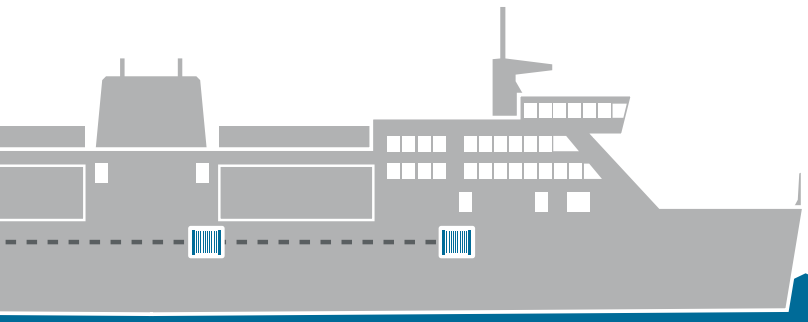
e4ships
Fuel cells in marine applications

e4ships
FUEL CELLS IN MARINE APPLICATIONS
2016- 2022



CONTENT

GREETING

by State Secretary Susanne Henckel

Dear Readers,

The current developments on the political world stage are a dramatic reminder that to ensure a sustainable future energy supply we must pursue decarbonisation with resolve, and that diversified energy sourcing will be of paramount importance. There is hardly another mode of transport making this more apparent than shipping, where the first steps in the right direction have already been taken.

Acknowledging that the global shipping sector handles 90 % of the global transport of goods while emitting close to 3 % of global CO_2 emissions, the International Maritime Organization (IMO) created an initial framework for decarbonisation and passed binding measures for oceangoing ships to reduce their CO_2 emissions by 50 % (based on 2008 values) by the year 2050, and to eliminate them entirely by the end of this century. The ambitious goal of achieving a zero-emission global merchant fleet by 2050 is still being discussed at IMO but has been receiving broad support.

In addition, at the European level the draft regulation "FuelEU Maritime" proposes to reduce the carbon intensity of ship fuels progressively year after year to achieve a 75 % reduction by 2050 compared to the reference year 2020. This will increase the demand for renewable and low-carbon fuels significantly.

The European Commission aims for a 55 % overall reduction of carbon-intensive emissions by the year 2030, and a reduction of absolute emissions by 90 % compared to 2005 levels. This net-zero goal sends a strong signal to energy suppliers, ship builders and engine manufacturers to accelerate and increase their investments in alternative propulsion technologies and green fuels.

For some years now the Federal Government has been working with the maritime industry in a strategic partnership to drive the development and testing of alternative propulsion technologies. The National Hydrogen and Fuel Cell Technology Innovation Programme (NIP) plays a key role in these endeavours. Going beyond conventional R&D activities, it includes initiatives to advance the market ramp-up of hydrogen and fuel cell technology with the aim to achieve market maturity as soon as possible. It is important to take an approach that is open to any technology to draw the best possible benefits from all potential solutions without excluding any technology prematurely.

Fuel cell systems for maritime applications are a key driver of the progressing transformation seen at German shipyards and in the supply industry.

The e4ships innovation cluster has run successful maritime demonstration projects since 2009 and taken an active role in incorporating the technical insights gained into the safety regulations for the approval of ships with fuel cell propulsion systems which have been developed by the IMO.

Leading German shipyards and ship-owners began cooperating with fuel cell manufacturers at an early time to engage in a lively dialogue in support of the development of fuel cell systems for the specific needs of ocean and inland ships while contributing to the development of international regulations for inland and ocean shipping. The publication of the 'Interim guidelines for the safety of ships' by the IMO Maritime Safety Committee in April of this year, along with other achievements, highlights the success of this work.

The experiences and results that have emerged from e4ships deliver a technologically innovative answer to the challenges of environment and climate protection. They are a valuable and operationally validated contribution to the ongoing effort to create the right conditions for fuel cell and hydrogen technologies to establish a permanent basis within Germany as an industrial nation, and in particular, in the shipping industry.

