of the challenges of integrating fuel cells into heavy-duty transport and improvements in European FC technologies for this transport sector.

2 Introduction

FELICITAS – Fuel Cell Power Trains and Clustering in Heavy-Duty Transport – has been executed from April 2005 to March 2008 within the scope of the 6^{th} European Research Frame Work.

The proposal for FELICITAS has been initiated as response to a call by the European Commission – DG Research – as part of the strategic program for ´sustainable development, global change and ecosystems' to investigate into Fuel Cell Technologies for Heavy-Duty Transportation.

FELCITAS project has been a programme of basic and applied research, together with demonstrations, which are supportive of commercial opportunities of the industrial companies within the project.

3 FELICITAS – contributions in spirit of the European strategic research agenda

The FELICITAS project has been undertaken at the same time as the work by the European Commission and the European Hydrogen Platform on the creation of a public-private joint undertaking to accelerate the commercialization of fuel cell technologies in Europe. This entity will stimulate research, development and deployment of fuel cell technologies, fuel cell applications and hydrogen infrastructure for commercial operation.

These activities are based on the common understanding that hydrogen fuel and fuel cell applications will contribute significantly to the European public policy objectives for

- Energy security,
- Air quality and reduction of greenhouse gas emissions,
- Increased use of renewable fuels and
- Industrial competitiveness.

As a result of these discussions the European Research Agenda in this area today comprises technological development with the following key challenges as top priorities:

- Improvements in fuel cell (FC) durability, performance and economics,
- Reforming technologies,
- On-board hydrogen storage systems for vehicles,
- Competitively-priced hydrogen (production & distribution costs),
- Development of mass production technologies for fuel cell stacks & systems.

FELICITAS undertook fundamental research in line with these priorities. In adopting a range of technologies all focused on the needs of heavy-duty transport the FELICITAS project provided a holistic approach to the issues drawing upon both Solid Oxide (SOFC) and Polymer Electrolyte (PEM) Fuel Cell technologies, as well as high power electrical energy storage systems and reformer technologies for different Hydro carbon fuels.

In the specific area of Heavy-Duty Transport, FELICITAS contributed specifically to

- Development of fuel cell technologies in different modes (for heavy-duty transport) including the adaptation of high power Solid Oxide Fuel Cells (SOFC) and Polymer Electrolyte Fuel Cell (PEFC) clusters, the enhancement of FC performances, lifetime extensions and on-board reforming technologies,
- Investigation in specific applications of fuel cell systems that are part of larger systems, i.e. electrical drive trains need to be understood in their entirety including the fuel cell as well as energy storage, thermal or kinetic recuperation facilities and/or advanced control, management or diagnostic functions,
- Materials research as it relates to reforming as well as hydrogen and fuel cell technologies.

In contrast to other research projects – generally concentrating on very specific issues – FELICITAS provided room for both the top down approach investigating into requirements of the most important Heavy-Duty Fuel Cell Applications as well as the bottom up approach concentrating on specific details that are most important for a commercial success of each technology.

By contributing on such a wide range of aspects FELCITAS pioneered the idea of a holistic approach, however criticism may be that the complexity of the project has been underestimated.

Though FELICITAS covered a very wide field of technologies the structure of the project allowed each of the 15 partners to focus on its specific field whilst also being aware of the scientific and technical activities being undertaken elsewhere in the project.

4 Objectives

The objectives defined for FELICITAS had been the development of fuel cell drive trains capable to meet the demands of heavy-duty transport for road, rail and marine applications. To achieve these objectives the following parameters were chosen

- Powerful units of more then 200kW electrical output,
- High reliability and long system durability – >10 000 hours operation time,
- High system efficiency > 60%,
- Operating with different hydrocarbon fuels as well as hydrogen.

As a response to the needs of a range of Heavy-Duty Applications two technologies were included in the Project, SOFC and PEFC technologies. At the start of FELICITAS in 2005 neither technology had demonstrated the ability to meet the objectives above.

FELICITAS focused on:

SOFC technology – given its comparative immaturity appraisal and feasibility of the technology rather than demonstration in real applications,

PEM technology – had began demonstration on a larger scale to be feasible for powering passenger and heavy-duty vehicles such as inner city buses, but degradation mechanisms in operation and durable system technologies were required.

Thus FELICITAS was structured to focus on the most important questions and technological developments to cover the requirements of the different modes of heavy-duty transport (see figure 1).

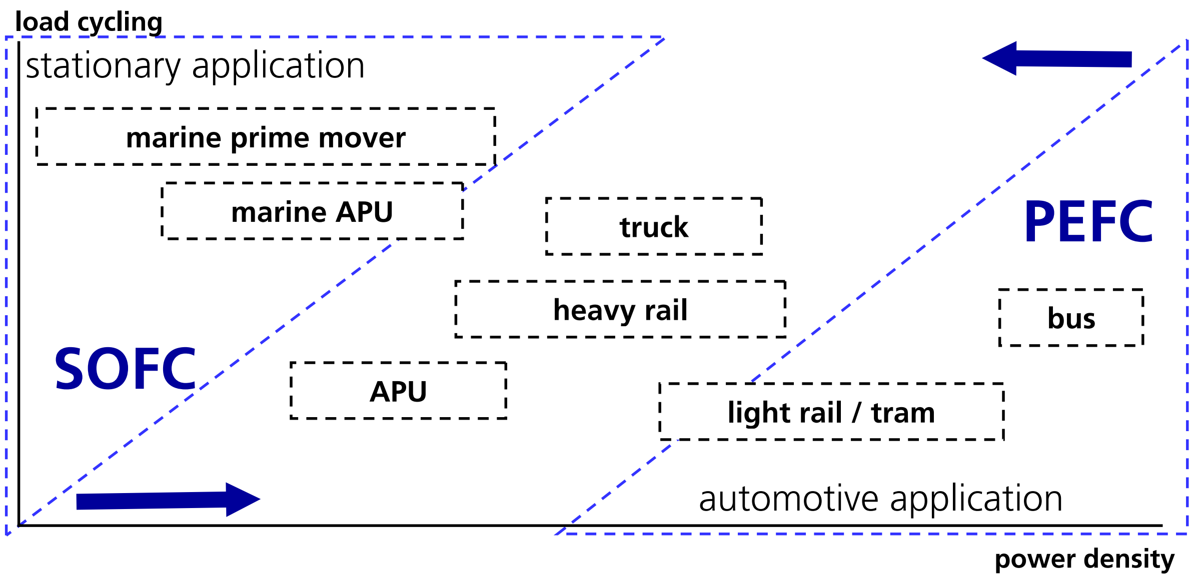


Figure 1: FC development regarding heavy-duty requirements within FELICITAS

The FC manufacturers within the consortium have investigated and undertaken adaptations and modifications necessary for successful deployment of fuel cell systems in heavy-duty transport. The research institutions were principally employed in the development challenges common to SOFC and PEFC based modular power train concepts.

FELICITAS was primarily a research programme that adds to and improves the European knowledge base to permit successful future demonstration projects. Thus demonstration activities were not the principal activity of the project, and those undertaken were part of Phase 2 of the project.

5 Project execution

The FELICITAS project comprised four subprojects, each focusing on a main topic of fuel cell system and drive train development.

Activities in the subprojects were managed by the subproject leaders who reported to the project coordinating committee (PCC) of the consortium, the leading committee within the project. The PCC met on a regular base either as part of the bi-yearly consortium meetings (general assembly) or where necessary on telephone conference calls. This plus the use of e-mails ensured that all partners were informed promptly and thoroughly.

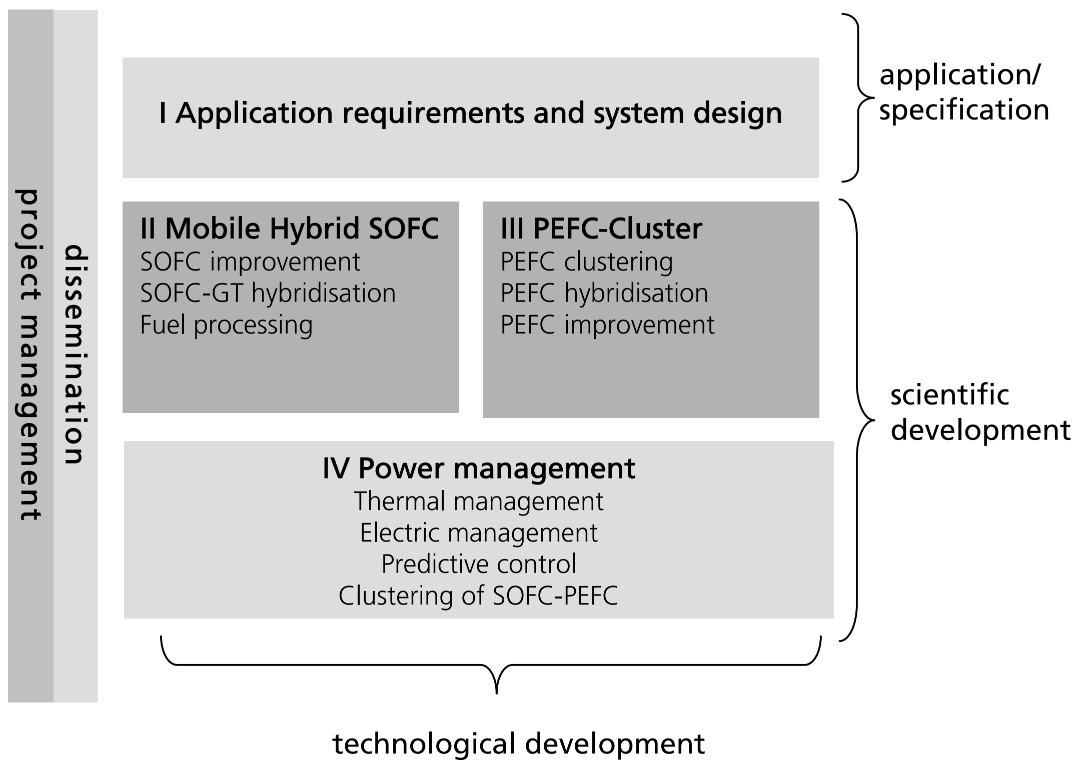


Figure 2: Subproject structure of the FELICITAS project

5.1 SP I Application Requirements and System Design

Subproject I has been structured into two work packages.

Subproject I	***Application Requirements and System Design*** Lürssen	
Work packages	Specification, defining of application requirements and standardisation Lürssen, FhG IVI, AVL, HAW, Rolls-Royce, INRETS, VUZ	System design and simulation FhG IVI, AVL, CCM, Lürssen, HAW, ICL, NTUA, Rolls-Royce, INRETS, UTBM, VUZ
Tasks	User requirements in urban transport	Concept of FELICITAS simulation platform
	User requirements in heavy truck and rail applications	Multi-level-simulation of FC based power trains
	User requirements in waterborne transport applications	Hybrid concepts for FC power trains

Table 1: FELICITAS - Structure of SP I

5.2 SP II Mobile Hybrid SOFC

Subproject II has been structured into four work packages.

Subproject II	***Mobile Hybrid SOFC*** Rolls-Royce			
Work packages	Development and marinization of a 250kW SOFC unit Rolls-Royce, Uni Genoa	Testing of marinized 60kW sub-system and stationary power 250kW generator module Rolls-Royce	Fuel processing Rolls-Royce, Lürssen, HAW, Uni Eindhoven, Uni Genoa	SOFC power management, controller design, and simulation Rolls-Royce, Lürssen, Uni Genoa
Tasks	Testing and deve-lopment of compo-nents – Rolls-Royce	Testing Activities	Assessment of fuels and processing technologies	SOFC mechanical installation, packaging and fuel systems
	System modelling of pressurised hybrid SOFC in marine environment		Development of fuel processing regime	SOFC-GT power management
			Initial concept and design	
			Fuel processing design for the medium- and long-term	

Table 2: FELICITAS - Structure of SP II

5.3 SP III PEFC-Cluster

Subproject III was broken into three work packages.

WP III.1 included investigations and configuration activities for fuel cell clusters. This included both the fuel cell system itself and the auxiliaries, the connection to an electrical architecture as well as safety related considerations and finally the design of such a prototype system.

WP III.2 concentrated on the test activities including investigations and preparation of a ´close to reality´ drive cycle and load profile of an inner city transit bus as well as investigations and measures taken to improve operation conditions of the fuel cell systems in a hybrid environment.

WP III.3 included the integration of the Fuel Cell Cluster into a research vehicle of the Fraunhofer Institute and test operation to verify the function of the overall system.

Subproject III		***PEFC-Cluster***	
		NuCellSys	
Work packages	Cluster Development	PEFC-Cluster reliability assessment	PEFC-Cluster implemented in a test vehicle
	NuCellSys, FhG IVI	NuCellSys, FhG IVI	FhG IVI, NuCellSys, CCM
Tasks	Cluster concepts	Relieved operating strategies with regard to system durability	Hardware implementation
	Auxiliary systems	Durability testing with relieved operating strategy	Verification of controller and energy management strategies
	Electrical Systems		Verification of hybrid propulsion
	Safety concept		
	Prototype building		

Table 3: FELICITAS - Structure of SP III

5.4 SP IV Power Management and Hybridisation

Subproject IV consisted of three work packages.

Subproject IV	***Power Management and Hybridisation*** FhG IVI		
Work packages	Processing of thermal energy ICL, Lürssen, NTUA	Controller design for PEFC-Clusters FhG IVI, NuCellSys, CCM	Components for SOFC-PEFC coupling Uni Belfort, FhG IVI, AVL, CDL
Tasks	Thermal management requirements	Power management of hybrid PEFC-Clusters	Layout and prototyping of new components, experimental research on components, simulated coupling experiments
	Thermal recuperation	Reliability centred power management	Modelling, parameterisation, and scalability analysis
	Thermal management	Limited operation and predictive diagnostic strategies	Optimization of flow chart and system layout versus the application load profile
	Gas turbine development	PEFC-Cluster controller structure	

Table 4: FELICITAS - Structure of SP IV

5.5 Schedule

The project had been broken down into several phases.

In the **initial phase** of the project the partners worked on the theoretical aspects of using the selected fuel cell technologies in heavy-duty applications. This included the definition of application requirements for different transport modes, the principal layout and design for the fuel cell modules and power trains – including on board reforming and turbo machinery for the marine SOFC –, as well as system simulations at various stages in such power trains.

In the **development phase** these investigations were evaluated against the available technologies and the defined requirements. Technological assessment and developments were initiated for both SOFC and PEFC technology to cover these requirements.

Finally on the PEM side the improved system technology was integrated into a research vehicle of the Fraunhofer Institute for evaluation and testing.

6 Approaches

6.1 Requirements of fuel cell applications in heavy-duty transport

All investigations to general requirements and technical, legal or economic preconditions for the implementation of Fuel cell power trains into different heavy-duty transport modes were summarised in Subproject I, which was **led by Fr. Lürssen Werft GmbH & Co. KG.**

To achieve FELICITAS' key objectives the following scientific and technical activities were necessary:

- Analysis of requirements specific to FC application, specifications and standardisation to FC based power trains in road, rail and waterborne heavy-duty transport modes,
- Development of test codes for FC based power train concepts,
- Development of design and simulation tools for FC based power train concepts,
- Life-time analysis of PEFC technologies,
- Development of advanced power management strategies to provide high power dynamics and reliability centred operation, and
- Investigation and development of safety standards.

The investigations dealt with

- Bus and tram (light rail) applications,
- Implementation of FC in trucks,
- Heavy rail applications,
- Marine applications

and led to development targets concerning

- Electrical requirements, e.g. power,
- Mechanical requirements, e.g. packaging, mechanical stress,
- Fuel system, e.g. refuelling cycles, tank capacity,
- Reliability and maintenance,
- Safety standards.

6.2 Marinization of high power SOFCs

The FELICITAS Subproject II focused on the issues required for the marinization of the RRFCS 1MW Pressurized SOFC design for a 250kW APU. It was **led by Rolls-Royce Marine Electrical Systems Limited** working with Lürssen as shipbuilder, and three Universities; Genoa, Eindhoven and Hamburg. The approach to marinization was to minimise design changes to system architecture and thus additional development and product cost for a marine version of the existing stationary power Rolls-Royce Fuel Cell Systems Ltd (RRFCS) SOFC design. Extensive design changes and additional equipment would adversely affect the commercial prospects of a marinized stationary fuel cell system. The RRFCS 1MW System design is shown below, together with the concept for a 250kW Generator Module. The latter would be the foundation of the marinized APU.

Figure 3: Stationary Power 1MW Hybrid SOFC System and 250kW Generator Module of RRFCS.

The FELICITAS Project focused on key aspects of marinization of the RRFCS SOFC design:

- Impact of the marine environment on the operation of the fuel cell, e.g. humidity and salt air, and fuel contaminants as they affect electro-chemical performance;
- Issues associated with vessel motion on the fuel cell system, e.g. shock loads, as well as vibration effects from other propulsion units in a vessel e.g. diesel engines;
- Effect of the power demands of a marine application on a fuel cell unit, especially the varying 'hotel' loads;
- Fuel availability and choices for fuelling fuel cells in a marine application.

This work comprised a mixture of desk studies and laboratory based activities.

Part of the SPII carried an investigation of the integration challenges of a fuel cell system into a yacht. Lürssen undertook a detailed study of the specific interfaces between the yacht including:

- Water supply by means of a two stage system to meet the water requirements of an SOFC system;
- Fuel supply and fuel storage;
- Energy storage system for load following;
- Fuel and exhaust piping;
- Power management system.

And the necessary indirect interfaces to:

- Safety equipment (sensors, fire fighting equipment, explosion safe equipment);
- Ventilation and cooling rooms.

The use of fuels other than natural gas (the preferred fuel for stationary power fuel cell systems) required fuel pre-processing and a part of SPII undertook detailed investigations of fuel options for a marine SOFC APU. The objective was to understand the challenges of fuel processing for an SOFC marine APU and recommend a concept that was realisable in the medium term. The fuel processing group, RR together with Lürssen and the three Universities, adopted an approach that would support a commercial system with long-term reliability. In developing a fuel processing concept for a marine application, aspects of the challenge included:

- Fuel preferences and requirements of the commercial customer;
- Physical and technical constraints of the vessel;
- Technical requirements of the SOFC system, and
- Available fuel processing technologies.

The fuel processing group undertook careful consideration of the conflicting fuel requirements of commercial operations, preferences for marine diesel, and the acceptable quality and standards of the fuel used by the RRFCS SOFC System, natural gas.

The FELICITAS project therefore comprised a mixture of basic and applied research with the objective of understanding the challenges and providing information for future route mapping to successful on-board demonstrations.

The Subproject represented one of several such marine fuel cell projects supported by the European Commission under the Framework 6 Programme: others include MCWAP (Molten Carbonate Fuel Cells for Waterborne Applications led by Ansaldo), MethAPU (SOFC units for APUs on vessels led by Wartsila) and New H Ship (specific supportive action). These projects have all sought to understand the issues of marinizing fuel cell technology designed for stationary power generation and follow-on, in part, from the Fellowship project, also supported by the European Commission under Framework 5.

6.3 Onboard reforming processes for marine applications and land based vehicles

As mentioned above, besides pure hydrogen, the use of different hydrocarbon based fuels was a main research topic of FELICITAS and a precondition for most heavy-duty applications. The development of appropriate on-board fuel processors has been shown as an ambitious task, which is embedded in many similar R&D activities around the world.

As a focus of FELICITAS fuel processing has to convert hydrocarbon fuels

- Marine diesel,
- Conventional diesel,
- LPG and
- CNG

to hydrogen and carbon monoxide to be utilized in high temperature SOFC stacks. The performance of fuel processors affects

- The total fuel cell system efficiency,
- The longevity of the supplied FC system and
- The operational behaviour of the overall system.

Fuel processing is the key to make hydrocarbon based fuels available for SOFCs. The choice of suitable fuel option mainly depends on application issues such as required energy density and available infrastructure. However, the feasibility of fuel processing technologies, namely

- Steam reforming,
- Partial oxidation (POX) and
- Auto-thermal reforming (ATR),

is also a fundamental factor. Thus depending on the envisaged application and technical constraints, it is possible to reach different conclusions regarding suitable fuel processing techniques.
Within FELICITAS fuel processing was part of a dedicated system development programme, on the one hand for the marine SOFC and on the other for land based applications like APUs for trucks and as the methodological basis for SOFC-PEFC coupling.

6.4 Hybridization of high power SOFC

For SOFC the intelligent reuse of thermal energy generated by electrochemical reactions is the main key to achieve high system efficiency. The thermal management of the SOFC covers all measures related to:

- Heat recuperation for preheating of inlet mass flow,
- Management of heat sinks like internal fuel processing and
- Using heat by-product by gas and in some cases steam turbines.

In particular the introduction of gas turbines (hybrid SOFC-GT system) offers a remarkable increase of electrical efficiency but on the other hand requires also a very careful system design and management.

Therefore, FELICITAS had to provide a set of modular component models of key concern within the planned hybrid simulation studies. The majority of this work focused on the development of the SOFC-GT sub-system simulation, for both steady-state and transient behaviour. As defined within the Work Programme, a simple transient had to be shown for the SOFC-GT model.

For such hybrid systems the thermal management was a critical issue especially during part load and off-design operation. The interaction between gas turbine and fuel cell plays the important role for the control of the temperature distribution. Often the requirements of the gas turbine are opposite to the fuel cell demands leading in some cases to surge or over-speed conditions. The objective FC has to keep the fuel cell stack in a safe operating condition avoiding thermal stress and hot spots. Moreover the thermal management depends strongly on fuel composition: the hydrocarbon content at the inlet of the stack determines the heat removed from the cell by the endothermic steam reforming reaction. For this reason the variations at the anodic side often have repercussions at the cathodic side, necessitating substantial modifications of the gas turbine.

6.5 Clustering of PEFC systems

Subproject III has been assigned to investigate the usage of PEM Fuel Cell Systems for heavy-duty transport applications. The aim was a market orientated approach by using fuel cell systems developed for the automotive industry to be adopted in operation strategies for hybrid configurations for heavy-duty applications. Subproject **leader was NuCellSys GmbH**.

The strategy was based on the assumption of emerging markets for Zero Emission passenger vehicles providing the benefit of synergies and higher volumes for products in heavy-duty applications. The objectives of the strategy were substantially lower cost and risk connected with increasing quality for fuel cell systems in heavy-duty markets.

Due to the technical attributes PEM fuel cells systems are considered to be the most viable solution for fuel cell based transportation applications such as buses, trams and light rail propulsion systems, however the specific challenges for heavy-duty transportation such as

- Significantly higher power levels from about 200kW up to 600kW,
- The demand for high reliability and system durability,
- The desired high system efficiencies

require further knowledge and investigations into PEM technology as well as the capabilities of electrical drive trains

The focus of SP III in terms of the structure and development activities has been to address these special requirements, to find short-term solutions to match existing technologies with application requirements as well as to detect areas for improvements.

Therefore special attention has been paid to the operation modes of heavy-duty transport vehicles/vessels. Those applications are operated under a variety of different power profiles for drive cycles that can be grouped into three areas:

- High dynamic power profiles caused by frequent acceleration and braking, e.g. in case of public urban transport due to short distances between stations,
- Profiles with little power dynamics due to long distance driving under nearly constant conditions, e.g. heavy-duty rail vehicles or overland buses, and
- Power profiles with almost no dynamics, e.g. transport ships.

With an initial view these load profiles are in no way beneficial to fuel cells since they are sensitive to high dynamic power profiles as well as long time constant operation. However, as part of an all-electrical, hybrid drive train the described operating profiles and the operating profile of the fuel cell system can be decoupled.

In that regard the fuel cell system can – to some extend – operate independently from the immediate drive train power requirements and therefore an additional degree of freedom can be used to improve capabilities of the PEM technology with regard to the abovementioned challenges.

Based on these considerations the idea to convert Hydrogen into electrical energy with a flexible and modular system has been developed and investigated as part of FELCITAS. Due to the combination of several energy converters and/or electrical storages in one system the approach has been named **PEFC – Fuel Cell Cluster** (Polymer Electrolyte Fuel Cell Cluster).

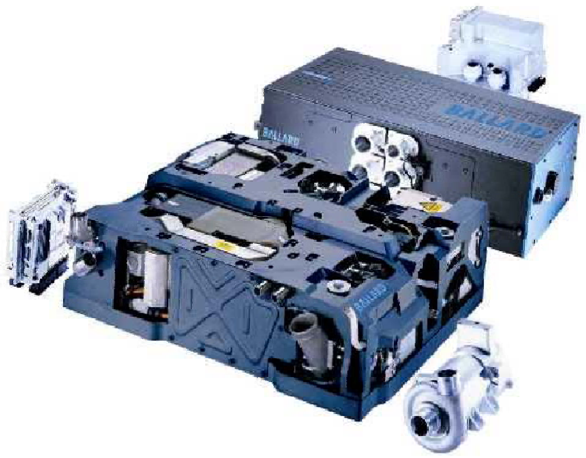


Figure 4: HY-80 FC system from NuCellSys - the 80kW basis component for cluster configurations

The approach to tackle the most dominant issues to introduce Fuel Cell Technology for Heavy-Duty Applications with the PEFC Cluster concept seemed to be a viable solution with the technologies available today.

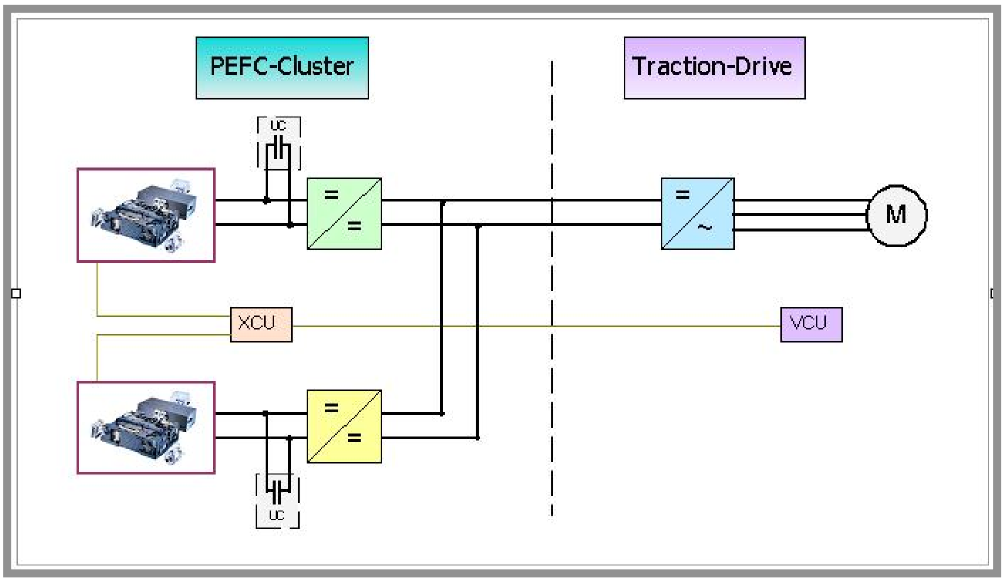


Figure 5: Twin cluster concept investigated in FELICITAS

The work performed as part of SP III included considerations and the layout of two, respectively four fuel cell systems running in a cluster configuration. The principle of the cluster concept and hybrid configurations have been studied with a twin cluster meaning the configuration of two combined compact fuel cell systems.

FELICITAS objectives include the investigation into highly reliable and robust fuel cell system technology in heavy-duty transport applications. These investigations needed to be based on ´close to reality´ load profiles of the individual application. Therefore an important part in FELICITAS has been Subproject I including the investigations in typical load profiles for different applications.

Based on those investigations and the existing experience with failure modes of the HY-80 system (see figure 4) and the Ballard Mk902 stack module under full dynamic stress load conditions the technical objective of WP III.2 has been to develop an operating strategy for the PEFC-Cluster for a specific heavy-duty profile that is able to meet the performance requirements of the application as well as avoiding operating situations of the fuel cell systems causing major stress to the components – mainly the stack.

To verify the improvements with regard to system robustness and lifetime a test has been developed and executed to operate a PEFC system under the investigated heavy-duty operating profiles.

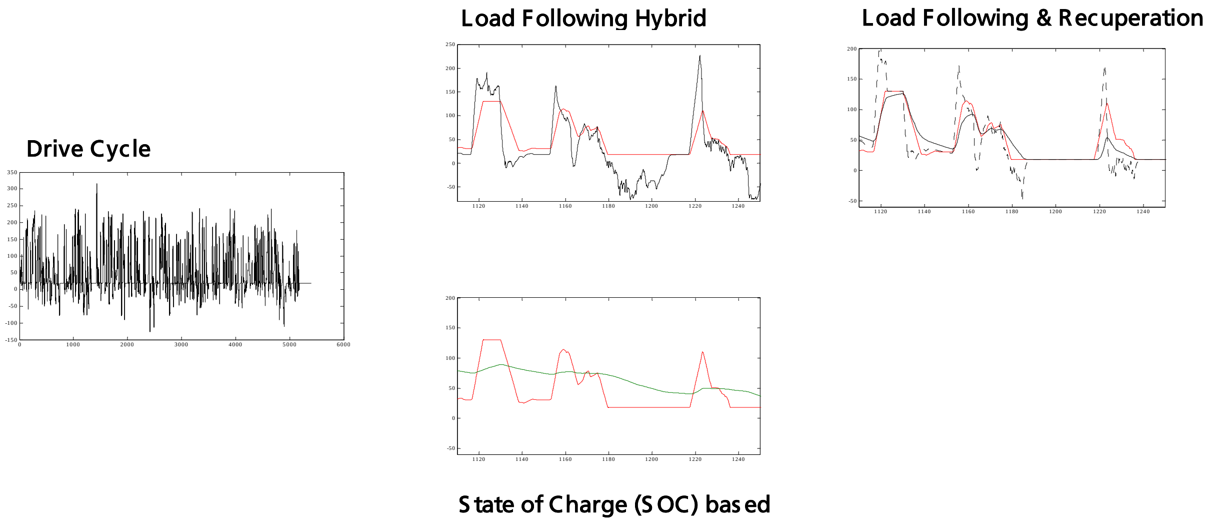


Figure 6: Operation modes of Fuel Cell Systems during drive cycle in practice

The overall results of that test have been very promising in the way that operation time achieved under test conditions have been approx. two times higher then the expected and so far achieved operation time of the MK 902 Stack Module under operating conditions in the HY-80 system. Within the HY-80 system BOP just one higher rated failure occurred that has already be known being a design weakness in the system.

To verify the function and the operation strategies of the fuel cell cluster in a hybrid environment Period III of the program has been dedicated to the integration of the cluster into a test vehicle AutoTram (see figure 7) of Fraunhofer Institute IVI including operation and specific testing.

Figure 7: AutoTram test vehicle for PEFC cluster

6.6 Hybridisation of PEFC clusters

A crucial point in the FELICITAS project is the utilization of energy storage devices in the fuel cell drive train in order to obtain the degrees of freedom necessary to achieve the main objectives of the project. These objectives include the

- Maximum lifetime of the fuel cell system by
  - Flattened dynamics of the fuel cell system, which decreases the mechanical stress of the fuel cell auxiliaries (e.g. of the compressor) as well as the mechanical stress of the membrane (due to lower pressure differences between the anode and the cathode), and allows an increase in accuracy of cooling temperature control,
  - Avoiding of operating ranges which affect the lifetime adversely (idle and nearly-idle operation includes the risk of local drying out of the membrane) as well as frequent start-ups and shutdowns of the fuel cell (which lead to high mechanical stress of the membrane during start-up and to an accelerated aging of the membrane during the cooling down process after shutdown),
- Increased reliability and durability of the fuel cell system by
  - Ensuring the above mentioned conditions for a maximum fuel cell lifetime since these are also relevant criteria to the reliability and durability of the fuel cell system,
  - Utilization of existing highly developed fuel cells (avoiding a redevelopment of a high power fuel cell) which is possible by clustering and – owing to the use of an energy storage device – by downsizing the fuel cell system.

Moreover, since recuperation of braking energy is possible with the energy storage device, decreased overall fuel consumption can be achieved.

Due to the additional weight and volume caused by the onboard storage device, the major challenge was not only to find a storage device that is technically mature, but offers both a high energy density and a high power density at the same time. The flywheel of the FELICITAS project partner CCM shown in figure 8 was the most promising technology that accomplished with those requirements, and therefore, it was chosen to be used for the practical tests within the FELICITAS project.

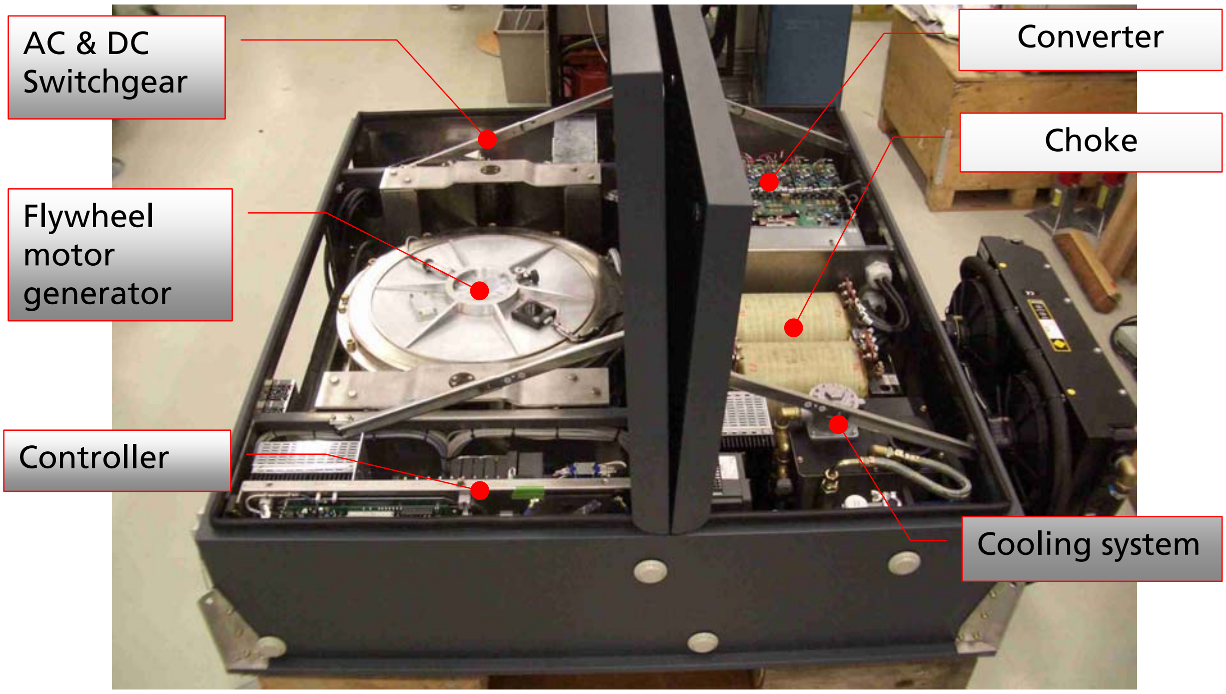


Figure 8: EMAVER (320kW / 4kWh) flywheel system for heavy-duty hybridisation from CCM

6.7 Advanced energy management of hybrid FC systems

Among the variety of proposed energy management strategies for hybrid fuel cell drives, optimal predictive control strategies are considered to be the most powerful ones. The main advantages are the capability of including information about the future traction power demand (which acts as a disturbance to the hybrid drive control system) into the calculation of the power flow within the drive system and the explicit consideration of the constraints inherent to the system, e.g., limited capacity of the storage unit and limited fuel cell power.

The challenges in the development of a dedicated energy management for hybrid fuel cell clusters were

- The analysis and enhancement of available models of hybrid fuel cell drive trains and the description of the control objectives (which include the above mentioned lifetime and reliability/durability criteria as well as the minimum fuel consumption) in an appropriate way,
- The classification of operating conditions determined by the vehicle and the environmental conditions, the driving task etc., in order to build-up suitable models for the prediction of the future traction power from measurements available in the vehicle,
- The identification of relevant constraints and objectives and the adequate modification of the resulting power split optimization problem in order to reduce the computational effort for the real-time solution of the energy management problem on a vehicle controller,
- The treatment of implementation aspects in order to cope with the limited memory space and computational power of a vehicle controller.

6.8 SOFC – PEFC coupling

Merging the advantages of SOFC and PEFC technologies was the most visionary research within FELICITAS and had been dealt with direct coupling of SOFC and PEFC systems.
This approach could be described as a special reforming technology for PEFC stacks and had been considered in Subproject IV.

Previous work on the coupling of SOFC and PEFC regarded an application as a stationary system with typical requirements for distributed power generation. In contrast FELICITAS examined a coupled system with regard to an application as a propulsion system for heavy-duty vehicles in which requirements and demands for the propulsion system are substantially different.

The aim of work package IV.3 was the study of the serial coupling of a SOFC and a PEFC. The coupling could combine the advantages of each technology and lead to a better overall efficiency of the system compared to a single technology. The SOFC is used both as a generator of electricity and a contribution of the remaining carbon monoxide oxidation in the reformation of diesel. Five objectives had to be fulfilled:

- First, the development of an efficient Diesel reformer with a relevant method considering the heavy-duty transport application (water balance and heat balance have to be taken into account).
- Second, the development of a micro-reactor for the purification of the SOFC downstream to supply the PEFC. The CO content has to be as low as possible otherwise the performances of the PEFC decrease with time in a cumulative way. The CO has then to be removed from the electrode catalyst to recover the performances. The used technology is the impregnation of a large surface area on micro-structured metal plates for impregnation with catalytically active substances; the process aims base to be optimized to reach stable and homogeneous catalysts layers.
- Third, the development of component models with a macroscopic approach in order to be able to implement them in the simulation of the global system.
- Fourth, tests of the components in operating conditions as closed as possible from the ones in the system.
- Fifth, the simulation of the global system to quantify its performances.

7 Results achieved

As described above the objectives of FELICITAS covered a range of basic and applied research. The solutions developed and tested in FELICITAS can be seen as a pragmatic compromise for FC applications in heavy-duty transport, but currently they represent the most feasible alternative to meet the demands of heavy-duty transport.
Not all the objectives of FELICITAS have been achieved due to technical complexity, an unforeseen incident as well as resource and timing issues.

7.1 General requirements

The specific requirements of the applications bus, tram (light rail), trucks (APU as well as traction) and yacht (APU) were defined in detail by the FELICITAS project. Based on these requirements the concepts of the fuel cell systems for different applications were developed in the subsequent tasks.

The **assessment of the requirements** shows considerable differences regarding the power density, maximum weight and maximum costs for the different applications. In addition the load demand, load changes, fuel requirements have been analysed in detail.
Figure 9 illustrates the differing requirements of heavy-duty transport modes. This provides the FC manufactures with the definition of development targets and first markets.

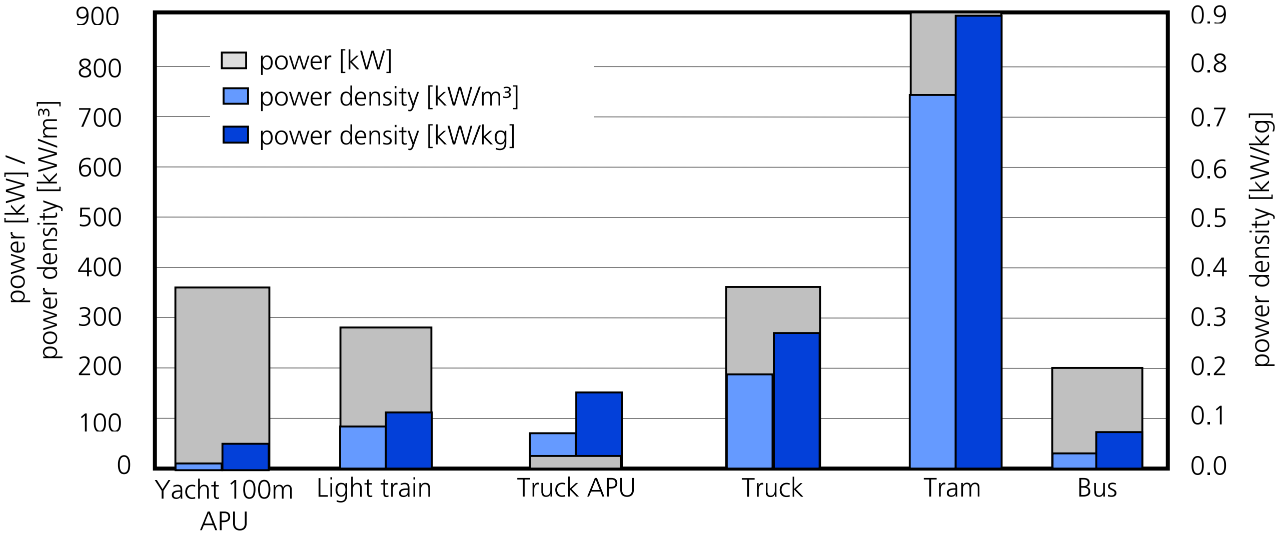


Figure 9: Comparison of the requirements on power, gravimetric and volumetric power density of different modes of heavy-duty transport

The pre-existing standards and codes have been evaluated with respect to their applicability for the related application.

7.1.1 Marine application

Mega yachts are considered to have a high potential as an early market for large quasi-stationary FC applications in form of APUs: the characteristics of fuel cells, e.g. low emissions and high efficiencies are likely to appeal to the owners of such vessels, who are in a position to pay a premium over existing equipment.

To define the interfaces for such an FC based APU and to promote the related market entry, the mechanical integration of SOFC onboard a mega yacht by means of virtual 3D constructions was a first step. This involved determining the volumetric constraints, mechanical and electrical interfaces as well as safety and security relevant issues.

Figure 10: Mega yacht exemplary basis of virtual SOFC implementation

Prior to FELICITAS the integration of fuel cells has been investigated only in conceptual studies (e.g. FCShip). Within FELICITAS Lürssen has elaborated such a virtual integration of the Rolls-Royce SOFC onboard a mega yacht.

An existing hull design for a mega yacht (see figure 10) has been reconfigured in order to create room for the fuel tanks, the fuel treatment, the fuel cell and the auxiliary systems like ventilation, etc. The relevant components of the SOFC system, including an energy storage system, have been placed into the new structure and the components have been virtually connected to the yacht system.

The basic layout of the system arrangement (see figure 11) is based on the rules of Germanischer Lloyd. Due to the fact that the study was done for an existing ship design the possible modifications were limited. Especially length, width and deck height could not be changed.

Furthermore the available rules for integrating a fuel cell and the gas components need to be reconsidered to some extend.

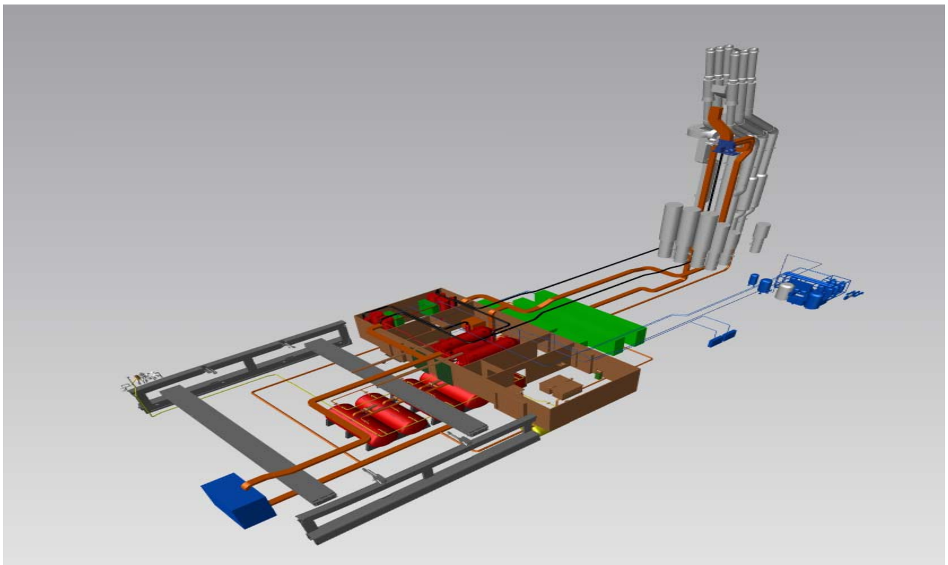
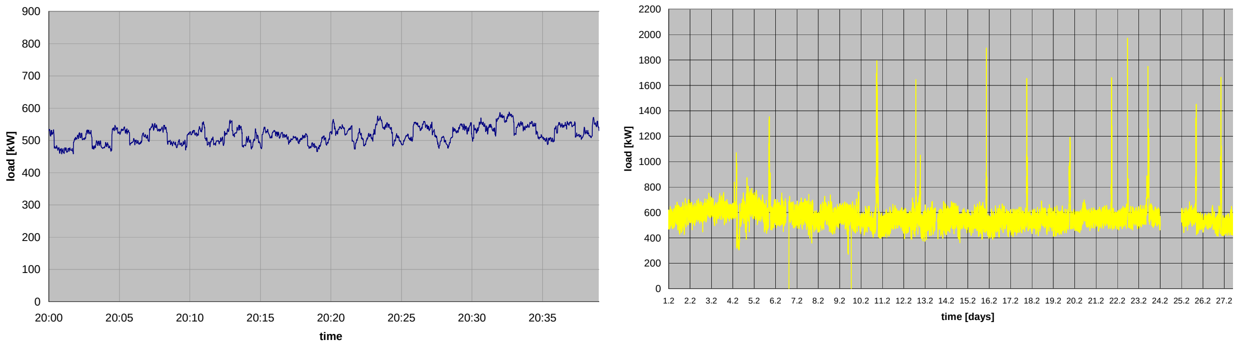


Figure 11: 3D model of integrated SOFC including auxiliary equipment and piping (most of the already existing components of other systems are not shown)

The real time load assessment of such a yacht was a further goal. Three yachts had been equipped with measurement devices and data loggers to be able to measure the electrical load during different operation modes (see figure 12).



short term measurement long term measurement

Figure 12: Load profiles measured to design the SOFC APU

The evaluation of the measured data shows that significant load fluctuations occur during operation, which cannot be compensated by the fuel cell itself. The rapid load changes vary between ±30 to ±100kW. The measured load profiles were used for the design of the electrical system and the determination of an energy storage system.