Susanne Henckel
State Secretary
Federal Ministry for Digital and Transport

FOREWORD

by Kurt-Christoph von Knobelsdorff

Ladies and gentlemen,

Various bodies at the international and European levels are in the process of agreeing binding measures to decarbonise shipping. For ship-owning and shipping companies, shipyards, suppliers and energy providers, this implies the necessity to decide today how they will go about making tomorrow's fleet operation both climate-friendly and economical. Against this background, it is of paramount importance to drive the development of suitable technologies as well as the availability and economic feasibility of fuel cell systems and renewable fuels. To this end, leading German shipyards, ship owners, suppliers and research institutes have joined hands to form the innovation cluster e4ships with support from the National Investment Programme for Hydrogen and Fuel Cell Technology (Nationales Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie; NIP), and are cooperating on innovative technology demonstration projects. They are jointly promoting the development of technologies, the transfer of knowledge, and the establishment of safety standards at the international and European levels.

In the current, second phase of the NIP (2016-2026), the e4ships consortium has reached major milestones, including the commissioning of the world's first combined battery and fuel cell hybrid pusher boat ELEKTRA and the development and live trial of HT PEM fuel cells on board passenger vessels such as MS Mariella. Furthermore, in 2022 the International Maritime Organization (IMO) passed its safety requirements for the approval of ships equipped with fuel cells. These requirements are in part based on results made possible by the NIP's long-term research and development support. All these efforts have paved the way for the market ramp-up of this technology in the shipping industry. Advanced development and trial work on NT PEM and SOFC fuel cell systems using various alternative fuels such as methanol, hydrogen or low-sulphur diesel are helping the NIP-supported maritime projects deliver a technology advantage to the shipping industry.

The National Organization for Hydrogen and Fuel Cell Technology (NOW) has been coordinating and assisting the NIP›s maritime projects. Several support programmes have been combined to achieve the overarching goal: Climate-friendly shipping. We believe that maritime fuel cell applications can be a key lever for upscaling this technology, and we are expecting synergies for land-based applications to emerge from it. Apart from the technology innovation itself, achieving market maturity and securing the availability of renewable fuels are further challenges to making sustainable maritime mobility a reality. We address them by driving the overall concept of renewable fuels so as to underpin the energy transformation and promote the use of fuel cells.

At NOW we firmly believe that the fuel cell demonstration projects in maritime applications and the supporting e4ships innovation cluster are doing trailblazing work to advance the market entry of fuel cell technology. They are key components of the NIP programme, and we are looking forward to accompanying the next development steps of the innovation cluster, involving stakeholders from all segments of the e-fuel supply chain for maritime fuel cell applications.

Kurt-Christoph von Knobelsdorff
CEO & Speaker
Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW)

INTRODUCTION

by Dr. Ralf Sören Marquardt

With the innovation cluster e4ships – Fuel Cells in Maritime Applications – Germany has set course for the destination of Sustainable Shipping. For the mobility of the future it is not sufficient to lower emissions here or there; rather, it is necessary to take a holistic approach so as to make significant contributions towards several sustainability goals. The discussion is no longer limited to climate-relevant gases and air pollutants but also addresses water protection, avoidance of noise emissions, and establishing a circular economy.

Sustainable transport by ocean and inland waterways requires energy-efficient, low-emission, low-noise propulsion and a carbon-neutral energy supply. Fuel cells are a key technology in this scenario. Able to use many alternative fuels, they are a means to promote the energy transition in the shipping industry and in other sectors.

With support from the Federal Ministry For Digital And Transport (BMDV), leading German shipyards, ship-owning companies, fuel cell manufacturers, research institutes, classification societies and the German Shipbuilding and Ocean Industries Association (VSM) have coordinated their research efforts to find joint answers to core questions about climate protection, ship safety and the economic feasibility of hydrogen and fuel cell technology.

Through its four lighthouse projects ELEKTRA, Pa-X-ell, RiverCell and Multi-SchIBZ, the German shipbuilding industry has taken the lead in the development of this technology and implemented practicable systems for major ship types and modes of transport. The spectrum comprises cruise ships, yachts, specialised and inland vessels as well as a variety of fuel cell types and primary fuels with a range of properties and associated safety requirements. These projects not only realise custom-tailored solutions for European ocean and inland waterway shipping but also open up perspectives for export to the world market.

To develop this potential successfully, it is essential to create a suitable regulatory and political framework. Powerful fuel cell systems cannot be established in international shipping on a broad basis unless a set of binding approval requirements consistent with the rapid technology development provides the necessary legal certainty.

The e4ships innovation cluster has accounted for this by addressing three key issues: Development of regulations; publicity work; and political strategy development. By facilitating the exchange of information, networking, and transferring knowledge between companies doing research, regulatory bodies and political decision-makers, key regulatory milestones have been reached which now enable efficient use of fuel cells on board oceangoing and inland vessels without requiring time-consuming and costly individual approvals.