A detailed analysis had shown that CCM flywheel storages could be a preferable solution considering the results of FELICITAS within the first stage. However, the flywheel accident at the end of 2006 has interrupted these developments.

The long-term measurements had shown that the base load, which can be supplied by a fuel cell in combination with an energy storage device covers more than 80% of the total power demand. Only the additional less than 20% of required power needs to be supplied by conventional generators.

This also means that the environmental and efficiency benefits have a big effect over the lifetime of a yacht or other ship types.

The application oriented requirement analysis was completed by technological investigations about the present state of the art of SOFC technologies. So, an extensive literature review[1] has been carried out to establish the present state of knowledge regarding the materials used in land-based SOFC systems under the conditions likely to be experienced in marine applications. This included details of known failure mechanisms, material and/or system performance degradation, etc. for both stack and system materials.

7.1.2 Land - based applications

Land-based FC applications were divided into different transport modes on rails or streets.

7.1.2.1 Heavy-duty trucks

Outlined by AVL the basic requirements were covered for fuel cell applications in **heavy-duty trucks**. The requirements are specified into general, legislative, economic and safety requirements.

For the simulation work during this project a representative drive cycle, recorded with a 40t heavy-duty truck was presented.

[1] Rolls-Royce Fuel Cell Systems Ltd., "Literature Review of Material Stability in a Marine Environment", FELICITAS Project Deliverable DII.1.1.1, 2006.

For the implementation of fuel cells in heavy-duty trucks, two application fields were identified:

- Main propulsion and
- Auxiliary power units.

For both application fields, the requirements mentioned above were defined (see figure 9).

7.1.2.2 Heavy-duty rail applications

Heavy rail vehicles are operated for different purposes:

- Local passenger service,
- Suburban passenger service,
- Regional and long distance passenger service,
- Freight service (local and regional), and
- Shunting.

The optimal rating which must be realised by a FC propulsion system depends on the:

- Kind of operation mode,
- Permitted track speed,
- Average and maximum track gradient and
- Potential train mass.

These different operation conditions were to be considered during the specification of mechanical and electrical requirement of high power FC systems designed and simulated in frame of the FELICITAS project. The presented results did not give comprehensive answers to the open questions regarding the utilisation of fuel cells in heavy-duty applications. However, the results suggest that heavy-duty rail applications are not suitable for the utilisation of fuel cells, at least not for propulsion purposes.

7.1.2.3 Bus and tram applications

The requirement specification of the **fuel cell cluster for bus and tram** applications contained a comprehensive survey on state of the art analyses, which tried to face the reality with the elaborated requirements in the bus application sector.

Extensive measurements of time- and track-related electrical parameters both in buses and in trams in daily service operation were done by Fraunhofer IVI throughout the years 2006 and 2007. The collected data gave a representative overview on the power and energy consumption of ordinary busses and trams in public transport service. Based on these data the PEFC clusters for specific bus and tram applications were designed.

Furthermore the data were used as input parameter of an advanced predictive energy management concept developed in Subproject IV.

The investigations within FELICITAS, uniting the requirement deliverables for bus and tram FC applications, present a picture of the current status of urban transport road and light rail traction equipment.

Within this scope, electrical, mechanical, safety, operational, environmental and quality requirements based on conventional vehicles have been defined. Only the economical requirements could not be defined as precisely as intended since vehicle manufacturers and operators keep a tight guard on all data concerning their financial calculations.

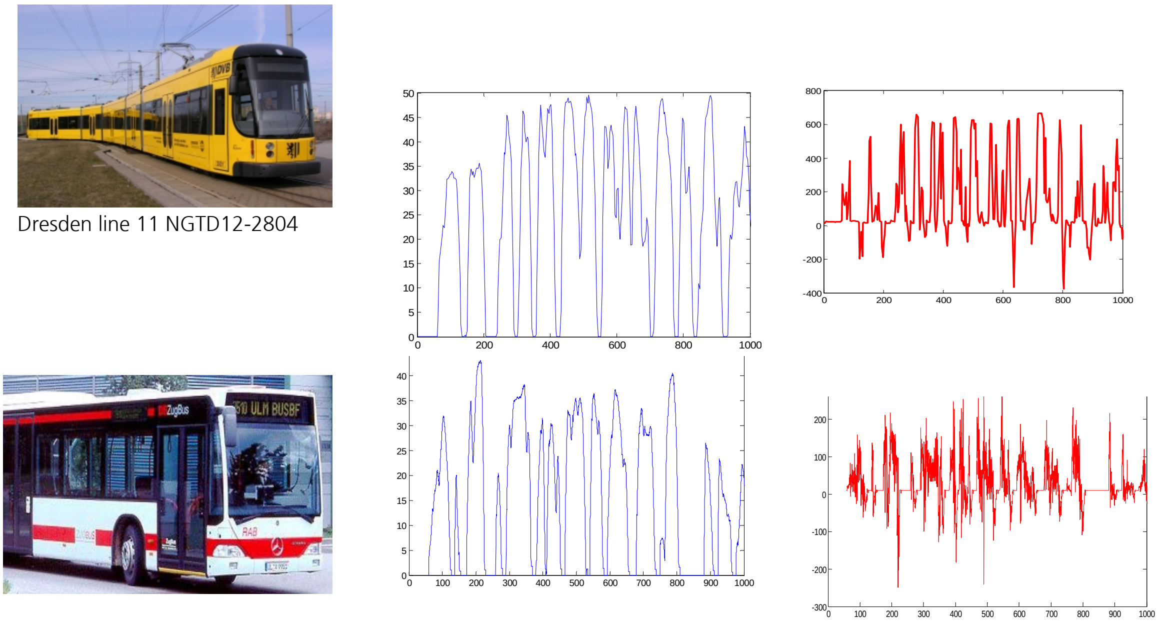


Figure 13: Examples of measured speed (blue) and load (red) cycles of buses and trams operating on line service in a German city

A virtual integration (see figure 14) and simulative investigations of a hybrid PEFC cluster were done for a requested tram application in both urban and suburban line operation without catenaries.

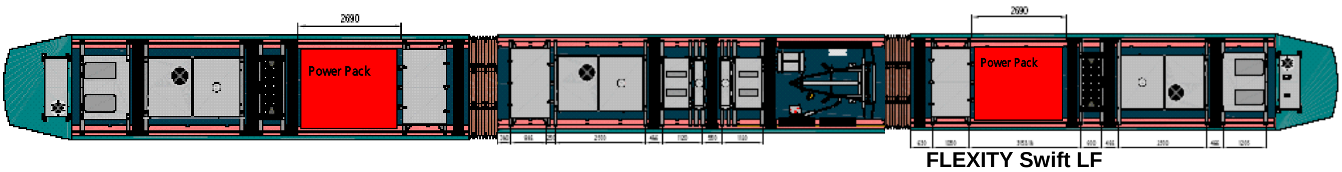


Figure 14: Virtual integration of hybrid FCC based power pack into FLEXITY Swift L (Bombardier)

Using the FELICITAS simulation tools it could be shown that for 12 - 20h daily operation of this 60t-tram by assumption of a 250 - 350km operating range

- H_2-consumption 75 / 95kg
- H_2-storage volume 4 300 / 5 500l
- H_2-storage weight 1 400 / 1 800kg

have to be foreseen.

Regarding other additional masses like FC systems, energy storages, cooling systems or power electronics the mass balance of such a tram is oversized in a non-tolerable way. This technical barrier reflects other general oriented investigations of FELICITAS, too.

The investigations to gravimetric and volumetric requirements were completed by studies done by INRETS to safety relevant issues for FC applications in urban transport. INRETS focused its contribution on the inventory of the legal regulations and standards concerning railway applications and possible implementation of fuel cell generators on rolling stock engines (hybrid locomotives, light trams …) as well as reliability requirements and safety issues concerning the implementation of fuel cell generators on light urban railway vehicles.

7.2 Simulation tools for design processes

The development of simulation tools was manifold within FELICITAS. By means of simulation the design processes for appropriate SOFC/PEFC clusters or hybrid configurations were supported on different levels.
At the beginning of FELICITAS a detailed analysis showed that a lot of simulation tools were already available, other tools were stimulated by the preparation of this project and most of these tools were focused on the application level.
Therefore, the development of a common FELICITAS simulations platform were placed back in favour to an open exchange of models within the consortium and to well-defined interfaces to allow interactions between the models if deemed necessary.

An overview about FELICITAS' simulation environment gives the following table.

Name	author	level	purpose	basis
CRUISE	AVL	application	CRUISE is a highly sophisticated vehicle and drive cycle simulation tool developed for standard and hybrid power trains. Based on user defined drive cycles, vehicle parameters, maps of energy converters, component maps, and power train configurations, output parameters like emissions, consumption, dynamic behaviour and vehicle properties can be calculated.	C++
FELISim-G	FhG IVI	application	FELISim-G is the first step for researching a HEV configuration. A rough estimation of power demand, energy consumption and sets of suitable configurations can be delivered very fast.	Matlab / Simulink
FELISim-F	FhG IVI	Intermediate level	FELISim-F is the following step after FELISim-G. With detailed modelling of the used components accurate results can be achieved. New control strategies can be developed and tested to increase the efficiency of the configuration.	Matlab / Simulink
TRACAL	VUZ	application	To reach an optimal traction vehicle concept for rail vehicles TRACAL considers the train operation modes as railcar or locomotive and the energy consumption in dependency of train mass and track gradient.	Matlab / Simulink
VEHLIB	INRETS	application	VEHLIB includes the electrical models of components and devices like semi-conductors for power converters, supercaps, and batteries. For specific light railway mission profiles power and efficiency will be provided as model inputs. The tool is able to adapt all types of input power sources like a diesel, catenary network, battery or fuel cell.	Matlab / Simulink

Name	author	level	purpose	basis
HVS	ICL	application	HVS is used for the macroscopic modelling of hybrid power-trains. Components like chassis, wheels, batteries, flywheels, supercaps, gearboxes and controllers are considered in an open structure. On the basis of module specific parameters and duty cycles, the system performance and the optimal power train component size will be calculated.	C++
MARINE-HYBRID-IP-SOFC	UNIGE	intermediate level	The tool describes FCs and technical components like turbomachinery, heat exchangers, ejectors, and fuel processing under marine conditions. In dependence of input parameters like network and FC voltage, power demand, and fuel composition, the performance of these components can be calculated. The model focuses on the performance in steady state and under variable ambient conditions as well as under planned transients (load steps like known load switching events) and unplanned load steps like protection events.	Matlab / Simulink
Network Interface Unit	R-R	intermediate - component level	The tool describes technical components like controllable voltage source inverters, power electronics, interface transformers, and local energy storage. In this way, the model acts as interface between the FC and the host electrical network within the mentioned performance demands of the FC.	Matlab / Simulink
	HUAS	energy balance	This simulation tool integrates a diesel steam reformer into the SOFC stack and simulates SOFC hybrid system processes. The model describes fuel pre-reforming processes like cracking and gas purification as well as fuel reforming and the fuel cell stack itself. Chemical and thermodynamic values and connections act as model inputs, heat, mass and energy balance are output parameters.	Matlab / Simulink and FEMLAB
FESS_Sim_Model	CCM	component level	FESS can be applied for the sizing of the flywheel energy storage system as well as for the development of the control strategy of the power management of the hybrid drive system. Components like power converters, switch gears, controllers, and auxiliary systems are included. The simulation model has been validated by adequate hardware testing at CCM.	Matlab / Simulink

Name	author	level	Purpose	basis
	Nucellsys FhG IVI	component level	A black box model was developed to describe the FC system Xcellsis HY80. On the basis of FC current, coolant inlet temperature and mass flow, conditions of air inlet, H_2 inlet, and ambient output parameters like air and hydrogen mass flow, coolant outlet temperature and fuel cell voltage can be calculated. FhG IVI participated with a tool modelling FC systems and auxiliaries. It describes the FC stack and system module including the compressor and cooling system with its components. On the basis of a macroscopic modelling level, dynamic calculations of the FC's heat release are possible for designing the optimal cooling control strategy.	Matlab / Simulink
NTUA1.-6.	NTUA	component level	The tool describes the optimum dimensioning for turbo-machinery components like compressors and turbines for a given specification, the production of performance maps for these components for given component geometry, the computing of 2D/3D flow, and the peripherally meridional flow in the components and compute the thermodynamic cycle parameters for gas-turbines. An additional tool was necessary for dimensioning the gas turbine components, when requirements were imposed on both SOFC and GT. These requirements reflected operating points of nominal and off design conditions.	
PEFC stack and gaslines	UTBM	component level	The tool describes a PEFC generator including stack, hydrogen line, and air line on a macroscopic level. The stack model is based on a semi-empirical approach. The hydraulic behaviour of the gas lines has been modelled by means of an electric analogy in order to be easily implemented in electrical engineering software.	Matlab / Simulink
SOFC-PEFC coupled systems	FhG IVI	energy balance	This simulation model describes the process of coupling of SOFC and PEFC.	Matlab / Simulink

Table 5: Simulation tools developed or improved within FELICITAS

To demonstrate the details of FELICITAS' simulation tools **Rolls-Royce**'s model of a marinized SOFC and its interface to a network should be demonstrated exemplarily. This model comprises a dynamic model (with a bandwidth of around 1Hz) of an auxiliary power unit based on a FC operating in parallel with a high speed gas turbine which can be used to perform whole ship system simulations in an acceptable time.

This reduced model consists of the following dynamic models:

- APU Control
- Load cycles
- Gas turbine - FC
- Gas turbine governor - FC governor
- Gas turbine DC bus - FC DC bus
- Gas turbine converter - FC converter
- Gas turbine converter control - FC converter control
- Gas turbine AC link - FC AC link

The overall APU control system changes the FC output in discrete steps of 10% of its rating with a hysteresis controller. Load following is performed by the gas turbine.
The simulations indicate that a FC / gas turbine hybrid system is capable of meeting the requirements of a marine auxiliary power unit.

Furthermore, **Rolls-Royce** developed a Cracking Number approach, a simplified analytical model based on elastic behaviour and a finite element simulation have been used to predict the effect of thermal expansion mismatches in the Rolls-Royce' SOFC multi-layer cell structure. The Cracking Number approach was shown to offer the best method for predicting layer integrity.

A simulation model for a heavy-duty truck equipped with a FC power train was elaborated by **AVL**. The simulation was performed by the well established software AVL CRUISE – a validated and effective applicable software tool for simulation of various vehicles concepts and its driving conditions. A fuel cell system model was build-up in Matlab/Simulink and integrated into the CRUISE environment. The necessary schematics of the power electronics and the vehicle controllers were developed and integrated.
For the defined 22.5t heavy-duty truck used in the simulation two propulsion concepts (FC and ICE) were simulated and compared. The drive cycle efficiencies for ICE propulsion reached 40% and for FC propulsion 38%.

The **Fraunhofer IVI** simulation tool FELISim-G also belongs to the application level. It aims at power train dimensioning of hybrid heavy-duty vehicles in public transport and can be used for a simple approximation of energy and power requirements. The energy demand of a hybrid fuel cell vehicle and the distribution to the fuel cell system and to the energy storage unit can be easily calculated by this simulation tool. The results of FELISim-G help to find the right hybrid configurations of power train units for a given route.

The results of fuel processing simulation done by **HUAS** can be summarised as follows:

- **Optimum operation temperature in steam reforming** and auto-thermal fuel processing were found **between 650°C to 800°C** where the whole hydrocarbon content is converted to hydrogen and carbon monoxide.
- The most promising **steam to carbon ratio** (S/C) is expected to be **about 2** for the steam reforming process. There is a risk of carbon formation at lower ratios. The concentration of hydrogen and CO (wet concentration) in reformed gas decreases at higher ratios. Therefore, the heat duty of fuel processing increases.
- Oxygen to carbon ratio controls the conversion of PO_X and steam reforming reactions in an auto-thermal fuel processor. At higher O_2/C ratios, the concentration of hydrogen and CO in reformed gas decreases. Consequently, required **thermal energy** of the whole process **decreases** when a **higher conversion of PO_X** reaction takes place **in the auto-thermal reactor**.
- The thermal energy requirement of the fuel processing system (main reactor and pre-heater system) can be provided partly or completely by the produced thermal energy of the fuel cell stack. The **required thermal energy** of a fuel processing system with diesel

as primary fuel, especially a **diesel steam reformer, is much higher than an LPG fuel processing system**. Up to 90% of the produced thermal energy of the fuel cell stack should be supplied to the diesel steam reformer in order to produce the required amount of reformed gas for the Rolls-Royce fuel cell stack

- In PEM applications, the concentration of **carbon monoxide can be reduced to 5 000ppm in a low and high shift reactor**. The remainder of the CO is removed in a SELOX reactor to decrease the concentration of CO to 100ppm or less

Demonstrating the simulation results fuel processing the concentration of different components at the outlet of LPG steam reformer versus reactor operation temperature is shown in figure 15. The steam to carbon ratio is kept at 2 in this case.

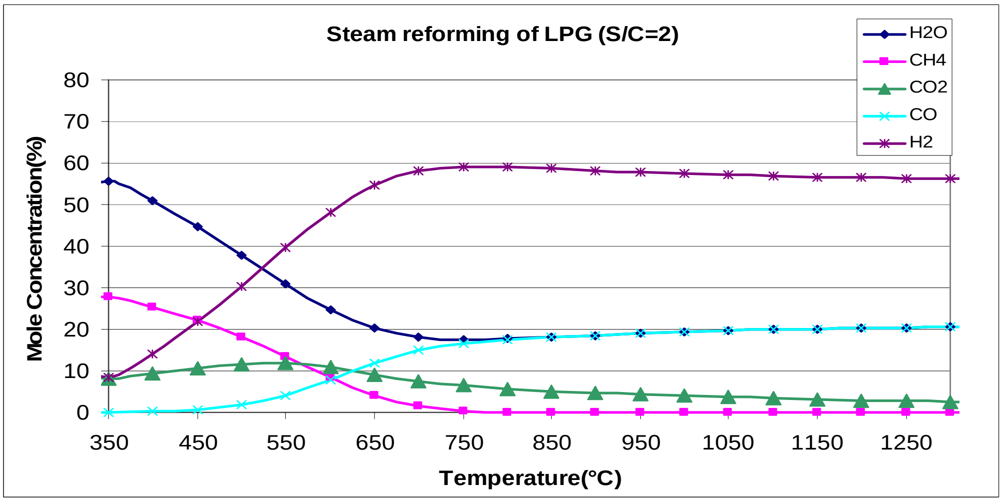


Figure 15: Reformatted gas composition at different operation temperatures

All above mentioned advantages have shown that there is no preferable primary fuel and fuel processing method. The optimal fuel processing method and the primary fuel can vary depending on the system specification and requirements.

All related topics concerning the coupling and hybridisation of PEFC and SOFC were covered by simulation or modelling tools of the project partners, too. Most of these tools include aspects of at least two topics, which mean either hybridisation or coupling.

UTBM developed a generalized model of fuel cell stacks, the PEFC and the SOFC. A macroscopic approach has been chosen to build up the coupled system.

The stack is modelled by a single cell. Its behaviour is representative of the average behaviour of the stack cells. The three energy flows

- Electric,
- Thermal and
- Fluidic

are taken into account in the FC stack models. The approach leads to three interconnected models. The electric response has been described by a quasi-static equation, based on Nernst- and Tafel-laws. In the fluidic model, each component was represented by an RC cell. The thermal model describes isothermal volumes, centred on the anode. Each node is connected to the others trough thermal conductance and associated to a heat capacity. The heat balance resulting from the first principle of thermodynamics is written to compute the temperature at each node.

7.3 SOFC Technology for Marine Applications

This project focused on exploring and achieving a much better understanding of how the Rolls-Royce Fuel Cell Systems (RRFCS) Solid Oxide Fuel Cell (SOFC) system would perform under marine operating conditions. These conditions included integration in a moving vessel, operating in a high humidity salt environment, with marine type fuels, under potentially intense vibrations whilst meeting the power needs of a vessel in an Auxiliary Power Unit Configuration.

The underlying philosophy was to take the RRFCS SOFC System being developed for land based stationary power generation, to marinize this with minimal changes to achieve high design and component commonality. This approach would keep additional costs to a minimum and open up a larger market for fuel cells.

The project undertook investigations in six areas:

- Electrochemical performance
- System material degradation
- Mechanical integrity of fuel cell stack
- Marine fuel processing
- System operation
- SOFC unit/vessel integration.

The work was undertaken by five collaborators: **Rolls-Royce, Luerssen, Universities of Eindhoven, Genoa and Hamburg**.

In summary the project substantially advanced the understanding of the challenges of marinizing an RRFCS SOFC system, demonstrating the following:

- Electrochemical performance – SOFC performance is likely to be adversely affected in terms of the power output when operating on a different lower energy dense fuel and when operating under high humidity and saline conditions. Further there is evidence that contamination due to system materials corrosion and possibly salt and other elements in the marine environment would be detrimental to the lifetime of the fuel cells.

- System material degradation – The humid and saline environment is likely to exacerbate material corrosion in system pipe work when compared to a land based system. This will release higher quantities of chromium oxides into the system and this species is well known for accelerating fuel cell degradation reducing the lifetime of the stack.

- Mechanical integrity of the fuel cell stack – Under vibration and shock loads the project demonstrated that the RRFCS stack design was robust and with suitable mountings and appropriate shock resistance could be used in a marine vessel. Vibration modes for the stack were compared with power spectral densities specific to marine vessels.

- Marine fuel processing – This element of the project highlighted the paradox of utilising existing marine fuels and the preferred fuels for SOFC systems. The former are available throughout the world, have high energy density, but require extremely intensive processing; whilst the latter, including LNG and LPG are not universally available, have lower energy densities, but present a more straightforward processing challenge.
  The use of diesel was investigated but current technologies point to the need to use partial oxidation of the fuel and higher quantities of water for processing. The latter is an issue for marine vessels in terms of quantity and quality. Additionally partial oxidation is thermally less efficient. LPG however is not without its challenges and the higher level of hydrocarbons is still sufficiently different to require optimisation of current catalysts.

- System operation – A series of investigations into the operation of the RRFCS SOFC was undertaken including modelling and experimental work with a micro-turbine-plenum simulator.
  The latter was run at steady-state and transient conditions to simulate operational requirements of an APU. This showed that the lower LHV fuel compared with natural gas required an increase in fuel mass flow and increased the total mass flow entering the expander of the micro-turbine resulting in the machine operating close to its surge line with over-speed issues. This issue would potentially lead to a re-design of the gas turbine. Modelling results demonstrated that the SOFC unit would operate best in a steady state mode as an APU, as anticipated. However, in order to cope with electrical load transients the supplemental power would be needed, a stand alone gas turbine for example, or the unit would be subject to rapid load and thermal changes which would likely damage the system. In terms of control systems, taking account of the more challenging system power management on board a vessel a new system was investigated including modification to temperature and fuel controllers. This system was modelled and showed very good stability and robustness.

- SOFC unit/Vessel Integration - A concept study has been worked out in an early design stage. The concept study focused on the arrangement of the necessary components of the SOFC, its auxiliary equipment and the fuel tank arrangements. A detailed study of the specific interfaces between an existing yacht design and a RRFCS fuel cell system based APU was undertaken using virtual 3D constructions. The volumetric constraints, mechanical and electrical interfaces as well as safety and security relevant issues were addressed. More specifically the study looked at:
    - Water supply by means of a two stage system to meet the water requirements of an SOFC system;
    - Fuel supply and fuel storage;
    - Energy storage system for load following;
    - Fuel and exhaust piping;
    - Ventilation
    - Maintenance spaces (stack change)
    - Power management system and
    - The necessary indirect interfaces to safety equipment (sensors, fire fighting equipment, explosion safe equipment); ventilation and cooling rooms.

In addition, a real time load assessment was carried out. Three yachts had been equipped with measurement devices and data loggers to be able to measure the electrical load during different operation modes. The evaluation of the measured data shows that significant load fluctuations occur during operation, which cannot be compensated by the fuel cell itself. The measured load profiles were used for the design of the electrical system and the determination of an energy storage system. The long-term measurements showed that the base load, which could be supplied by a fuel cell in combination with an energy storage device, would cover more than 80% of the total power demand.

Finally, the SOFC system and the energy storage system generate DC but the board net is AC, therefore a DC/AC-Converter was also added to the concept study.

In summary the project successfully investigated the range of issues that would affect the marinization of a RRFCS SOFC system. It is clear however that the philosophy of minimal changes from a stationary land based power generation SOFC unit is not possible. Substantive changes will be required, and these will consume considerably more time and resources than originally envisaged to achieve a successful transfer of the technology.

The **University of Genoa** has collaborated with Rolls-Royce in focusing on the marine application of SOFC based hybrid system developed by RRFCS as auxiliary power units. The simulation models already created at the University of Genoa have been enhanced and tailored for a marine application where in general the available fuel will not be natural gas and some kind of external fuel processor will be necessary to provide a feasible fuel stream starting from the fuel better suited for a marine environment. In particular during the project LPG and marine diesel where considered the fuels of choice for a short-medium and long term application respectively and moreover better satisfy SOFC system and shipbuilder requirements. Nonetheless, results have a more general value since the fuel streams considered despite being the result of a specific fuel processing system cover a wide range of compositions that could be the result of a much wider variety of fuel processing options. The results of the study are reported in the Confidential Reports.

The University of Genoa has been also involved in building of the "Hybrid system emulator" test rig. The test rig designed for hybrid system emulation is composed of a commercial recuperated micro-turbine package (Turbec T100 PHS Series 3) modified for the fuel cell emulator connection (figure 16), a set of pipes designed for measurement reasons and to widen the operative range of the machine with a bleed, five valves to control the flow rates, and a high temperature modular volume for the fuel cell stack physical emulation.
The test rig has been developed starting with a complete theoretical analysis of the micro gas turbine design and off-design performance and with the definition of the more flexible lay-out to be used for different HS emulation. The lay-out of the system (connecting pipes, valves, and instrumentation, in particular mass flow meter locations) has been carefully designed. The modular high temperature volume has been designed using a CFD commercial tool (Fluent).

Figure 16: The modified micro-turbine package

The main objective of the thermally insulated connection pipes (see figure 17) is the coupling of the machine with the fuel cell volume emulator, joining the two flows at the recuperator outlets towards the volume inlet and splitting the volume outlet in two flows for the combustor inlet pipes. The connection pipes have been also designed to measure the flows with pitot devices and to avoid excessive pressure losses. A cold by-pass has been included to connect the volume directly with the compressor or to mix the compressor outlet flow with the air coming from the recuperator. This layout is essential for a gradual heating and cooling of the fuel cell as required during start-up and shutdown phase emulation. At the compressor outlet a bleed line has been designed with a globe valve in order to discharge a part of the flow when operative conditions are approaching the surge region. This bleed line allows to reintroduce the flow downstream of the cell volume or to discharge the bleed air directly to the pipe of the turbine ventilation air evacuation. The plant includes an additional pipe, equipped with a mass flow rate meter, to directly connect the recuperator outlet with the combustor inlet, as in a typical recuperated commercial machine.

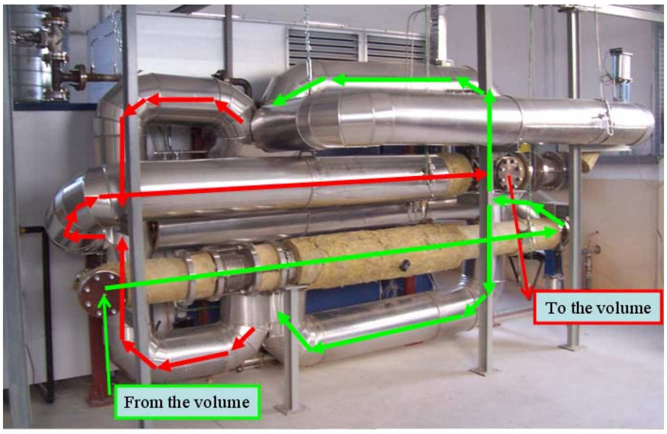


Figure 17: The connection pipes (final layout)

The fuel cell physical emulator is a thermally insulated modular volume connected between the compressor or recuperator outlet and the combustor inlet, as in a real hybrid system. Even if the real fuel cell stack is not present in the rig, a volume coupled with the machine combustion chamber can be used, to generate both pressure and thermal effects typical of a high temperature fuel cell. The absence of a real fuel cell allows to perform tests looking for new operative conditions, preventing expensive damages coming from surge conditions, excessive differential pressure between anode and cathode, not sustainable thermal gradients or too low Steam-To-Carbon Ratio problems.

Figure 18: Test Rig Final Configuration

The final layout of the test rig, with the modified commercial machine, the connection pipes, and the volume, is reported in figure 18.
Several tests have been carried out at different load values and at both steady-state and transient conditions.
Moreover the emulation of the hybrid system start-up and shutdown phases has been carried out. A valve control system has been studied and applied to perform a gradual heating up and cooling down of the fuel cell volume, using the cold bypass line, three high temperature valves, and the machine load control system. This approach is necessary to avoid high thermal stress on the cell material, extremely dangerous for the plant life.

The main results obtained in this work are:

- The design of a new test rig based on the coupling of a 100kWe commercial recuperated micro gas turbine with a high temperature modular volume for the fuel cell emulation.
- The design of a set of external pipes, equipped with transducers, for the connection of the machine with the volume. This layout has been chosen to perform the largest number of measurements for the hybrid system improvement and the model validation.
- The design of an apt modular volume to test the coupling of the machine with different kinds of fuel cell dimension or technology.
- The installation of the modified machine and the external pipes at TPG laboratory.
- The presentation of the test rig transient model used for the plant component design. After a preliminary model verification at design and transient conditions, this report shows the off-design results and the machine performance using a bleed valve to discharge a part of the compressor flow directly to the outlet stack.
- The tests operated at volume zero configuration focusing the attention on a 75kW load rejection.
- The preliminary tests operated with the modular volume connected with the machine. In particular, this report shows a surge happened during a shutdown at this configuration.
- A 60kWe load rejection comparing the rig behaviour with the machine operating with the direct line (VM fully opened, and VR, VO, VC and VB fully closed) or connected to the whole modular volume.
- The development of a new control system for valve management to generate the requested volume inlet temperature ramp, during hybrid system start-up and shutdown emulation. Even if different control strategies are under development by industry, the solution presented here is extremely essential for a wide commercialization of plants based on commercial machines.
- The definition of six phases for the start-up emulation, and other six phases for the hybrid system shutdown. This approach is essential for the control strategy definition with the objective to avoid dangerous or stress situations during the fuel cell heating and cooling.
- The control of both volume inlet and outlet temperatures during hybrid system start-up and shutdown emulation. It is important to highlight that both heating and cooling volume inlet temperature ramps are obtained with good accuracy (performing errors under 1% between the ideal ramps and the measured ones), as requested for the real systems.

Regarding the widespread application fields of FELICITAS optimisation of thermal SOFC management and development of special micro turbines therefore was addressed by **Imperial College London** (ICL), and **Technical University of Athens** (NTUA), too. The mentioned above marinization of the Rolls-Royce 250kW SOFC has shown quite specific problems so that suitable technologies for the utilisation of thermal energy were developed in a parallel task with respect to the special requirements of SOFC/GT systems in surface transport.

The results showed that a further efficiency improvement is possible if SOFC-GT units are designed as integral units, which has not been the case in previous efforts. For this reason Technical University of Athens decided to develop a gas turbine especially for this application and not installed as an afterthought.

NTUA focused on not using an off-the-shelf gas turbine for heat recovery. This is because, while using an existing gas turbine was a reasonable approach at the early development stage, it penalized the system performance in the long run.

The detailed aero-thermodynamic and structural design of the optimized GT unit was performed taking into account the following points:

- Identification of areas where improvements/changes in the GT configuration can benefit the system efficiency.
- Existing gas turbines are designed for a smaller pressure drop between compressor exit and turbine inlet. When a FC unit was introduced the GT operating point shifts from the optimum. For this reason the dimensioning of the gas turbine was performed by NTUA on the basis of considering simultaneously the SOFC and GT operation for the whole operating range, in order to obtain the desired results.
- Off design operation of the hybrid system was considerably different from that of a simple gas turbine, as a result of the limitations imposed by the need for stable operation of the FC. For this reason, the power split in SOFC and GT should be taken into account.
- Transient response was different, as there was a large thermal inertia of the system. In addition to that, rapid temperature changes in the fuel cell should be avoided.
- In order to avoid compressor surge at part load operation, suitable strategies were conceived and applied, demanding, also, optimal efficiency for the SOFC-GT system.

The results of the final tests provided the necessary feedback for more detailed system simulation, resulting in an optimum operation strategy for the hybrid system. The work performed by NTUA was mostly focused on future optimised systems for use as prime mover units in transport applications.
As a result of the nature of this application, optimising the gas turbine alone would not solve all problems, so operating strategies including power storage and energy management were investigated by Imperial. Nevertheless, using the computational tool developed by NTUA for the design of the gas turbine components, this goal was achieved but at the same time the power split SOFC-GT was determined and the control system proposed by NTUA resulted in an effective avoidance of compressor surge, during off design operation of the SOFC-GT system. The resulting computed efficiency of the SOFC-GT system was found to be over 60% for the whole operating range of the system and GT components could be aero-thermodynamically and structurally designed with high-efficiency. Verification of the design GT components was foreseen by the project, but was not realised, because a project extension was not accepted by the EC.

7.4 Fuel processing

Based on the necessary requirements of the different applications the partners for marine applications (**Rolls-Royce, Eindhoven University of Technology, University of Genoa, HUAS, Lürssen**) and land based applications (**AVL, FhG**) came to the following selection of development targets

	marine application	**land based application**
time line	medium term	long term
fuel remarks	LPG containing sulphur	diesel sulphur free
fuel processing remarks	steam reforming enough water available	ATR, POX water resources limited

Table 6: Development targets for different applications

The Rolls-Royce system was currently designed to operate on natural gas and a significant feature of the system design is the close coupling of an internal steam reformer with the SOFC stack; this recuperates waste heat from the stack and utilises stack exhaust gases.

To maximise commercial practicality and competitiveness of a marine product, the differences from this base system were minimised within FELICITAS. So, the internal reformer was included in a marine-based product. But, the required product stream from a fuel processing unit was atypical having high methane content in addition to hydrogen and carbon monoxide. Therefore, in addition to the thermodynamic calculations and system design, the catalytic processes were optimised experimentally, which was a significant body of work.

In FELICITAS' project time scale it was necessary to concentrate most of the effort on one fuel only. Of the currently available options, LPG was the fuel that best meets all the technical requirements and it was therefore possible with currently available technologies to design a system to run on this fuel.

However, development of a reformer system suitable for a marine-based SOFC system still presents considerable technical challenges.

Initial thermodynamic models have been run to determine operating regimes that produce a suitable fuel compatible with the rest of the system. These studies have shown that for the Rolls-Royce system the optimum fuel processing regime is steam reforming.
Partial oxidation should be avoided if possible as it is thermally less efficient and significantly reduces the calorific value of the fuel as in a real system air would be used rather than pure oxygen. It has been assumed that in most marine applications a pure water supply would be available for this purpose.

Significant catalyst development was carried out by the **Technical University of Eindhoven** mainly to develop novel catalysts that are sufficiently active and selective under the optimal conditions dictated by thermodynamic requirements of the overall system.

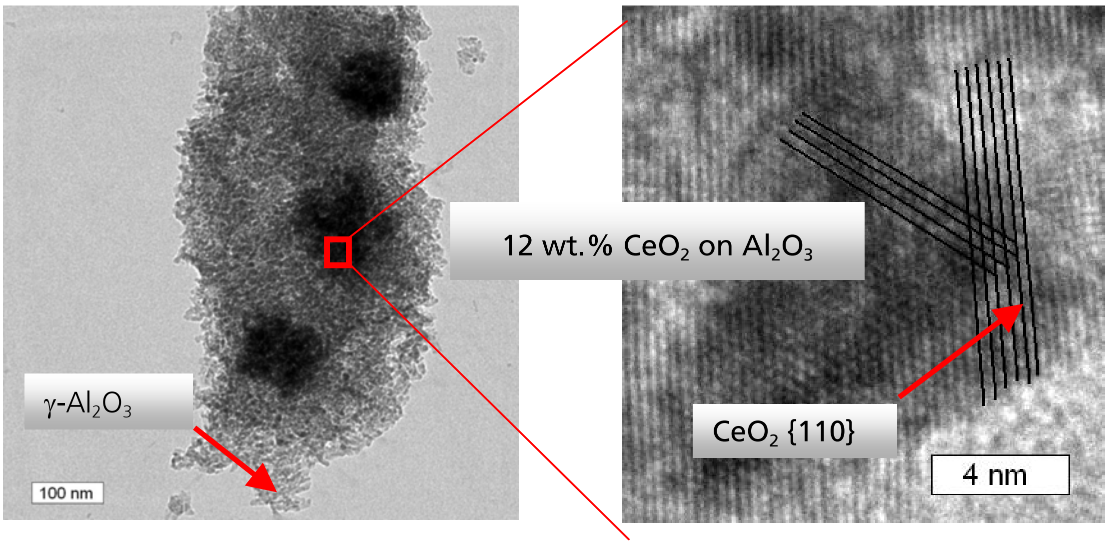


Figure 19: High-resolution electron microscopy micrographs of reforming catalysts

Novel compositions consisting of a noble metal Rh catalyst promoted by Ni so as to lower material cost were identified and in a second step metal-support interactions were optimised by including reducible supports. A **first generation RhNi catalyst** proved very active and stable, even in the presence of small amounts of olefins that are typically present in LPG.

Figure 20: Dedicated setup for studies on LPG reforming

Possibilities for integration into the Rolls-Royce' SOFC were further evaluated by carrying out LPG steam reforming at higher pressures.

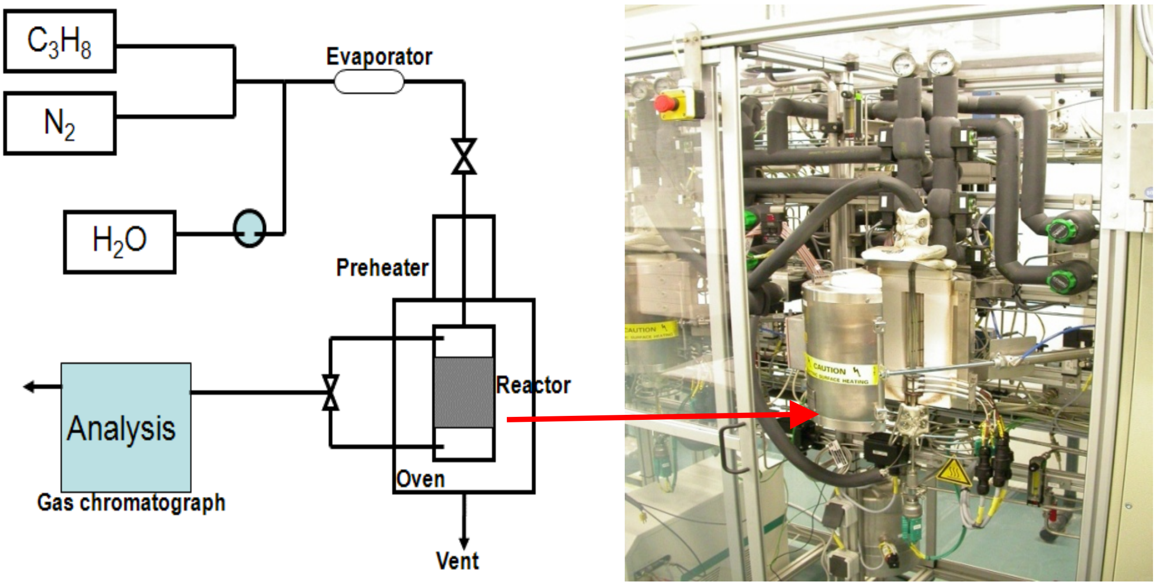


Figure 21: Dedicated setup for kinetic measurements LPG reforming

A global kinetic model of this catalyst was formulated. It can be included in simulations of the overall external reformer/internal reformer/SOFC system. Sulphur management in the external fuel processor was addressed by comparing various methodologies – **adsorptive desulphurization appears to be a viable method** and a ship-based unit could be easily accommodated. From the thermodynamic and kinetic studies, an overall fuel processing concept was drawn up. Some work carried out to assess feasibility of diesel reforming indicated that system integration with the RR-SOFC system is not straightforward.

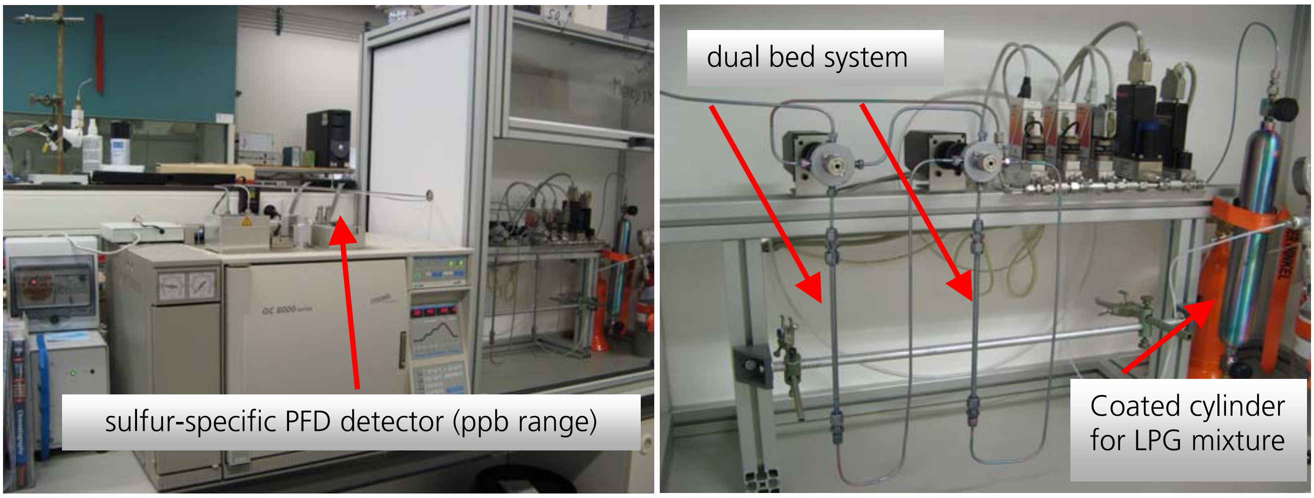


Figure 22: Dedicated setup for studies on sulphur adsorption from fuels

Methodological as well as experimental contributions to the proposed fuel processing concept came from the **HUAS** also modelling and developing Micro Steam Reformer including concepts for mechanical design and integration of this fuel processing technology with marine vessels.

A special test rig was constructed for basic research purposes. Figure 23 below shows this experimental platform.