Both the energy portfolio and the regulatory concepts are being expanded continuously: In future, additional sources of energy such as ammonia and hydrogen will be available not only as propulsion fuels but also for energy imports to the EU. But they come with new technical and political challenges.

To tackle these tough challenges, we will once again need efficient innovation clusters which will help strengthen the competitiveness of German products.

Apart from witnessing the progress made on the regulatory front and the growing public awareness, seeing mutual trust grow among the stakeholders through close cooperation has inspired my personal enthusiasm. Not only has the innovation cluster enabled the transfer of knowledge, but it has also given rise to a spirit of cooperation which enables us to overcome the ever-increasing challenges: This is how carbon-neutral shipping can become a reality in Europe by 2050.

Dr. Ralf Sören Marquardt
Chairman, e4ships Status Assembly
General Manager, VSM

REGULATORY WORK AT IMO – CESNI

DEVELOPMENT OF REQUIREMENTS

In view of the worsening climate and energy crisis, the maritime economy is facing the challenge of having to transform the entire ocean-going and inland shipping sector. Not only is it necessary to develop green technologies and energy sources to market-readiness; there also needs to be a competitive legal framework for the approval and operation of ships with innovative propulsion systems using alternative fuels. To enable broad, industry-wide implementation, international technical standards are needed which allow fast, consistent certification without requiring individual prototype approvals.

It is therefore imperative for sustainable shipping to become a reality that proactive steps are taken by the committees in charge of maritime international law so that successful innovation can be translated to significant emission reductions and improved competitiveness of German companies. The relevant decision-making bodies for the shipping industry are the London-based International Maritime Organization (IMO) and the Strasbourg-based CESNI (Comité européen pour l'élaboration de standards dans le domaine de la navigation intérieure). Forward-looking standards have been passed successfully by these bodies based on well-documented experience from research and practical applications in individual demonstration projects as well as the e4ships innovation cluster.

e4ships delegation representing at the IMO

REGULATORY WORK AT IMO – CESNI

8

New, forward-looking standards introduced

To this end, concrete, practicable requirements were developed working closely with universities and classification societies, and submitted to the relevant IMO and CESNI committees by the Federal Ministry For Digital And Transport (BMDV) and the European shipbuilding Associations CESA and SEA Europe for discussion and approval. Thanks to technology-agnostic consolidation within the innovation cluster, it was possible to finalise and pass generalised regulations covering a variety of fuel cell types (PEM and SFOC), propulsion concepts and ship types.

The Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations passed by the IMO Maritime Safety Committee in May 2022 (MSC.1/Circ. 1647) make a highly efficient energy conversion technology available to the international shipping world while expanding the portfolio of available fuels by reformed hydrogen. As a consequence it is now possible to install larger fuel cell systems on board internationally operating merchant ships, such as the cruise ship AIDAnova. Similar to the LNG boom initiated when the International Code for the Safety of Ships using Gases or other Low-flashpoint Fuels (IGF Code) entered into force in 2016, this milestone has already begun to have an impact on German shipyards in the form of numerous new orders and projects for carbon-neutral cruise ships and yachts.

Other, parallel efforts aim to expand the portfolio of fuels available to oceangoing ships to enable zero-emission transport throughout all geographical deployment areas. e4ships played a key role in the development of the Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circular.1621 of December 2020) and is currently in the process of finalising the safety requirements for carbon-neutral e-fuels, such as green hydrogen and ammonia as well as synthetic diesel.

To accelerate the development of rules significantly, the e4ships project partners prepared an Acceleration Plan for Alternative Fuels which has been fully implemented by IMO since the third quarter of 2022. Future sessions of the responsible IMO subcommittee Carriage of Containers and Cargoes (CCC) will be expanded accordingly, and the individual development efforts parallelised. This massive increase of capacity, which will allow ambitious reduction goals to be achieved rapidly, requires dependable delivery of results by e4ships and other providers of know-how so that existing regulation gaps related to safe bunkering, storage and use of alternative fuels can be closed soon.