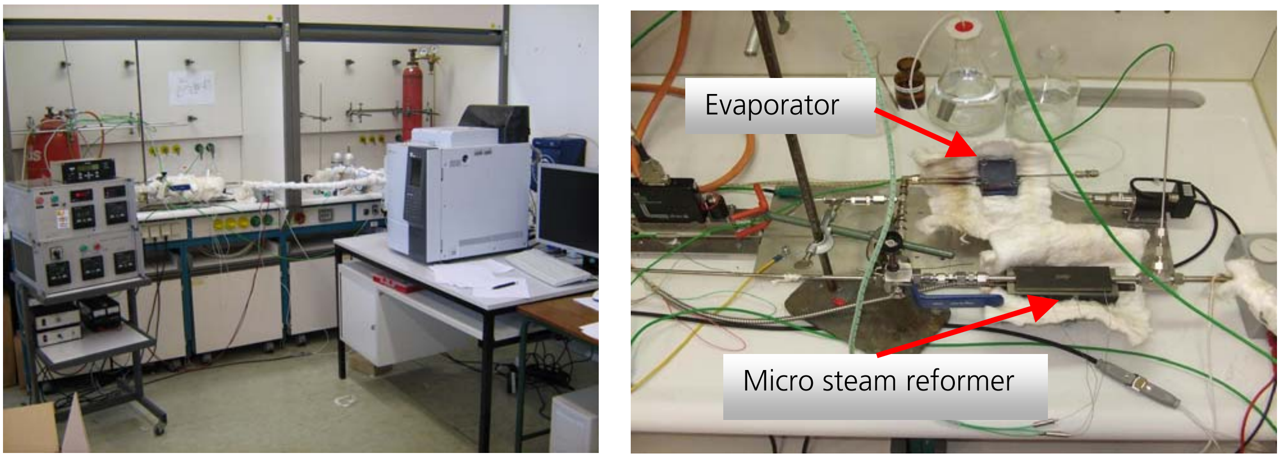


Figure 23: Propane micro steam reformer

The fuel reforming work for land based applications was performed mainly by **AVL and CDL / TU Graz**. The results fed the SOFC-PEFC system simulation at FhG. AVL brought experience from the automotive industry into the FELICITAS project which focused on a land based transport application achievable in the long term.
The fuels for such vehicles usually are gasoline and diesel due to their high energy density. These fuels will also play an important role within the coming decades. Diesel (as well as synthetic diesel) will be the fuel for on-road heavy-duty applications in the years to come.

Nevertheless, reforming of diesel for feeding high power fuel cell systems in particular is very challenging and is the object of long-term development. Compared to gaseous fuels, removal of sulphur, homogenous heating and vaporization, as well as homogenous contact with the active catalyst requires a larger reformer and more complex fuel processor technology for liquid diesel fuel. On the other hand, heavy-duty applications especially require a fuel with high energy density in order to maintain an acceptable vehicle range for the customer.

Thus the group came to the conclusion that the very simple storage and widely available fuelling infrastructure combined with the high energy density make the liquid fuel attractive and the more complex fuel processing acceptable for a long haul application.

Thus AVL had performed experimental work on diesel reforming in order to fill the gap existing between current state-of-the-art fuel processing development and the performance required for heavy-duty applications.

Figure 24: Heavy-duty diesel reformer and test bench developed by AVL

The diesel reforming method investigated in FELICITAS was selected by the boundary conditions predicted for a mobile application. A constant water supply for the fuel cell system is, in general, in land-based mobile applications not available. Hence, only a self-sustaining system in terms of the water balance is possible. This requirement is only fulfilled by a POX or ATR approach. Reformers for both processes has been developed and successfully evaluated on the test bench under stationary and transient conditions. To allow a transient and automated operation, a controller was developed. The results have indicated the best suitable reforming process for the coupled SOFC-PEM system, too.

In the first part of this project high- and low-temperature water gas shift reactions in micro-reactors were examined by **CDL / TU Graz** with the aim to decrease the CO fraction of the synthesis gas down to a level tolerable for proton exchange membrane fuel cells. These gas purification methods had the advantage of a higher hydrogen yield being achievable by "converting" CO into H_2, thus leading to a higher overall efficiency of the fuel cell system. The performance of micro-structured reactors with different commercial catalysts, as function of temperature, gas flow rate, and gas composition is shown in figure 25.

The preparation and optimization of new, suitable catalysts for the water-gas shift reaction in a micro-channel reactor were investigated in the second part of the experimental work. The catalysts had to exhibit high catalytic activity, strong adhesion to support foils and long-term stability, especially during start-up/shutdown procedures. The coating of micro-channel metallic plates was performed first with nanopowders/support materials by coating methods. The dispersion stability and the detailed interaction between particles were determined by zeta-potential analysis. The catalytic active materials were deposited during the impregnation method and accomplished the formation of the two catalyst systems. Well-adhering wash coats were obtained on micro-structured foils (see figures 26 and 27). A detailed investigation about the influence of different variables on the coating uniformity has led to a coating of catalysts with good adhesion inside stainless steel micro-channels. The adhesion was highly dependant on the nature of binder, initial particle sizes, pH and also surfactant addition.

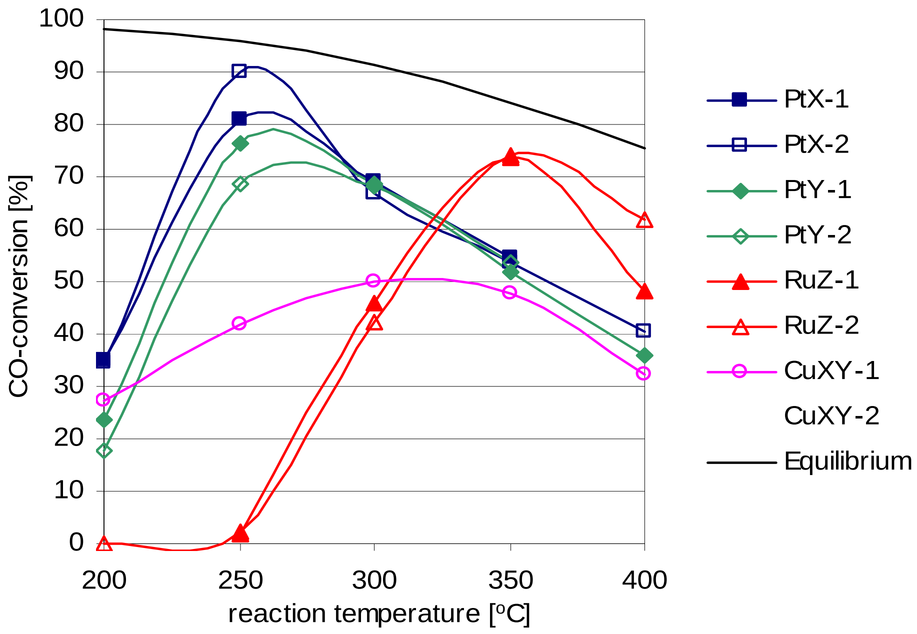


Figure 25: CO-conversion at 558ms residence time and 2.1 H_2O/CO-ratio over the industrial catalysts as a function of reaction temperature; HTS-input gas: CO = 8vol.%, CO_2 = 12vol.%, H_2 = 23vol.%, N_2 = 30.6vol.%, H_2O = 17vol.%[2].

The dispersion stability and the detailed interaction between alumina and cerium dioxide particles were established by zeta-potential measurements, which allowed the flocculation and dispersion stages for solid medium in the suspension to be controlled. The highest-resulting Al_2O_3 surface reached 216.4m^2/g. The catalysts exhibited strong adhesion to support foils and proved long-term stability, especially during several start-up/shutdown procedures[3].

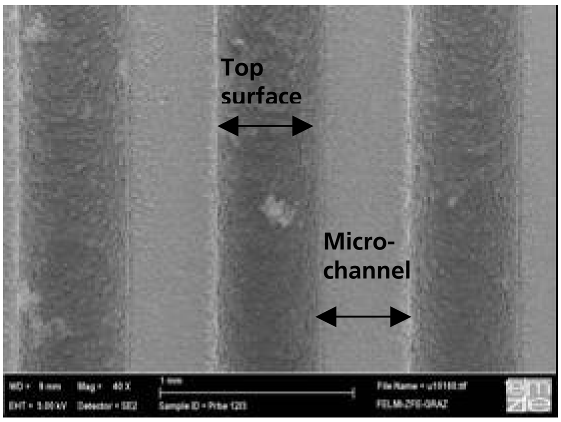


Fig. 26 Surface morphology of $Pt/CeO_2/Al_2O_3$ catalyst in micro-channels

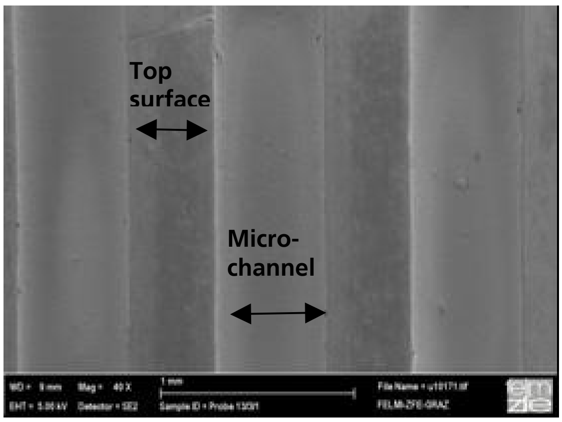


Fig. 27 Surface morphology of Pt/CeO_2 catalyst in micro-channels

The catalysts were tested at reaction temperatures between 200°C and 450°C in one-stage water-gas shift reactors (see figure 28). The catalyst loading, the surface area and platinum amount had a significant effect on the activity of both $Pt/CeO_2/Al_2O_3$ and Pt/CeO_2 catalysts.

[2] Pawlak, M.; Thaler, M.; Hacker, V.: Characterisation of HTS and LTS reactions in micro-structured reactors. - in: Energy & fuels 21 (2007) 4.

[3] Pawlak, M., Hacker, V., Siebenhofer, M.: Hydrogen purification using microstructures Part I: Preparation of Al2O3-and CeO2 washcoats in microchannels in: Chemical Engineering Communications – submitted.

The high thermal catalyst stability with high activity of the $Pt/CeO_2/Al_2O_3$ catalyst was proven under the condition of water-gas shift reaction. The 1wt.%Pt/24 wt.%CeO_2/Al_2O_3 catalyst was the best catalyst for the WGS reaction compared to the 1wt.% Pt/CeO_2 catalyst and the industrial 2wt.% Pt/CeO_2 catalyst, especially in the case of a low reaction temperature (250°C). The 94.4% of CO conversion was close to the thermodynamic equilibrium of the water-gas shift reaction at a WHSV of 14.3N l/(h g_{cat}). The 12vol.% carbon monoxide content in the outlet reformat gas was decreased to 0.6% at 250°C in a one-stage WGS reactor[4].

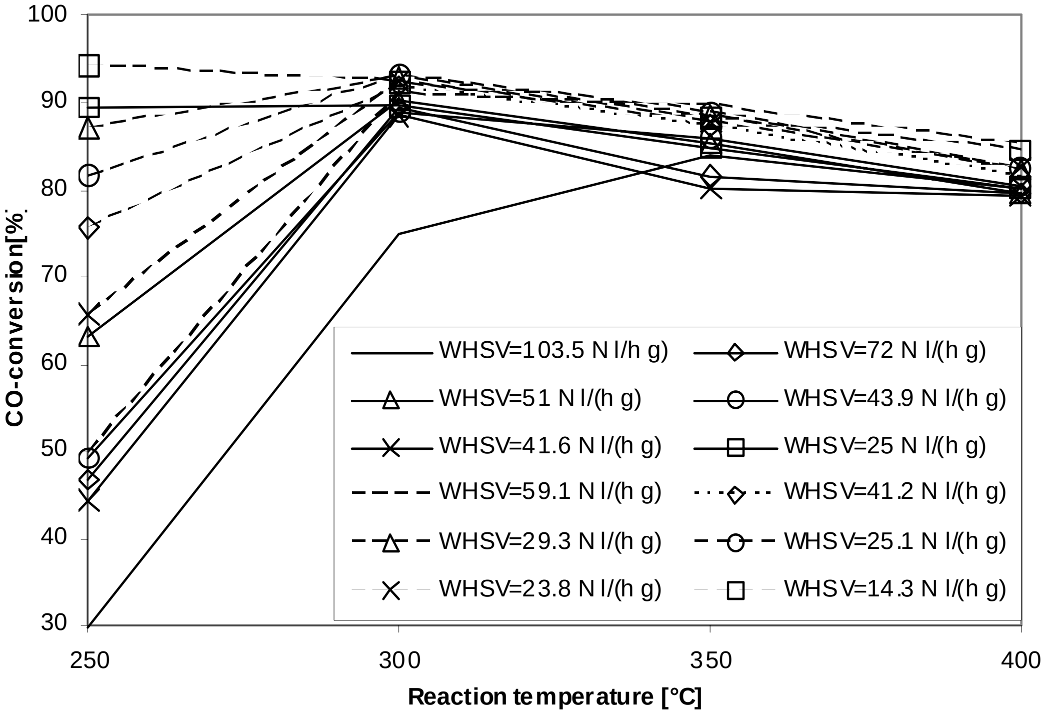


Figure 28: CO-conversion over $Pt/CeO_2/Al_2O_3$-catalyst samples; S/G = 0.72; total feed flow rate: 40mln/min (dashed line), 70mln/min (continuous line)[4].

7.5 Improved PEFC technology

The success of introducing fuel cell technologies to transportation markets is finally depending on whether the advantages of the technology – being potentially independent on fossil fuels, locally exhaust emission free and less noise creating – can exceed potential disadvantages such as high cost and less durability.

When starting FELICITAS in 2005 CUTE (Clean Urban Transportation for Europe) a comprehensive, European wide and European funded demonstration project for fuel cell buses and hydrogen infrastructure delivered initial results. For NuCellSys being on a rapid path to commercialization of fuel cell technology several result of the CUTE project became high priority to be immediately addressed.

First, fuel cell drive trains in inner city operation cycles need to be combined with an electrical storage system to increase efficiency and to reduce weight and complexity of the fuel cell system.

Second, reliability and durability of the Fuel Cell Systems need to be increased and service ability simplified to satisfy customer needs.

[4] Pawlak, M., Hacker, V., Siebenhofer, M.: Hydrogen purification using microstructures Part II: Catalytic performance of nm-Pt-catalyst for water gas shift on microstructured plates in: Chemical Engineering Communications – submitted

Third, integration into heavy-duty applications should not be dedicated to the application but as a building kit to cover a wide range of applications with similar systems.

Fourth, cost for the development, the manufacturing and the service of the fuel cell systems need to be reduced.

As a consequence it became clear that a development approach covering one specific application with a specific fuel cell system cannot be successful. This left two possibilities to move forward.

Either: Develop a specific Heavy-Duty Fuel Cell System to cover a wide range of different applications in the HD transportation market.

Or: Develop the HD strategy on the bases of the main development line of NuCellSys that are automotive fuel cell systems.

Having this decision in mind NuCellSys entered into FELICITAS. The project provided NuCellSys with the chance to investigate into both paths, since it provided a deep insight into several heavy-duty application requirements as well as the possibility to test automotive fuel cell systems under heavy-duty conditions and build a vehicle to show feasibility in a hybrid drive train.

The main focus of the development of the PEFC Cluster has been on the definition of the control interface between the cluster and the applications master controller as well the investigation into provisions for fuel cell operation to increase reliability and lifetime of the systems.

The results of the work performed have been filed in several reports as defined for deliverables in the project. The following results can be highlighted as being the essence of such reports.

As part of WP III.1 it has been demonstrated that the approach to use Fuel Cell Systems developed for automotive applications in a heavy-duty vehicle environment is feasible and can be performed. The PEFC Cluster investigated and developed in FELICTAS is a redundant composition of FC modules, including optimal adapted auxiliary components, to provide sufficient power in a hybrid drive train and a great flexibility in terms of operation modes and reliability of energy supply.

The PEFC Cluster concept is following a new philosophy in propulsion system developments providing the following benefits in an all-electrical drive train.

- Achieving modular and scalable power supply devices with a maximum of system flexibility that can be adapted to different application needs easily,
- Achieving a flexible and efficient power production by splitting the power demand between the FCs and operating them with an optimal power profile and at optimal working point,
- Providing high dynamic power supply and recuperation of energy by combining PEFC Systems with higher power dynamics obtainable and using appropriate fast onboard energy buffer technologies, for applications with high dynamic power profile,
- Increasing the durability of the FC component by reducing the dynamics of the power drawn from each of the FCs,
- Increasing the overall durability of the propulsion system by redundancy of the FC units, presently regarded to be the component which is most vulnerable to failures,
- Application of an energy management system optimizing the operation conditions of the components of the propulsion system to gain maximum reliability and a high efficiency factor,
- Increasing availability using principles of graceful degradation.

As part of WP III.2 it has been demonstrated that modifications in operation modes for the fuel cell system under the conditions of an all electric drive train can substantially improve the lifetime of system operation and provide the bases for using automotive systems in heavy-duty applications.

In order to minimise degradation effects of the fuel cell stack and the system components several FC system modifications have been performed to adopt the NuCellSys HY80 FC system for the operation in a heavy-duty transportation environment. These compromised

- Adjustment of the purge strategies of the system,
- Load reduction depending on coolant temperature and
- Separation filter with minor mesh width.

Additionally to these modifications considerations for the integration of the FC system into the application were developed including

- The avoidance of extensive start-up and shutdown cycling
- The use of forced cooling of the stack after shutdown
- Reduction of the fuel cell system dynamics to 21A/s
- The idle power should be kept above 9kW for each system
- The avoidance of static operation in certain load range (19 – 29kW)

Prior to implementing these modifications, simulation of a demanding drive cycle of an urban transit bus has proven that those recommendations can be considered under real life conditions.

Considering another result of FELICITAS, which is the growing awareness that both core **FC technologies PEM as well as SOFC will require an environment** in the individual application that is capable **to store energy** and can cope with some kind of load changes, it has been a main objective of FELICITAS to develop an operating strategy for the PEFC-Cluster for a specific heavy-duty profile that is able to meet the performance requirements of the application as well as avoiding operating situations of the fuel cell systems causing major stress to the components – mainly the stack.

To verify the improvements with regard to system robustness and lifetime a test has been developed to operate a PEFC system under the investigated heavy-duty operating profiles.

This lifetime test has been performed with a HY80 PEFC System in a simulated environment of a hybrid PEFC twin cluster for a bus application. The **achieved lifetime of the system of 2238 operating hours** before reaching the defined end of life criteria **indicates the potential of PEFC twin clusters in a hybrid environment for heavy-duty applications**.

The end of life criteria defined has been an internal leak rate of the PEFC stack, which caused emergency shutdowns during the start-up of the system.

The overall results of that test have been judged as being very promising in a way that operation time achieved under the test conditions have been approx. two times higher then the so far achieved operation time of the MK 902 Stack Module under operating conditions in the HY80 system.

Measurement data of tests have been used by Fraunhofer IVI and Nucellsys to build a degradation model and to develop a new signal theoretic approach to identify degradation mechanism while FC operation. The parametrical diversification of the stack behaviour using a semi-empirical model approach does allow a component-specific observation of ongoing degradation effects. The numerical solution of the methodology is based on a nonlinear parametrical regression of the fuel cell voltage and current behaviour. The consistency of measurement data and the model approach has been proven to be very good.

An important **part of WP III.3 activities** had been the testing and integration of the flywheel energy storage system provided by CCM. The flywheel would level the load and allow the PEFC cluster to operate at constant average load. Unfortunately by the end of Period 2 it became obvious that this work had to be interrupted due to an accident of the flywheel.

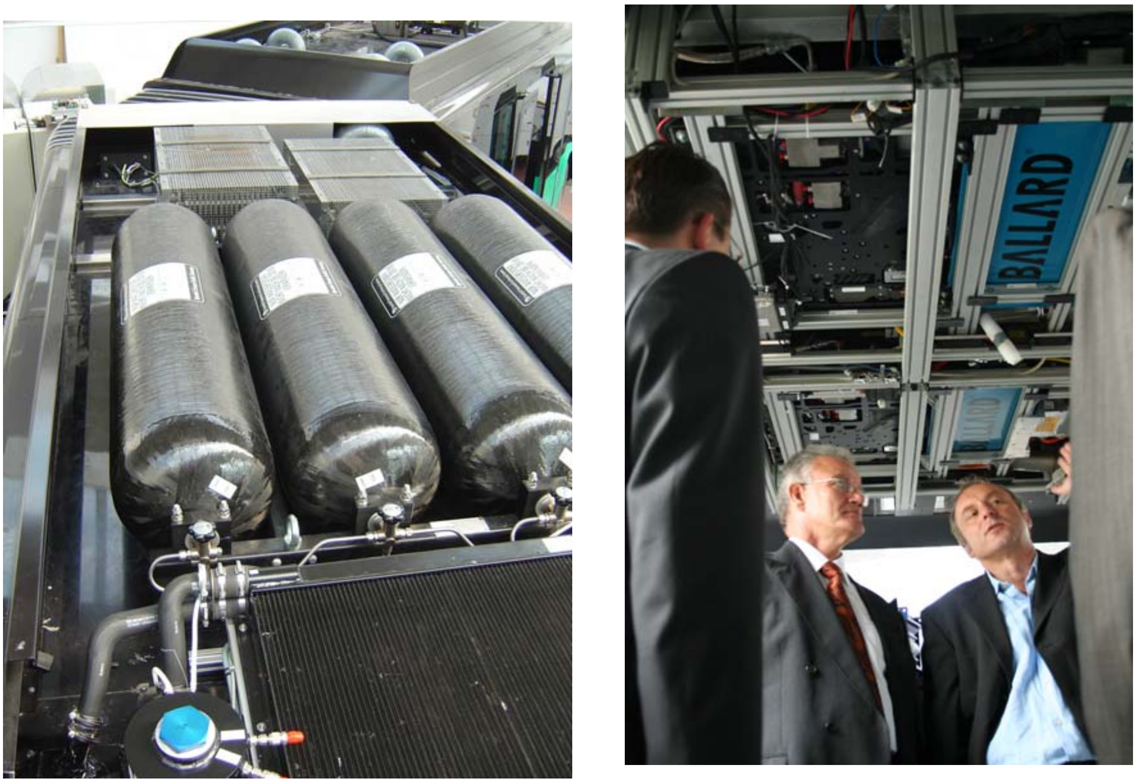


Figure 29: H_2 storages and PEFC twin cluster installed under the roof of the AutoTram

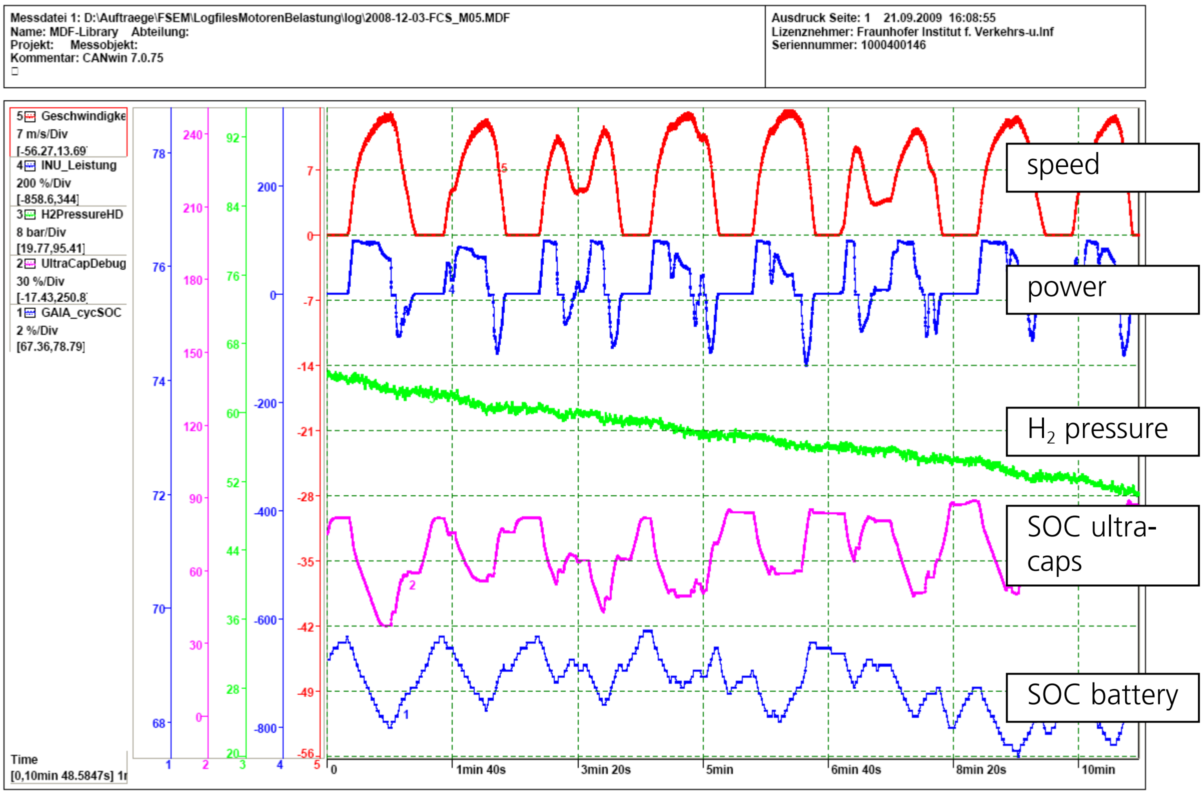


Figure 30: Test results of a PEFC twin cluster hybridised with a dual storage system in operation within the test vehicle AutoTram

This led to a decision to stop all further activities regarding the integration of the flywheel into the test vehicle and at the same time to new considerations for an electrical storage with similar performance characteristics. Following some further investigations into the subject it had been agreed on to start a new development path for an energy storage as a combination of Ultra Capacitors and Li-Ion batteries to cover both performance attributes of the flywheel, quick charge and discharge as well as energy storage.