Technology transfer to London

Remaining regulation gaps must be closed

Regulatory work at the CESNI level is likewise progressing as intended: Although hydrogen and fuel cell technology were added to the CESNI agenda as late as 2020, the newly-established working group CESNI/PT/FC has since developed key rules which will amend the technical requirements for inland vessels (ES-TRIN) very soon. In a first step, ES-TRIN chapter 30, which has been revised to address fuel cells and methanol, as well as Appendix 8 will come into force. The draft version of the regulation addressing hydrogen storage on board inland vessels is likewise approaching finalisation.

Here again CESNI has benefited from the intense involvement of e4ships partners. Following the commissioning of the world's first hydrogen-powered fuel cell pusher boat ELEKTRA, the innovation cluster now has profound technical know-how while being able to draw on its long-standing IMO experience gained in its regulatory lobbying efforts in Strasbourg.

Similarly, many parties' objections were resolved quickly and successfully with the help of practical demonstrations and internationally proven partnerships of member countries and NGOs.

In particular, land-based testing facilities, such as the RiverCell Demonstrator for an inland waterway cruise ship, have played a key role in this process. In committee sessions, some of which are held on site, technical questions can be answered directly to arrive at consensual decisions faster.

Developing environmental requirements and political strategies the industry can implement

These regulatory successes have put the innovation cluster in a position to become a valuable driver of safe decarbonisation. e4ships has been helping develop environmental requirements and political strategies the industry can implement. After all, innovative energy systems will not succeed in the market solely by demonstrating their operational safety. It is necessary to establish internationally binding emission reduction targets to make the industry actually adopt the technical advances enabled by innovation.

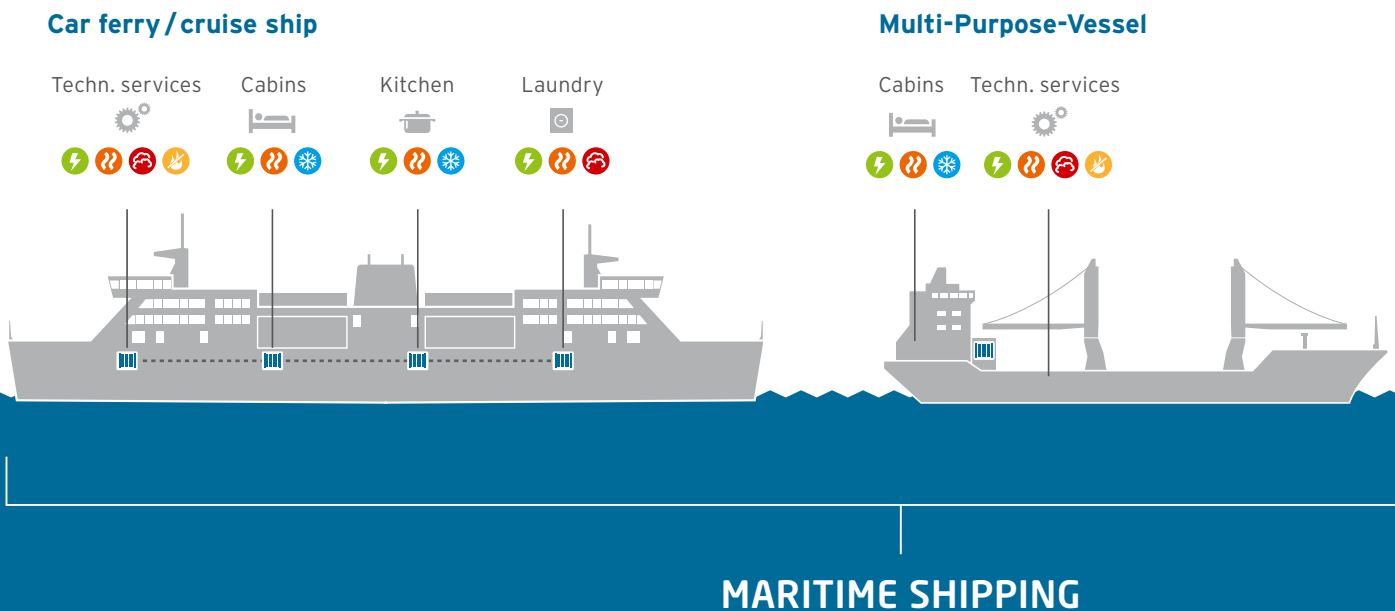
For this purpose, e4ships submits relevant reports to the committees working on the IMO GHG Strategy and the revision of the MARPOL convention, both of which must be updated to account for more efficient energy conversion technologies and carbon-neutral e-fuels (Life Cycle Assessment). The same goals are being pursued by relevant EU organisations such as the European Sustainable Shipping Forum (ESSF) and the Sustainable Finance Platform (SFP). It is imperative to implement assessment criteria that are consistent across Europe as well as internationally to ensure that fuel cells and hydrogen-based e-fuels are technically accepted as sustainable solutions and incentivised financially through CO_2 taxation and green ship finance.

Fuel cells: Practicable for many ship types

The work of e4ships has demonstrated the practicability of fuel cell technology for a wide range of ship types while defining a regulatory framework to support marketability. Nevertheless, development efforts continue to prepare the ground for higher performance classes and complete the regulatory framework so as to create a global, level playing field of binding rules for all energy sources and propulsion options. Innovation clusters are an essential means to ensure that regulations can be updated efficiently to reflect the scientific and technical state-of-the-art as well as industry-specific requirements.

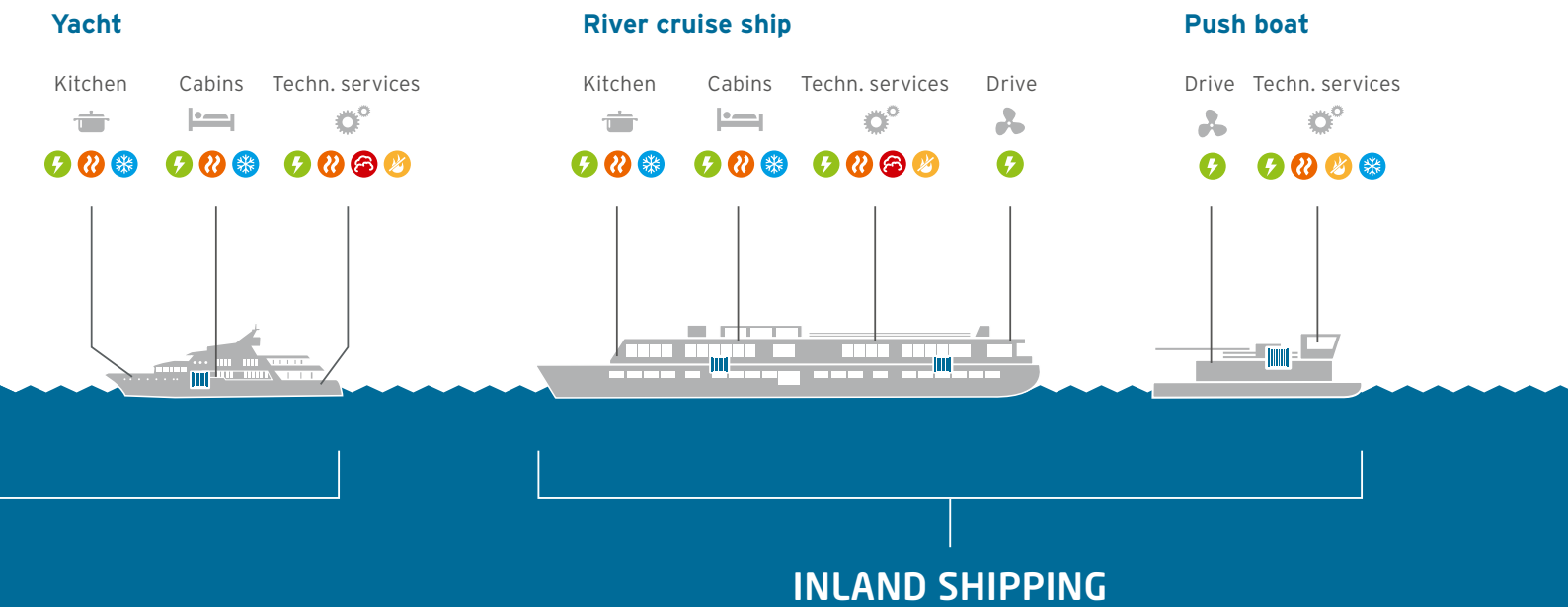
e4ships is a joint project of leading German shipyards, shipping companies, fuel cell manufacturers and classification societies funded by the German Federal Government within the framework of the National Innovation Program Hydrogen and Fuel Cell Technology (NIP).