The development of a so called dual storage turned out to be more complex then expected and could just be finalized and integrated by the end of Period 3. However, testing of the entire system in the vehicle could not be performed anymore as part of FELICITAS.

However, to complete the work done in FELICITAS the implementation (figure 29) and test phases of the running PEFC twin cluster were completed after FELICITAS. The measurement results in figure 30 show the load profiles of the different cluster components in a stop and go test cycle.

7.6 Hybridization technologies

A main issue of hybridisation was the implementation of electrical energy storages both in SOFC–GT configurations and in PEFC clusters.
Most of the descriptions of strategies, design considerations and advanced control strategies which were developed for the Flywheel Energy Storage System (FESS) in FELICITAS can also be applied for other storage configurations using batteries or/and super-caps for instance.

CCM provided an Energy Management Unit for a hybrid transmission system based on the EMAVER Flywheel Energy Storage System (FESS) that is used to smoothen the power demand placed on the Primary Energy Source (PES), for instance the SOFC or PEFC system, Diesel genset or conventional overhead line.

The two most important aspects for energy management were:

- Power smoothing - smoothen the dynamic power demands placed on the PES, both in amplitude and rate. For instance the “power step” that is demanded from a PES is often leading to over-dimensioning and also leads to an unfavourable operation with respect to efficiency and emissions.
- Energy saving - recuperate as much “braking” energy as possible.

If the load cycle is known and a precise model of the complete drive system and auxiliaries is available, including various losses, an energy management system can be based on the law of conservation of energy. The energy in all relevant system parts is computed, added, and the sum compared to a desired level. Any deviation from the desired level is used to adjust the mean power for charging/discharging the FESS, thereby keeping the maximum and minimum of the FESS charge in bounds.

It could be demonstrated in FELICITAS that the use of a hybrid transmission can have the following advantages:

- The net fuel consumption of the PES with FESS can be lower than for a configuration without FESS. For vehicular applications saving potentials ranging from 20 to 40% are possible. Demonstrated by test runs and numerous real time measurements were **20% savings in road vehicles** and **up to 40% for rail based vehicles**.
- The wear and tear of the PES should become lower, leading to lower maintenance cost.
- Possibly operation of the PES with lower installed power is possible, leading to lower investment costs.
- The fuel is consumed in a best point operation mode of the PES so that emissions are cleaner for the environment.

These points together were the economical and environmental motivators for using the hybrid transmission. Which of the above aspects is most important depends on the application and the concerned investments and operational costs (fuel, maintenance) but also on environmental demands (pollution).
The energy management strategy for the FESS was optimised according to the above mentioned aspects. Therefore, a high sophisticated Predictive Energy Management Strategy was developed by **Fraunhofer IVI**. This Predictive EM Strategy increases the capability to

- Meet **lifetime-relevant operational constraints** for the FCS,
- **Minimize the fuel consumption** and
- Provide the required propulsion power with **smaller drive system components.**

The **controller uses positioning information via GPS, electronic maps, statistical measurement data** about load profiles (see figure 31). By means of a fast optimization procedure the operation of all components of the hybrid FC based power train could be coordinated in an optimal manner.

Figure 31: Test of the GPS (DGPS) based energy management strategy on the test side

Imperial College London dealt with processing of Thermal Energy and Hybridisation Studies in **Work Package IV.1**. Within this WP an assessment of the requirements to maintain an optimum thermal balance in the operation of a hybrid fuel cell and gas turbine system for rail, truck and future marine applications has been made. A driving aim is the enhanced use of energy in relation to the complete vehicle operation, leading to improvements of thermal efficiency as well as ensuring stable thermal operation in consideration of relevant duty cycles.

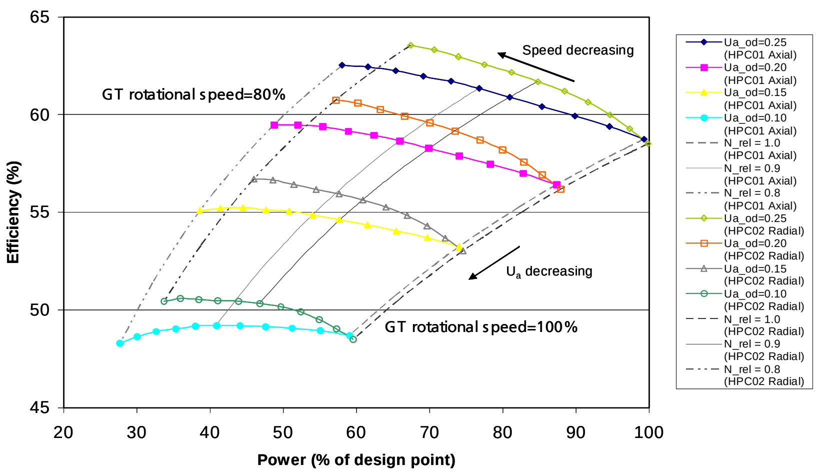


Figure 32: Influence of compressor choice on the performance of the Hybrid SOFC-GT system

The performance of a recuperated hybrid power generation schemes, coupling a solid oxide fuel cell with a gas turbine has been conducted over a wide range of operating conditions. The net efficiencies (based on Lower Heating Value of methane) of the system is 60% at a pressure ratio as low as 4 for the recuperated cycle. The off-design performance of the recuperated system was also calculated, for part-load operation. At part-load, constant mass flow rate and constant air utilisation factor operating methods are proposed to run the system. Scenarios of ambient condition changes were considered as well. The fuel cell allows a very efficient operation at part-load, with efficiencies staying at levels higher than 60% during moderate part-load operation. Results show that the hybrid system can operate from 27% to 100% of design point full load. The choice of compressor has a limited effect on the overall efficiency and operating power range (see figure 32).

A 3D Computational Fluid Dynamics (CFD) simulation model of a planar SOFC was built in order to integrate it in a vehicle simulation. The transient behaviour during start-up, restart, step change and shutdown conditions are determined. The 3D CFD geometry model of the SOFC models the physical properties of different components of the fuel cell, consists of electrochemical models that simulates of hydrogen and oxygen reactions. Convention and conduction are also simulated. Figure 33 shows the temperature against time profile for a fuel cell start-up condition, the slow nature of the fuel cell is demonstrated. The detail temperature distributions are also reported in the figure at four different times.

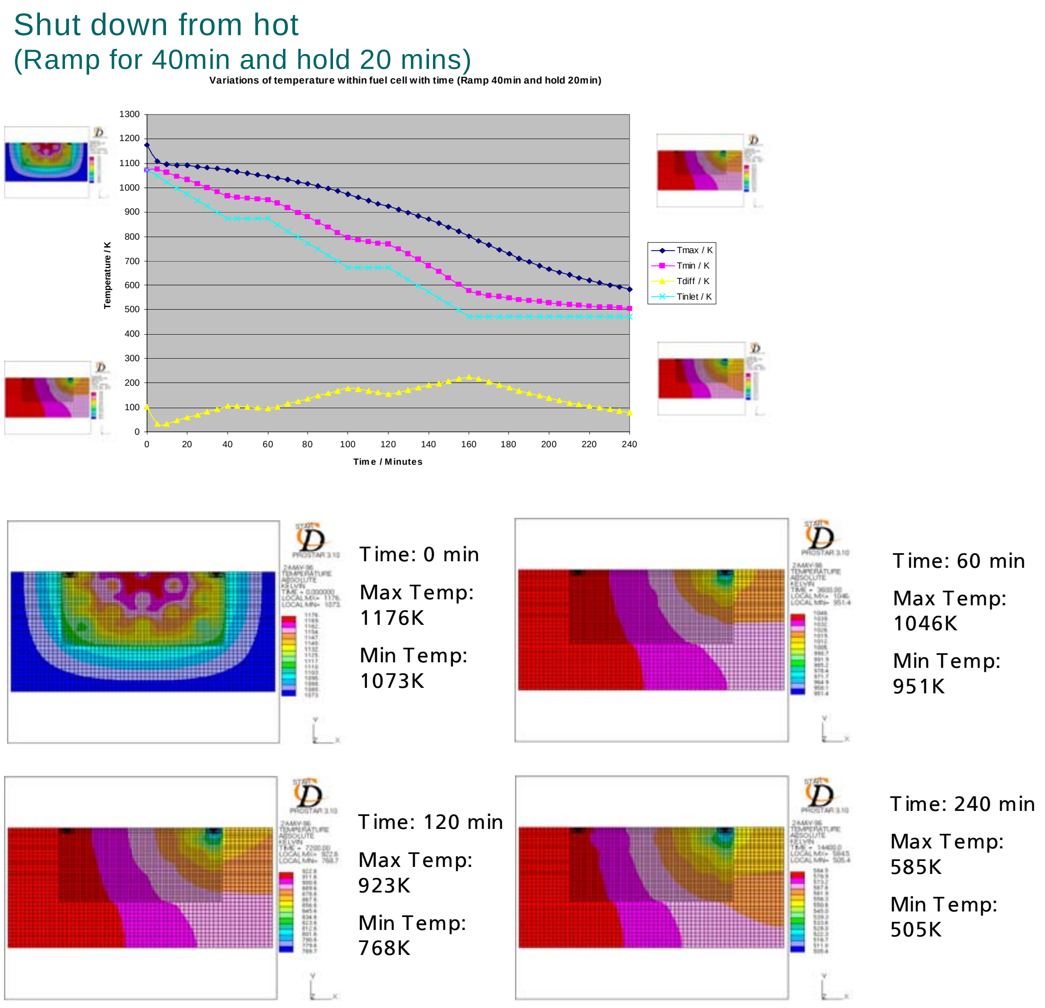


Figure 33: Fuel cell CFD temperature distribution with time for the shutdown procedure

Imperial College London has collaborated actively with **Lürssen Werft** in the simulation of various SOFC-GT system configurations for thermal management in a typical 50m long yacht. For a 1MW system, it is assumed that 250kW of electric power is provided by the SOFC-GT system, with the rest provided by existing Diesel engines. Two real ships operating power and HVAC units information are given by Lürssen. The work aims at investigating the feasibility of combining a SOFC-GT system and an Absorption Heat Pump (AHP) in a Trigeneration system to drive the HVAC and electrical base-load systems. A thermodynamic model is used to simulate the system, with various configurations and cooling loads. Measurements of actual yacht performance data forms the basis of this system simulation. Furthermore, an optimised Trigeneration system configuration study is presented (figure 34).

It is found that relative to the electrical power available for a SOFC-GT-Conventional HVAC system base load (50.5kW), the electric power increases by 156% for using double effect Saito absorption cooler; overall efficiency of 12.1% for base case, 34.9% for BROAD single effect absorption chiller, 43.2% for double effect absorption chiller. The overall efficiency of a trigeneration system is far higher when waste heat recovery happens. Furthermore, the reduction of the number of HVAC units leads to increase in net power available and also overall system efficiency. For 7, 4, 3 HVAC units, the net electric power available for SOFC-GT-Saito double effect Absorption Chiller-HVAC system are respectively 74kW, 140kW, 161kW. The corresponding overall system efficiencies are 43.2%, 58.8% and 64.0% respectively. Hence, the SOFC-GT-Double Effect Absorption Chiller-HVAC system is found to be the optimum system configuration for the ship application.

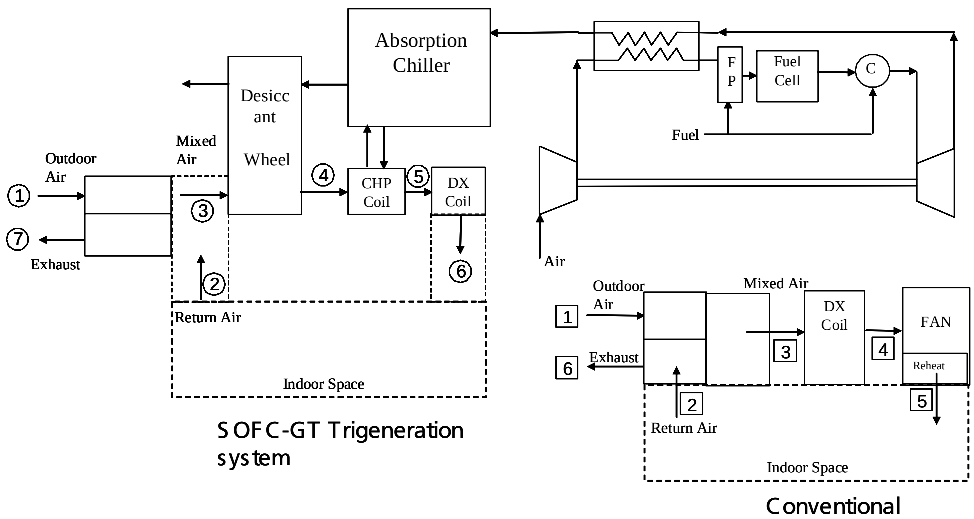


Figure 34: SOFC-GT-Trigeneration System studied compared to the conventional configuration

7.7 Visionary approach – coupling PEFC and SOFC

This part of FELICITAS comprises the theory and design of a **coupled SOFC-PEFC system** mainly. Unlike previous publications, which concentrated on stationary application this work examines the system **for an application as a heavy-duty propulsion** system. For such a purpose the requirements are different.

Generally mobile systems must work autarkic regarding process water and thermal management. This affects the fuel choice where diesel has been chosen instead of methane because of its higher energy density. For a practicable and efficient reforming process ATR has been selected.

A process chart (see figure 36) has been elaborated and was the basis for further work on the system.
A test bench has been built and testing in stationary conditions has been performed achieving a conversion of hydrocarbons up to 80% (see figure 35).

Concerning the gas cleaning, a micro reactor test rig has been built with a 6 line gas mixing station and a gas analyser. Different catalysts slurries have been prepared from commercial powders. They have been deposited onto micro-structured channels. The quality of the adhesion properties has been analysed by SEM.

Tests were performed to determine the performances of the coated catalyst layer in micro channel, i.e. CO conversion over temperature with different steam/carbon ratios and residence times. **At low temperature (250°C) CO conversion up to 90% has been achieved** which is nearly the thermodynamic equilibrium conversion.
The experimental characterization of two different technologies of SOFC stacks fed with hydrogen has been achieved in stationary conditions and constant current but also for load current steps. Limitations in SOFC operations in terms of pressure drop, gas flow, temperature range and load rate have been determined.

Focus had been made on the key components of coupled SOFC – PEFC systems, which are

- The diesel reformer,
- The fuel cells and
- The gas cleaning device.

Experimental results were reached in several steps.

Concerning the **development and the testing of a reformer**, the prototype of an auto-thermal Diesel reformer has been designed and built-up. Exceptional steady-state results have been obtained with an **efficiency of 85%** and a THC (total hydrocarbon) in the product gas of 0.1%. Various species of higher hydrocarbons found in the ATR product gas have been identified. The most important for SOFC degradation is benzene.

Then, **strategies to reduce benzene and all other higher hydrocarbons** have been elaborated. The auto-thermal Diesel reformer is compatible with BTL fuels and shows very good results (efficiency > 85%). A CPOX diesel reformer has been designed, constructed and built-up. A 2nd generation auto-thermal diesel reformer has been designed, constructed and built-up but it has not been possible to test it in the available time.

Concerning the **development and the testing of a micro-reactor for the purification** of the anodic downstream of the PEFC, an investigation of the properties of the catalyst slurry has been performed. Zeta-potential measurements have been carried out to describe the stability of the dispersion. The influence of different binder-types and binder content on agglomerate size in the catalyst slurry have been studied and the influence of surfactants on the agglomerate size as well. Catalyst slurries with appropriate parameters have been coated on micro-structured stainless steel plates and characterized with scanning-electron-microscopy. Adhesion tests, thermal shock and shear forces in an ultrasonic bath have been done and they have demonstrated strong influences of the layer thickness.

Concerning the **testing of SOFC**, a test bench has been designed and built-up to test stacks with a power of up to up to 1kW. Five stacks have been tested: two in a first design and the following three with a different design. They have been supplied by a Swiss company HTCeramix. A first structure of the test bench has been built-up for the first design (R-design). Then it has been modified for the testing of the second design (S-design). These four first stacks (2 for the R-design and 2 for the S-design) have been fully characterized by polarization curve measurements, impedance spectra collect and voltage response to current step, when supplied by pure hydrogen. The test bench has been modified a second time in order to feed the stack with a mixture of gas similar to the one at the outlet of the AVL reformer. The same tools have been used to characterize the stack.

The performances obtained with the reformate gas are much lower than the one with pure hydrogen. The maximum power has been divided by two. Furthermore, the operation of the stack is more difficult to stabilize.

A **PEFC stack has also been tested** with hydrogen. A test bench has been built up on the basis of a system supplied by NuCellSys in order to use test it with reformate gas but it has not been possible to perform the tests before the end of the project.

Each component of the system has been modelled with a 1D approach relevant for the system computation: the four key components (reformer, gas cleaning device, SOFC and PEFC stack) and auxiliaries as well (pumps, heater, etc.). The experimental results have been used to tune the parameters and to validate the models of the key components. Simulations of the global system have been carried out by implementing and coupling the component models. This enabled the evaluation of their efficiency and their power density.

An important gain on the efficiency has been computed

- **47% of the coupled system** compared to the
- **31% of the reformer-SOFC stand alone system**

but is not decisive enough due to the complexity of the gas shifting device and the water management.

The expected power density is not in favour of the coupling but the smaller required diesel tank could balance this drawback when long-range applications are concerned.

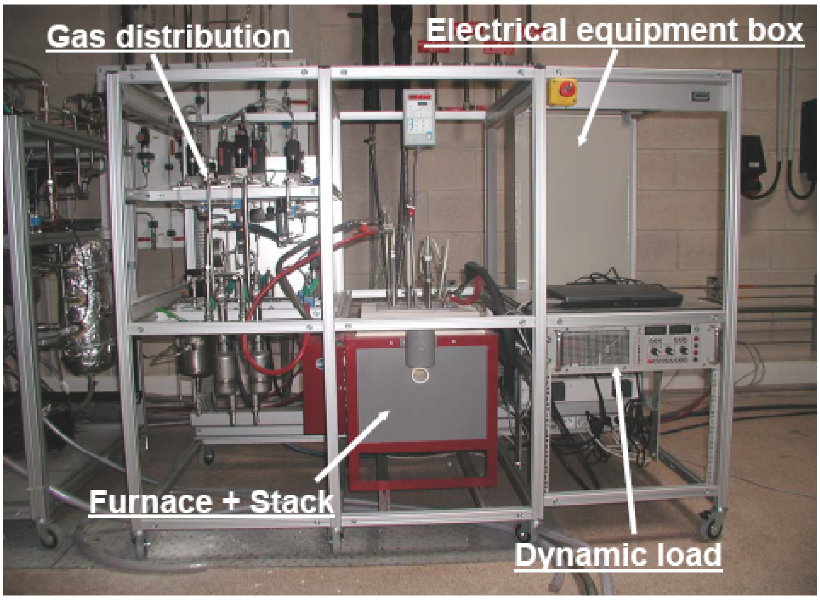


Figure 35: Test bench for SOFC – PEFC coupling at the University of Belfort-Montbeliard

To design the test rig (figure 35) detailed models of the PEFC and the SOFC at system level that accurately describe the tested fuel cells at UTBM laboratory and the auxiliary devices had to be developed and tested. Tests and simulations were performed with the developed simulation tool to evaluate the coupled system with regard to the initially defined objectives of the FELICITAS project.

The simulation of the shift reactors, which was started already in the second project year, has been completed and validation with the test results of **CDL laboratory** showing good correspondence. Extensive work has been dedicated to model the auxiliary devices in such systems. A Simulink toolbox has been developed that included important devices of FC systems e.g. heaters, controllers, pumps, etc. which can be reused for future analysis of fuel cell systems.

The result obtained from simulation did not fulfil the expectations in terms of an electrical efficiency above 50%. The reason for that principally lies in the chosen diesel fuel, which is difficult to reform with a high efficiency. Practically **diesel can be reformed** by application of ATR or CPOX as **demonstrated by AVL within FELICITAS**. However these techniques do not reuse the SOFC heat for reforming whereof the **system efficiency applying ATR is only about 41%** for the total system. The effect of the SOFC recycle loop has been studied and showed a positive effect on the reformer operation. It was shown in simulation and in the paper that the total efficiency rises considerably if endothermic reactions are applied.

Depending on the amount of **recycled SOFC heat** the **efficiency goes up to 47%**. However, it was shown that a coupling boosts the efficiency compared to reformer – SOFC alone systems. That combination applying diesel achieves only 32%, which is significantly below a serial coupled system. That effect is mainly due to the off gas shifting of CO and the serial coupling of the PEFC. In contradiction to earlier computations it was revealed that enough water for the system can be extracted from the PEFC condensers and can be fed to a steam generator for SR. Practically the problem of heat injection into the reformer requires a new design that has been considered in the paper as well.

Another problem with those systems has been identified. It concerns the complex humidification of LT-PEFC. Due to load variations the temperature and thereof the relative humidity of the fuel gas flow coming from the gas cleaning stage is very unstable. To achieve long life and good PEFC efficiency a contact saturator must be implemented. More promising here again is the HT-PEFC technique that strongly simplifies such a system. For instance the complete water management cycle can be neglected if steam for ATR is recycled. Therefore the **HT-PEFC technique should be studied in future projects**.

Based on current state of the art components a **power density** of the total hybrid system including a fuel storage tank of **10W/l** has been computed. It was shown that the larger size of the aggregate can be compensated by the improved efficiency.

Compared to a diesel aggregate the better efficiency requires a smaller tank. Therefore the power density of a coupled system becomes competitive especially when long-range applications are concerned.

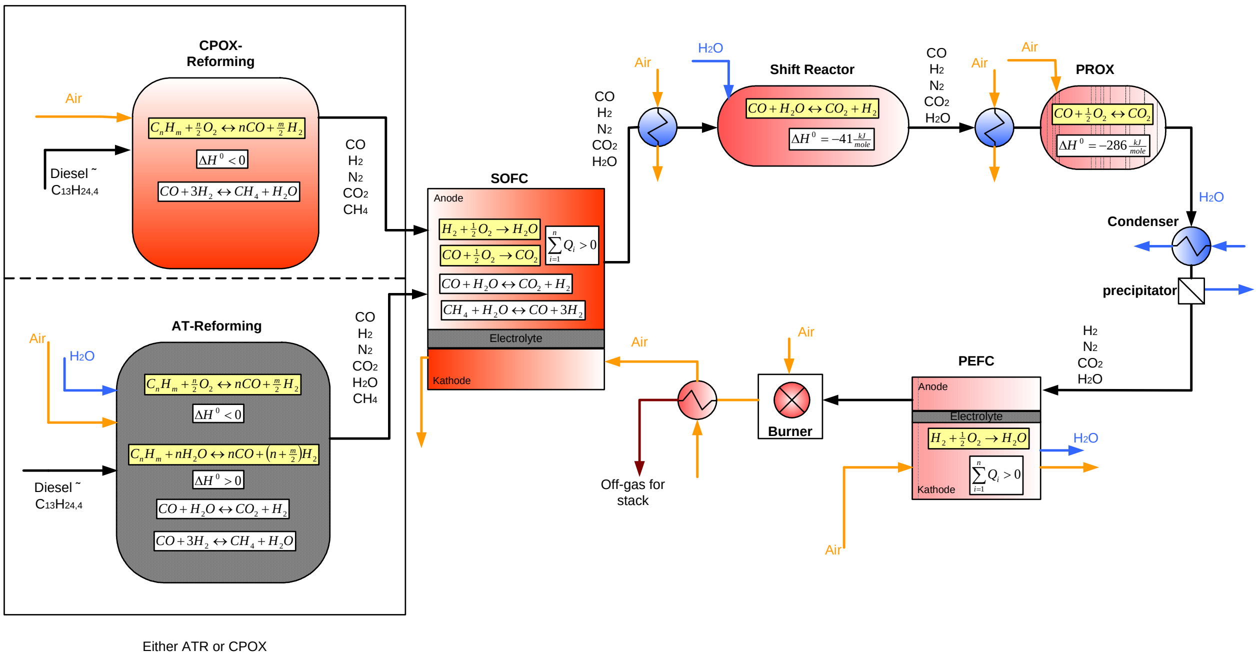


Figure 36: Preliminary flow chart of SOFC – PEFC system

8 Meeting the objectives

The **main objective** defined for FELICITAS was the development of fuel cell drive trains capable of meeting the demands of heavy-duty transport for road, rail and marine applications.

In summary:

- The hybrid PEFC clusters are well suited to public transport applications such as buses, light rail or trams in city/town operations;
- The Rolls-Royce hybrid SOFC design will require substantive modification before it can be successfully used in a marine environment;
- Neither hybrid SOFC nor PEFC clusters technologies developed within FELICITAS meet the requirements defined for FC systems in heavy rail or tram applications;
- Neither hybrid SOFC nor PEFC clusters technologies developed within FELICITAS meet the requirements defined for a FC based main propulsion of heavy-duty trucks;
- Low power SOFC technology in combination with new reformer techniques developed in FELICITAS is well placed for highly efficient APUs in heavy trucks.

The FELICITAS Project achieved the following outcomes:

- A much improved and detailed understanding of the impact of the marine environment, operation and application on a Rolls-Royce SOFC technology, notably a yacht, was achieved;
- Testing of Rolls-Royce SOFC materials and components in marine relevant conditions was successfully undertaken, and the results have substantially increased the appreciation of the marinization challenges for fuel cells;
- Testing of cathode materials and other materials was achieved and results fed back into the knowledge base;
- The Rolls-Royce stack concept and system showed a high mechanical integrity in marine motion conditions;
- A high system efficiency (> 60%) of hybrid SOFC configurations were verified by detailed simulations and partly by experiments;
- High advanced reformer technologies especially for Diesel and LPG were developed and tested;
- By means of the **hybrid PEFC cluster** concepts developed in FELICITAS, powerful units of more then 200kW electrical output are feasible;
- The functionality and the advantages of hybrid PEFC clusters were demonstrated in first test runs of the Fraunhofer AutoTram test vehicle;
- A remarkable increase (doubling) of lifetime could be reached for single PEFC systems in hybrid configurations;
- By means of partial redundant PEFC cluster configurations a system durability of more than 10 000 hours operation time seems to be feasible;
- Degradation processes which influence the durability of PEFC systems can be observed in operation using the in-situ diagnostic modules developed in FELICITAS;
- An improved reliability of PEFC systems was also achieved by means of a high advanced predictive energy management system which avoids operation modes with increased degradation potential;

- To raise the reliability of hybrid SOFC systems a hybridisation concept using high power energy storages was developed;
- A high system efficiency (> 60%) can be reached for PEFC systems by means of kinetic energy recuperation only. This however, limits the Heavy-Duty applications on buses or trams in city/town operation.

Some objectives of FELICITAS were **not achieved**, primarily:

- The reforming of marine Diesel with high sulphur contamination;
- Modification of a RR SOFC System for the marine environment and testing under marine conditions, and
- Extensive tests of the prototypic PEFC cluster implemented into the AutoTram under real conditions.

The FELICITAS Project has identified a number of challenges facing the Rolls-Royce SOFC system in the marine environment, the principal electro-chemical issues being potential or actual contamination by sodium chloride and chromium together with possible fuel contaminants where clean fuels are not used. Such challenges require further investigation and probable re-design of the system prior to demonstrating in a marine environment. As such the initial approach of a minimal redesign and modification of the RR SOFC System for stationary power was not feasible, and could not be undertaken within the resources or timeframe of the FELICITAS project.

9 Conclusions and recommendations

The development of high power FC systems which meet the demands of water, land or rail based heavy-duty transport was and is a very challenging task. The power ranges, fuels used, lifecycles, longevity and other operational issues all contribute to the challenge. Nevertheless the FELICITAS project provides clear direction for the structure of future research activities in this field.

Based on the requirements investigated in FELICITAS, the FC development undertaken and the current general development status of FC power train technology, the following conclusions can be drawn for **PEFC applications**.

For **standard buses** (12m) with a peak power demand of 160 – 260kW, the utilisation of a hybrid drive train including an energy storage system with an intelligent energy management is a potential solution.

Standard buses require approximately 33 / 55kg of hydrogen for a hybrid / non-hybrid design to cover a distance of 250km. The hybrid drive train developed in FELICITAS reduces vehicle energy consumption up to 20% with benefits to the weight and volume of hydrogen storages and the installed FC power on 120kW.

As **trams** are powered by electrical energy supplied by catenary through a pantograph, the main power train devices cannot be replaced in a FC powered mode. FCs can only augment the existing electrical power train. Depending on vehicle mass and operation conditions, an installed power of 190 – 400kW is necessary for propulsion. However, low floor requirements in modern tram constructions signify that the installation space for such high power FC system including the tank system for 75 / 95kg hydrogen is a challenge. Therefore hybrid FC clusters for tram applications are currently not feasible.

Lastly, trolley buses combine a tram traction system with the vehicle characteristics of a diesel bus. In this sense, the above stated conclusions apply, as well. Hybrid FC clusters developed in FELICITAS are well suitable to be implemented in catenary free trolley busses.

The survey of possible fuel cell types for serial electric hybrid drive trains has shown that the use of comparatively bulky SOFC is out of the question due to the space and weight restrictions on vehicles of urban transport applications.

Heavy-duty trucks are a very challenging application field for fuel cells and this element of the transport industry is very cost conscious. From today's point of view, the production costs of hybrid FC power trains are not competitive with incumbent technologies. Significant reductions in life cycle costs must be targeted to appeal to customers.

Furthermore market implementation is difficult because large heavy-duty truck engines have high efficiencies (25 – 30% drive cycle efficiency). Therefore the overall drive cycle efficiencies for conventional combustion engines and FC propulsion are very similar.

Due to the high fuel consumptions and very long driving intervals of trucks, a fuel with high energy storage density is required. From today's point of view, diesel will be this fuel in a mid term range.

The **reformation of diesel** has a negative impact on system efficiency. Within FELICITAS the field of research was restricted to a highway and a mountain drive-cycle with one truck, where efficiency gains of 60% with the FC power train were achievable.

Hydrogen as fuel for trucks, ships or heavy rail applications seems to be unrealistic because of low energy storage density, the lack of infrastructure and the – in the near future – uncompetitive price.

For FC systems in hybrid drive train configurations the knowledge about the relationship between load profile and degradation is important. This information is necessary for the design of lifetime optimised power strategies. In FELICITAS, a methodology was developed to reliably and quickly identify the degradation status of a FC stack in-situ from system related data. The advantage of the methodology is the independence on elaborate and complex measurements of internal electrochemical and material parameters.

The possibility to develop **hybrid SOFC-GT systems** with consistently **high efficiency (~60%)** was proven using optimised components and energy storage. The use of an appropriate GT system can add flexibility to the system and ensure surge-free operation in a wide range of conditions. In FELICITAS a variable geometry turbine was examined.

The hybridisation of FCs (PEFC as well as SOFC) by a flywheel or another energy storage system with a high power density enables the application of fuel cells in high dynamically loaded power systems in vehicular as well as marine applications. The flywheel can fully level the load and allows for a much smaller sized FC, operating at constant average load.

The FELICITAS Project has substantially advanced the state-of-the-art in understanding the issues facing the marinization of Solid Oxide Fuel Cells units. The team comprising Rolls-Royce, Lürssen, Eindhoven University, Genoa University and Hamburg University has improved the knowledge of how the Rolls-Royce Fuel Cell Systems (RRFCS) **Solid Oxide Fuel Cell (SOFC) system** would perform under marine operating conditions and identified the principle challenges for a marine application. The results of this work are summarized in Chapter 7.3 and 7.4.

The principle challenges by subject area are:

- The <u>electrochemical performance</u> of the RRFCS cathode material was investigated in cases where the test environment was contaminated with either sodium chloride or chromium species, in anticipation of typical operating environments. The results show that the electro-chemical performance is adversely affected.

  Chromium is a known ‘poison’ for the type of cathode used within the RRFCS design and is the subject of several literature references. Recommendations for further investigations fall into three categories:

  - The development of state-of-the-art cathode materials which are more tolerant to the existence of Cr species without compromising the functionality or stability of the cathode component,
  - The development of durable and low cost coating technology to minimise the loss of Cr from the metallic system components close to the fuel cell stack, and
  - The development of a modified advanced system cycle to allow for dehumidification of the cathode environment prior to the cathode flow reaching the stack.

  In relation to sodium chloride contamination and cathode related degradation mechanisms, no literature references were discovered during the length of the project. It is advisable that filtering technologies are investigated in order to ‘strip out’ salt residues from the humidified air before reaching the fuel cell stack.

- The <u>impact on system materials</u> of a marine environment was investigated, and this, as expected, demonstrated that degradation of materials is likely to be exacerbated. Such degradation will release metal species into the flows within the fuel cell system, impacting the cell and stack performance.

  To reduce the rate of system material corrosion and hence reduce the amount of chromium released into the system environment a revision to the alloys selected for component manufacture and, as noted above, the increased use of coating should be investigated. Special attention would need to be paid to components made from thin materials as nano scale coatings may be required in order to maintain flexibility whilst improving corrosion resistance, furthermore the composition of the coating would need to be investigated to ensure satisfactory stability and durability in environments with higher humidity.

- Investigations of mechanical integrity and of effects of integration of the RRFCS stack into a vessel showed that the ceramic stack is robust and when combined with appropriate mounting technology would be suitable for use in a marine environment.

  With specific reference to vibration and shocks anti-vibration mounting technology is readily available from a number of sources, and it is commonly used in the transportation of sensitive equipment such as satellites and medical scanning equipment. The mountings necessary to isolate the stack from external vibration can be obtained from standard suppliers without the need for development work, albeit integration of the design will be necessary for this specific application.

- The investigation of marine fuels and processing suitable for the SOFC unit highlighted the paradox between using fuels similar to natural gas e.g. LNG and LPG which are generally not easily available for marine use and the relative simplicity of processing, and common marine fuels e.g. diesel, which provide a much greater challenge.

  Given the sensitivity of all fuel cells to contaminants, it is critical that the chosen fuel processing technology is effective, but it also needs to reflect the space constraints on a vessel, the need or otherwise for water, safety on board a vessel and, if possible simplicity.

  The fuel processing technology for fuel cell applications is still very much at the development stage. None of the current methods have been identified as suitable to convert marine diesel to SOFC-compatible fuel; however processing catalyst performance has been observed for LPG reforming. Currently the main problem with diesel fuel is the high sulphur content, with a number of the compounds being extremely difficult to reduce to the level required or long-term SOFC operation.

In assessing current technologies the project identified considerable further work in the areas of:

- Desulphurisation and gas purification,
- Catalyst activities and durability
- Carbon formation
- Fuel conversion and reformer efficiency
- Optimal fuel/air/steam mixing ratios avoiding carbon formation.

The investigations have shown that the fuel/air mixing ratio required to avoid carbon formation when using LPG or diesel is not compatible with components used by the RRFCS system and conversion to run on marine fuels will require significant changes.

In assessing the impact of the marine environment and the demands of marine electrical loads on the RRFCS system it was noted that the **system operation** would be best at constant load and that excess requirements are met from alternative sources e.g. micro-turbines or storage. The start-up of an SOFC unit from cold is a long process and thus unlike a diesel engine the SOFC unit would need to operate constantly to be able to provide power. However, there are several issues arising from marine duties:

- In operating on marine fuels with lower LHV the system would need to be revised to operate at the most efficient state;
- The control systems would require modification to be able to interface with a vessel’s electrical system especially when coupled with alternative power sources for load following.

The **integration study** was based on an existing yacht design, which was slightly modified for the integration of the SOFC. However, the 3D virtual integration study revealed several issues that couldn’t be seen during the concept phase. These issues are mostly related to the additional pipes and ducts that are necessary for fuel supply and ventilation that conflict with the position and construction of the bulkheads. Consequently a new yacht design based on final schematic drawings for a Fuel Cell system and necessary infrastructure will be required for a successful technical solution.

In addition attention also needs to be paid to the fuel-bunkering concept. The bunkering process is one of the most safety critical aspect of vessel operation.

Finally a standardised fuel cell module has to be developed that allows the integration in many different vessels in order to allow mass production and price competitiveness.

10 Contact and further information

10.1 FELICITAS partners

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National Technical University of Athens / Laboratory of Thermal Turbomachines
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French National Institute for Transport and Safety Research / Laboratory of New Technology
Arcueil, France

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Technische Universiteit Eindhoven / Department of Chemical Engineering and Chemistry
Eindhoven, Netherlands

Università di Genova / Dipartimento di Macchine Sistemi Energetici e Trasporti
Genoa, Italy

Czech Railways - Railway Research Institute
Prague, Czech Republic

Table 7: FELICITAS consortium

10.2 Meetings

Date	place / responsibility	topic
09/05/05	Brussels / Coordinator	kick-off-meeting
18/05/05	Dresden / FhG IVI	SP IV meeting power management system simulation
10-11/10/05	Bremen / Lürssen	SP II meeting marine application
12-14/10/05	Dresden / FhG IVI	FELICITAS meeting, special topic: PEFC clustering
17-18/11/05	Bremen / Lürssen	SP I meeting requirements and system simulation
21-23/11/05	Kirchheim / NUCELLSYS	SP III WP IV.2 meeting
02/12/05	Rolls-Royce	SP II meeting fuel processing
07/02/06	Graz / AVL	WP IV.3 meeting
04/06	Derby / Rolls-Royce	FELICITAS meeting, special topic: marine SOFC
10/06	Bremen / FLW	FELICITAS Meeting, special topic: results of subproject I
05/06	Belfort / UTBM	SPIV meeting, components for SOFC – PEFC coupling
09/06	Brussels / Coordinator	project officer, status amendment
03/07	Athens / NTUA	FELICITAS Meeting, special topic: fuel processing, processing of thermal energy
01/08	Brussels / Coordinator	FELICITAS Meeting,
03/08	Brussels / All	FELICITAS Review Meeting Period 2

Table 8: FELICITAS meetings

10.3 Deliverables

Del. no.	Deliverable name	Leader
I.1.1.1	Requirement specification of the FC cluster for bus application	FhG
I.1.1.2	Generic requirement specification of FC clusters typically for tram implementation	FhG
I.1.2.1	General requirements on FC power trains typically for truck implementation	AVL
I.1.2.2	Generic requirement specification of FC clusters typically for heavy rail implementation	VUZ
I.1.3.1	Requirement specification of marine SOFC application	FLW
I.1.3.2	Feasibility study to marine diesel reforming	HAW
I.2.1.1	Survey of available modelling and simulation tools, FELICITAS - simulation concept	FhG
I.2.2.1	Drive cycle simulation tool for FC application in trucks	AVL
I.2.2.4	Simulation tool of marine SOFC applications	R-R
I.2.3.4	Simulation tool for SOFC – PEFC	UTBM
II.1.1.1	Literature review	R-R
II.1.1.2	Report on fuel composition requirements	R-R
II.1.1.3	Report identifying main elements of generators modules which may require change	R-R
III.1.1.1	Study to structural PEFC cluster design and specification to the PEFC basic module	NCS
III.1.4.1	Safety concept for a twin / double twin PEFC cluster	NuCellSys
IV.1.1.1	Simulation of the SOFC-GT for part-load and off-design	ICL
IV.1.4.1	Preliminary Design of Rotating Components for an optimised hybrid SOFC-GT System	NTUA

Table 9: Deliverables of 1st Reporting

Del. No	Deliverable name	Leader
I.1.1.3	Study to safety relevant issues for FC in urban transport	INRETS
I.1.3.3	Requirement specification of the marine SOFC - APU	R-R
I.2.2.3	Simulation tool of fuel processing	HAW
I.2.2.5	Model of FC based heavy rail applications	VUZ
I.2.3.1	Drive cycle simulation tool of hybrid fuel cell clusters	FhG
I.2.3.2	Sim tool for energy storages, power electronics, control and energy Management in hybrid FC clusters	CCM
II.1.1.4	Risk review	R-R
II.1.1.6	Material test results	R-R
II.1.2.1	New anodic recirculation configuration for marine conditions	UNIGE
II.1.2.2	Report on influence of ambient conditions	UNIGE
II.1.2.3	Recommendations on generator module design for demonstrator programme	UNIGE
II.1.2.4	Hybrid system behaviour under marine conditions	UNIGE
II.1.2.5	Anodic recirculation transient results	UNIGE
II.1.2.6	Cathodic recirculation test rig	UNIGE
II.1.2.7	Marine HS transient model and start-up results	UNIGE
II.3.1.1	Report on fuel options and fuel processing technologies	R-R
II.3.2.1	Initial report on reforming catalyst performance programme	TUE
II.3.2.2	Initial report on contaminant removal technology plans	TUE
II.4.1.2	Load assessment	FLW
II.4.2.1	Fuel cell power systems interface model	R-R

Del. No	Deliverable name	Leader
III.1.2.1	Auxiliary concept for a twin / double twin PEFC cluster	NCS
III.1.3.1	Electronic concept for a twin / double twin PEFC cluster	FhG
III.1.5.1 + III.3.1.1	Prototype of PEFC cluster components and hardware integration in a test vehicle	NCS
III.1.5.2	Evaluation of direct coupling of Ultra-capacitors and PEFC system	NCS
III.2.1.1	Optimised operation modes of the PEFC Twin Cluster	NCS
III.2.2.1	Test results from the PEFC-Cluster	NCS
III.2.2.2	Data survey and analysis concerning degradation mechanisms	FhG
IV.1.2.1	Development of specific components that will be needed for a virtual vehicle platform	ICL
IV 1.4.1	Preliminary design of rotating components for an optimised hybrid SOFC-GT system	NTUA
IV.2.1.1_part1 IV.2.1.1_part2	Report to hybrid power management strategies	FhG
IV.2.2.1	Literature review of degradation mechanisms	FhG
IV.2.4.1	XCU Controller design for a twin PEFC cluster	NCS
IV.3.1.1	Report to components on SOFC-PEFC coupling and experimental tests in stationary conditions	FhG
IV.3.2.1	Results on sim tool and preliminary report to component design and SOFC-PEFC configuration	UTBM

Table 10: Deliverables of 2nd Reporting

Del. no	Deliverable name	Leader
I.2.2.2_part1 I.2.2.2_part2	Model of ship side SOFC implementation environment	FLW ICL
I.2.2.6	Conceptual design of fuel cell implementation	FLW
I.2.3.3	Review and standardisation of drive and duty cycles	ICL
II.1.1.5	Report on multi-cell module testing under marine fuel compositions	R-R
II.1.1.7	Report on cathode durability testing	R-R
II.1.1.8	Report detailing the effect of thermal expansion on multi-layer cell structure	R-R
II.1.1.9	Report assessing suitability of RRFCS stack concept to marine applications in terms of mechanical integrity	R-R
II.1.1.11	Final technical report	R-R
II.1.2.8	Marine HS enhanced design and off design model results	R-R/UGE
II.1.2.9	Marine HS enhanced transient model results	R-R/UGE
II.1.2.10	Humidified Fuel ejector anodic recirculation design	R-R/UGE
II.1.2.11	Cathodic recirculation Test Rig Results	R-R/UGE
II.3.2.3	Report on desulphurisation results	TUE
II.3.2.4	Report on reforming catalyst performance	TUE
II.3.4.1	Report on design layout specification	UGE
II.3.4.2	Report on design specification of on-board fuel processing demonstrator	UGE
II.4.1.4	Concept of electrical integration	FLW
II.4.2.2	Fuel cell power system interface model with flywheel energy	R-R
II.4.2.3	Marine SOFC high frequency dynamic model	R-R/UGE
III.2.2.2	Data survey and analysis concerning degradation mechanisms	FhG
III.3.1.1_a	Development of battery and ultra capacitor based energy storage units for the AutoTram test vehicle	FhG
III.3.2.1	Documentation of the XCU Functionality Tests	FhG
III.3.2.2	Three dimensional efficiency map of the prototypical twin cluster and experimental model evaluation	FhG

Del. no	Deliverable name	Leader
III.3.3.1	Documentation of the PEFC cluster power management	FhG
IV.1.2.2	Implementation of a thermal management strategy for the different modes of operation	ICL
IV.1.3.1	Integration of the developed models into a single computational platform under realistic drive cycle	ICL
IV.1.4.2	Design and test of the necessary gas turbine components	NTUA
IV.2.1.1 part 2	Report to hybrid power management strategies	CCM
IV.2.2.2	Degradation model, Data analysis and Cost function for durability	FhG
IV.2.3.1	Predictive operation of FCS	FhG
IV.3.3.1	Report on optimization of SOFC and PEFC coupling	UTBM

Table 11: Deliverables of 3rd Reporting

10.4 Dissemination of knowledge

10.4.1 Publications as well as conference and workshop presentations

FhG

1. Bartholomäus, R., Fischer, A.: Energy Management of fuel cell vehicles operating in fixed-route service. 3rd European Polymer Electrolyte Fuel Cell (PEFC) Forum. Lucerne July 4 – 8 2005, Proceedings
2. Bartholomäus, R.; Fischer, A.; Klingner, M.: Energy management of hybrid fuel cell vehicles using prediction of power demand. In: 5th International Conference and Trade Fair on Hydrogen and Fuel Cell Technologies. H2Expo 2005. Proceedings: Hamburg, August 31 - September 1, 2005, pp. 2-20, 2005
3. Reuber,S., Schneider, M.: Gekoppelte Systeme aus Festoxid- und Polymerelektrolyt-Brennstoffzellen – Konzeptionen für den Einsatz im Schwerlastverkehr. 13. Symposium Nutzung regenerativer Energiequellen und Wasserstofftechnik, Stralsund Nov. 2006
4. Bartholomäus, R.: Prädiktive Steuerung von Brennstoffzellen-Hybridantrieben. Kolloquium des Instituts für Automobiltechnik Dresden IAD, Fakultät Verkehrswissenschaften, Technische Universität Dresden, 11. April 2007
5. Bartholomäus, R: Modellierung und optimale Steuerung von Antriebssystemen für Brennstoffzellenfahrzeuge. Dresdner Automatisierungstechnische Kolloquien, 18. Juni, 2007
6. Bartholomäus, R., Fischer, A. and Klingner, M.: Real-time predictive control of hybrid fuel cell drive trains. Fifth IFAC Symposium on Advances in Automotive Control, August 20-22, 2007; Monterey Coast, California, USA, pp. 103 - 110, 2007
7. Klingner, M.; Schneider, M.: Hybride Brennstoffzellencluster für Bus- und Bahnanwendungen im ÖPNV. Was published at 21. Verkehrswissenschaftliche Tage, Technische Universität Dresden,September 24-25, 2007
8. Schneider, M.; Klingner, M.: FELICTAS Fuel cell power-trains and clustering in heavy-duty transport. Was published at the European Hydrogen and Fuel Cell Technology Platform (HFP) ReviewDays'07, Brussels, October 10-11, 2007
9. Jonas, K.; Schneider, M.; Lehnert, M.; Klingner, M.: FELICITAS: Anforderungen und Umsetzungskonzepte für Brennstoffzellenantriebe im Light-Rail-Sektor. Was published at the Innovationsforum Schienenfahrzeuge, Berlin, Dezember, 2007
10. Lehnert, M. ; Klausner, S. ; Bartholomaeus, R.: Energieverbrauch bei Stadtbahnsystemen - Identifizierung von Einsparpotentialen. In: Moderne Straßenbahnen 2008 : Fahrzeugtechnik, Infrastruktur, Akustik; Bahntechnik-Fachtagung; Berlin, 14. und 15. Februar 2008, pp. 15-26, 2008

11. Jonas,K., 2008, "In-situ Alterungsdiagnose und belastungsabhängige Lebensdauerprognose von PEM-Brennstoffzellensystemen", Kolloquium der Institute Energie- und Verfahrenstechnik der TU Braunschweig, 24/04/2008.
12. Jonas,K., "In-situ Alterungsdiagnose und belastungsabhängige Lebensdauerprognose von PEM-Brennstoffzellensystemen", PhD Thesis, Technische Universität Dresden, completed
13. S. Reuber, M. Schneider, J. Rechberger, M. Thaler, M.C. Péra, M. Chnani Hybrid SOFC-PEFC system : a conceptual study of a heavy propulsion system" ASME Journal of Fuel Cell Science and Technology"
14. Bartholomäus, R., Klingner, M., Lehnert, M.: Prediction of power demand for hybrid vehicles operating in fixed-route service. 17th IFAC World Congress, July 6-11, 2008, Seoul, Korea
15. Jonas, K, Online-Alterungsdiagnose von PEM-Brennstoffzellen. 1. Sächsischer Brennstoffzellentag, Chemnitz, 28 November 2008
16. Jonas, K, Online Degradation Analysis of Running PEFCs. Fundamentals & Developments of Fuel Cells (FDFC) Conference, Nancy, 10 - 12 Dec. 2008
17. Jonas, K, Klingner, M, 2008, Online Diagnostics of Running PEFCs. International Workshop on Accelerated Testing in Fuel Cells, Ulm, 6 - 7 Oct. 2008

AVL

Rechberger J.; „Fuel Cells in Marine Applications"; SalonNautico, Barcelona; 10 December 2006

CCM

Dissemination of knowledge of Flywheel Energy Storage is done via several occasions: conferences, publications and direct contacts:

1. ECPE Seminar: "Energy Storage Technologies"; 27-28 June 2007, Aachen, Germany.
2. Second International Renewable Energy Storage Conference (IRES II); 19-21 November 2007, Bonn, Germany
3. E-mailing and giving presentations to OEM 's and end users of city buses & distribution vehicles; hoisting & lifting equipment; stand alone power grids
4. Cooperating in questionnaires

CDL

1. Pawlak, M.; Thaler, M.; Besenhard, J.: Characterisation of HTS and LTS reactions. Scientific Advances in Fuel Cell Systems (2006), S. P6.15 - P6.15 Fuel Cells Science & Technology Conference ; 2006
2. Pawlak, M.; Thaler, M.; Hacker, V.: Characterisation of HTS and LTS reactions in micro-structured reactors. - in: Energy & fuels 21 (2007) 4
3. Pawlak, M., Hacker, V., Siebenhofer, M.: Hydrogen purification using microstructures Part I: Preparation of Al2O3-and CeO2 washcoats in microchannels in: Chemical Engineering Communications - submitted
4. Pawlak, M., Hacker, V., Siebenhofer, M.: Hydrogen purification using microstructures Part II: Catalytic performance of nm-Pt-catalyst for water gas shift on microstructured plates in: Chemical Engineering Communications - submitted
5. Pawlak, M.; Hacker, V.; Thaler, M.; Besenhard, J.: Characterization of HTS and LTS reactions in micro-structured reactors. Fuel Cells Science & Technology Conference. Turin, Italy, 13 September 2006
6. Pawlak, M.; Rabenstein, G.; Hacker, V.; Hoch- und Niedertemperatur CO-Konvertierung in Mikroreaktoren (WGS). CDL Labor Workshop, Graz, 02 February 2007
7. Hacker, V.; Wallnöfer, E.; Thaler, M.; Baumgartner, W. R.; Fraser, S.; Rabenstein, G.; Pawlak, M.: Fuel Cell Components and Material Development. Conference Wasserstoff- und Brennstoffzellenprojekte. A3PS, Wien, 13 December 2007

8. Pawlak, M.; Reischl, M.; Hacker, V.: Catalyst preparation and coating optimization for CO-conversion in microreactors. DECHEMA ProcessNet-Jahrestagung. Karlsruhe, Germany, 07 October 2008

FLW

Wehrtechnisches Symposium: EE2006 Moderne Elektrische Energietechnik in der Bundeswehr, 11. – 13.12.2006 in Mannheim, Germany, Title of presentation: „Potential von Brennstoffzellen auf Überwasserschiffen“.

HAW

1. Riazi, A.: Thermodynamic analysis of the performance of different fuel processors for high temperature fuel cells. H2-Expo-Hamburg, Germany, 25 - 26 of October 2006. The complete text of article is available in FELICITAS web-site and H2-Expo (http://www.hamburg-messe.de/H2Expo/h2_de/start_main.php)
2. Riazi, A, Cunningham, R., Williams, M., Winkler, W.: Propane Micro Steam Reforming. H2-Expo-Hamburg, Germany, 22 - 23 of October 2008.

ICL

1. The 7th European Turbomachinery Conference was held in Athens in March 5-9 2007. Some of the results of the project were presented in a paper by NTUA entitled “Gas Turbine Components Optimised for Use in Hybrid SOFC-GT Systems”
2. Tse L.K.C., Wilkins S., Martinez-Botas R.F., May 2007, “Dynamic modelling of a SOFC-GT hybrid system for transport applications”, Conference Paper, 2nd European Ele-Drive Transportation Conference EET-2007, Brussels, Belgium.
3. Tse L., Wilkins S., July 2007, “Sustainable Energy – Solid Oxide Fuel Cell and Gas Turbine Hybrid System for Transport Applications”, Poster Presentation, London Technology Network “Developing an Integrated Sustainable Transport System”, London, United Kingdom.
4. Wilkins, S., Tse L., Martinez-Botas, R.F., December 2007, “Investigation of SOFC-GT Systems for Hybridised Heavy Duty Transport Applications”, EFC2007-39214, ASME 2nd European Fuel Cell Technology and Applications Conference, Rome, Italy.
5. Tse L.: Configuration and Sensitivity Analysis of Solid Oxide Fuel Cell/Gas Turbine Trigeneration System for Marine Applications, in preparation
6. Tse, L.K.C., Detailed Study of Solid Oxide Fuel Cell-Gas Turbine Hybrid System for Marine Applications, PhD Thesis, Imperial College London, in preparation.

NTUA

1. The 7th European Turbomachinery Conference was held in Athens in March 5-9 2007. Some of the results of the project were presented in a paper by NTUA entitled “Gas Turbine Components Optimised for Use in Hybrid SOFC-GT Systems”. (NTUA & ICL)
2. NTUA is organizing in collaboration with the University of Sheffield and the University of Patras, supported by FOI and within the frame of the ECATS Network of Excellence the Workshop “Initial Fuel Cell Activities” on the 23rd and 24th of June 2008 in Athens. This Workshop will be realized with the participation of industry and will be the first of a series. In this Workshop, NTUA will present the work realized in the FELICITAS project.

INRETS

De Bernardinis, A. Coquery, G.: Hydrogen application for railways. First approach and point of view. Workshop of the HYRAIL FP6 project, 27 June 2007, Bergamo, Italy

UTBM

1. M. Chnani, H. Maker, M.C. Péra, D. Candusso, D. Hissel: Electrical analogy modelling of PEFC system fed by a compressor. EPEFCF'05 European Polymer Electrolyte Fuel Cell Forum, July 2005, Lucerne, Switzerland, CD-ROM

2. M. Chnani, M.C. Péra, R. Glises, J.M. Kauffmann: Macroscopic model of a solid oxide fuel cell for integrating in a generator simulation, 7th European SOFC Forum, Lucerne, Switzerland, 3-7 July 2006, 19 pages, CD-ROM P0906
3. M. Chnani, M.C. Péra, R. Glises, J.M. Kauffmann, D. Hissel: Transient thermal behaviour of a solid oxide fuel cell. ASME-5th Fuell cell science, engineering and technology conference, 18-20 June 2007, New York
4. S. Reuber, M. Schneider, J. Rechberger, M. Thaler, M.C. Péra, M. Chnani Hybrid SOFC-PEFC system : a conceptual study of a heavy propulsion system" ASME Journal of Fuel Cell Science and Technology", Accepted in February 2008

UNIGE

1. Pascenti M., Ferrari M. L., Magistri L., Massardo A. F., 2007, "Micro Gas Turbine Based Test Rig for Hybrid System Emulation", ASME Paper GT2007-27075, ASME Turbo Expo 2007, Montreal, Canada.
2. Traverso A., Trasino F., Magistri L., Massardo A.F., "Time Characterization of the Anodic Loop of a Pressurized Solid Oxide Fuel Cell System", ASME Paper GT2007-27135, Montreal 14-17 May 2007 accepted for journal publication
3. Ferrari M. L., Pascenti M., Magistri L., Massardo A. F., 2007, "A General Purpose Test Rig for Innovative Cycles Based on a 100 kW Micro Gas Turbine", IGCT2007-TS-015, International Gas Turbine Congress, Tokyo.
4. Ferrari M. L., Pascenti M., Magistri L., Massardo A. F., 2008, "Emulation of Hybrid System Start-up and Shutdown Phases with a Micro Gas Turbine Based Test Rig", GT2008-50617, ASME Turbo Expo 2008, Berlin, Germany.
5. Ferrari M. L., Pascenti M., Massardo A. F., 2007, "Ejector Model for High Temperature Fuel Cell Hybrid Systems: Experimental Validation at Steady-State, Transient and Impulse Conditions", FC-06-1056, Accepted for publication on "Journal of Fuel Cell Science and Technology".
6. Ferrari M. L., Liese E., Tucker D., Lawson L., Traverso A., Massardo A. F., 2007, "Transient Modeling of the NETL Hybrid Fuel Cell/Gas Turbine Facility and Experimental Validation", Journal of Engineering for Gas Turbines and Power, Vol. 129, pp. 1012-1019.
7. Ferrari M. L., Traverso A., Pascenti M., Massardo A. F., 2007, "Early Start-up of Solid Oxide Fuel Cell Hybrid Systems with Ejector Cathodic Recirculation: Experimental Results and Model Verification", JPE438R1, Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy, Vol. 221, pp. 627-635.
8. Ferrari M. L., Pascenti M., Massardo A. F., 2007, "Ejector Model for High Temperature Fuel Cell Hybrid Systems: Experimental Validation at Steady-State, Transient and Impulse Conditions", FC-06-1056, accepted for publication on Journal of Fuel Cell Science and Technology.
9. Ferrari M. L., Pascenti M., Bertone R., Magistri L., 2007, "Hybrid Simulation Facility Based on Commercial 100 kW Micro Gas Turbine", FC-07-1134, submitted at "Journal of Fuel Cell Science and Technology".

Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
12 July 2005	Fraunhofer International Forum on Transportation	Higher education	Europe	Approx. 30	FhG IVI, Ballard
4 to 8 July 2005	3rd European Polymer Electrolyte Fuel Cell (PEFC) Forum	Research / Industry	International		FhG IVI
31 August & 1 September 2005	H2Expo 2005	Research / Industry	International		FhG IVI
November 2006	13. Symposium Nutzung regenerativer Energie-quellen und Wasserstoff-technik	Research / Industry	Germany		FhG IVI
11 April 2007	Kolloqium des Instituts für Automobiltechnik IAD Dresden	Research / Industry	National		FhG IVI
18 June 2007	Dresdner Automati-sierungstechnische Kolloquien	Research / Industry	National		FhG IVI
20 to 22 August 2007	5th IFAC Symposium on Advances in Automotive Control	Research / Industry	International		FhG IVI
24 & 25 September 2007	21. Verkehrswissenschaft-liche Tage der TU Dresden	Research / Industry	National		FhG IVI
10 & 11 October 2007	European Hydrogen and Fuel Cell Technology Plat-form (HFP) ReviewDays'07	Research / Industry	International		FhG IVI
December 2007	Innovationsforum Schienenfahrzeugtechnik	Research / Industry	National		FhG IVI
14 & 15 February 2008	Bahntechnik-Fachtagung	Research / Industry	National		FhG IVI
24 April 2008	Kolloqium der Institute Enegrie- und Verfahrens-technik der TU Braun-schweig	Research / Industry	National		FhG IVI
6 to 11 July 2008	17th IFAC World Congress	Research / Industry	International		FhG IVI
6 & 7 October 2008	International Workshop on Accelerated Testing in Fuel Cells	Research / Industry	International		FhG IVI
28 November 2008	1. Sächsischer Brennstoffzellentag	Research / Industry	International		FhG IVI
10 to 12 December 2008	Fundamentals & Developments of Fuel Cell (FDFC) Conference	Research / Industry	International		FhG IVI
10 December 2006	SalonNautico - Colloquium	Public / Industry	International		
27 & 28 April 2005	HY Profiles Conference Island	General public / Research / Industry	International	Approx. 50	Ballard
19 to 21 September 2005	CUTE Conference Stockholm	General public / Research / Industry	International	Approx. 50	NuCellSys
12 & 13 October 2005	FELCITAS Meeting - Meissen	Research / Industry	Europe	Approx. 30	all
17 & 18 October 2005	AGORA yearly meeting - Zurich	Industry	Switzerland / Germany	Approx. 50	NuCellSys
6 to 8 December 2005	EDTA Conference – Vancouver	General public / Research / Industry	North America	Approx. 80	NuCellSys

Dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible / involved
27 & 28 June 2007	ECPE Seminar: „Energy Storage Technologies“	Research / Industry	International	+/- 200	CCM
19 to 21 November 2007	Second International Renewable Energy Storage Conference (IRES II) – Bonn, Germany	Research / Industry	International	+/- 150	CCM
13 & 14 September 2006	Poster Presentation at Conference Fuel Cells Science&Technology 2006 (Marta Pawlak: Characterisation of HTS and LTS reactions in micro-structured reactors)	Research / Industry	International		CDL
2 February 2007	CDL Labor Workshop	Research / Industry	International		CDL
13 December 2007	Conference Wasserstoff- und Brennstoffzellen-projekte	Research / Industry	International		CDL
7 October 2008	DECHEMA ProcessNet-Jahrestagung	Research / Industry	International		CDL
11 to 13 December 2006	Wehrtechnisches Symposium, Moderne elektrische Energietechnik in der Bunderswehr	Industry / Research / Defence	Germany	130	FLW
25 & 26 October 2006	H2-Expo- Hamburg Conference/ Exhibition	Higher education/ Researchers / Industry (sector fuel cell / energy)	All countries (International Conference)	+/- 200	HAW
22 & 23 October 2008	H2-Expo-Hamburg	Research / Industry	All countries (International Conference)	+/- 200	HAW
2007	Birmingham conference; London Technology Network; ICL Energy Futures Lab poster session; ICL Mech Eng Thermofluids section poster competition; ICL Mech Eng Departmental poster competition	Higher education / Research / Industry	UK	50	ICL
5 to 9 March 2007	7th European Turbo-machinery Conference	Research	International		ICL
30 May 2007	2nd European Ele-Drive Transportation Conference	Research / Industry	International		ICL
11 July 2007	London Technology Network Conference	Research / Industry	International		ICL
11 December 2007	ASME 2nd European Fuel Cell Technology and Application Conference	Research / Industry	International		ICL
5 to 9 March 2007	7th European Turbo-machinery Conference	Research	International	300 - 400	NTUA
23 and 24 June 2008	Workshop on Fuel Cell activities (ECATS network of excellence)	Research / Industry	EU	20	NTUA
27 June 2007	Workshop of HYRAIL FP6 Project	Research / Industry	EU	Approx. 50	INRETS
July 2005	EPEFCF'05 European Poly-mer Electrolyte FC Forum	Research / Industry	International		UTBM

Dates	**Type**	**Type of audience**	**Countries addressed**	**Size of audience**	**Partner responsible / involved**
3 to 7 July 2006	7th European SOFC Forum	Research / Industry	International		UTBM
18 to 20 June 2007	ASME 5th Fuel Cell Science, Engineering and Technology Conference	Research / Industry	International		UTBM
14 May 2007	1st ASME Turbo Expo 2007	Research / Industry	International		UNIGE
5 September 2007	3rd International Gas Turbine Congress	Research / Industry	International		UNIGE
09 June 2008	4th ASME Turbo Expo 2008	Research / Industry	International		UNIGE

Table 12: Overview table on conferences and workshops

10.4.2 Exploitable knowledge and its utilisation

No.	Exploitable Knowledge	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved)
I	Coupling of dynamic Fuel Cell Systems and operation in connection with an electrical hybrid drive train (Cluster) a. Concepts of cluster configu-rations b. Safety aspects of cluster configurations c. Reliability assessment	HY80 – M Fuel Cell System	Transportation distribution vehicles city buses rail cars inland waterway passenger boats	2010 Project Business	none	NuCellSys GmbH
2	Design concept of a fuel cell based AutoTram vehicle a. FC based electric propulsion system b. Integration concept of hydrogen storages c. Safety concept	new generation of homologated AutoTram	Public Transportation	2012 in frame of the German Innovation program	none	Fraunhofer IVI
3	GPS based predictive energy management	High advanced energy management systems for hybrid propulsion systems	Public Transportation Heavy-Duty Transport	2012 first application in bimodal trams	none	Fraunhofer IVI
4	combined Li-Ion battery / super-cap storages	Dual energy storages	hybrid propulsion	2012 first application in bimodal trams	none	Fraunhofer IVI
5	Assessment of feasibility of flywheel energy storage	CCM RxV Flywheel Systems	Commuter & distri-bution vehicles; lifting & hoisting equipment; marine board grids	2012	Yes (3), regarding construction details Flywheel	CCM
6	Model based In-situ diagnostic functions for PEFC	health detector	PEFC based applications	2012 in frame of FC bus projects	none	Fraunhofer IVI

Table 13: Overview table on exploitable knowledge and its use

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