10



MARITIME SHIPPING

APPLICATION AREAS FUEL CELL



INLAND SHIPPING

PROJECT ELEKTRA

12

The subject of the demonstration project ELEKTRA has been the implementation and trial of hydrogen-powered fuel cells combined with batteries to provide all energy needed on board a commercial inland vessel. In implementing the emission-free ship, ecological requirements in sensitive areas, such as metropolitan regions, had to be accounted for.

The ELEKTRA in its Berlin home port at BEHALA

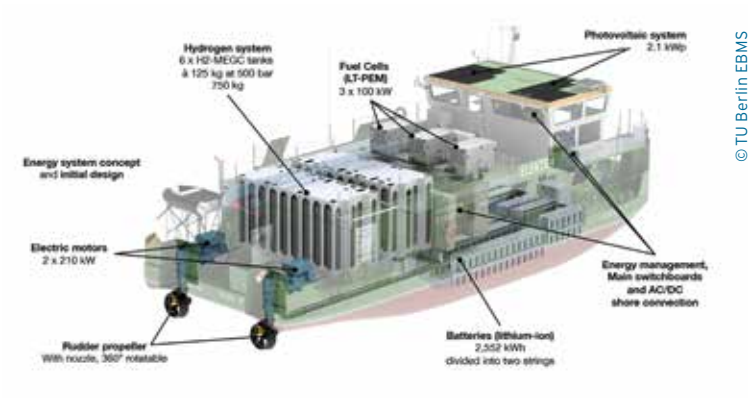
The pusher boat ELEKTRA built for this project was completed in May 2021 and has been undergoing trials, having passed a nautical check and been launched in spring 2022. The consortium comprises the project partners ANLEG, Ballard, BEHALA, EST Floattech, HGK Shipping, SER Schiffselektronik Rostock as well as the shipyard Schiffswerft Hermann Barthel, and is headed by the Design and Operation of Maritime Systems Division at Technical University Berlin (EBMS TU Berlin).

A comprehensive energy management system was developed for the hybrid electric propulsion system, which includes all energy generating and consuming equipment and makes optimum use of the limited energy resources available on board, enhancing the vessel's economic feasibility and competitiveness compared with conventionally-powered ships. The hydrogen-powered fuel cell technology generates the baseload energy required by the drivetrain and the on-board power grid. To handle peak loads during operation, batteries provide additional power. Furthermore, this vessel serves to test the technical feasibility of hydrogen as an energy storage medium in shipping applications in view of its specific properties and requirements. At the same time, concepts for a future infrastructure for the provision of shore power as well as hydrogen for the fuel cells are being developed. Initial functional tests of the electrical systems were completed without encountering any

difficulties. The operator BEHALA has installed 125 ampere charging stations at its port locations to back up the ship's energy supply, and intends to build additional charging points along the intended operating route for uninterrupted operability.

A contract for the supply of green hydrogen using Multiple Energy Gas Containers (MEGC) has been signed. The contract term runs until the end of 2024, the time the project is scheduled to complete. The MEGC containers can be swapped using an on-board crane. For connecting to shore power, a charging boom including a charging cable is available. This means that handling the cables, which are as thick as a human arm, is very easy, and connecting the ship to the charging station takes very little time without involving hazardous loose cables lying on the pier. The MEGC containers provided by ANLEG are currently undergoing technical approval while some initial trials of hydrogen bundles under low pressure and capacity are already in progress. A number of different power curves have been recorded with the ship in operation for further analysis.

With 750 kilograms of usable gaseous hydrogen at a pressure of 500 bar on board and a battery capacity of approximately 2,500 kilowatt-hours, the ship has a range of about 400 kilometres when pushing the loaded heavy-lift barge URSUS. This is why ELEKTRA needs only one additional shoreside charging and bunkering station outside of Berlin's Westhafen port for power and hydrogen within the operating region between Berlin and the Rhine/Ruhr area, Hamburg, or Szczecin, Poland. The pusher boat can push tows up to 150 metres in length. Some initial interregional tow trips from Derben to Berlin as well as to Niederfinow and Wusterwitz have been completed successfully without any incidents. Furthermore, various tow arrangements have been tested in limited areas with relatively deep water in the Berlin region. Future trials will follow from 2023, including a number of long-distance trips towards Hamburg.



© TU Berlin EBMS

Schema diagram of the ELEKTRA and its functional groups

© BEHALA

Ship launching of the ELEKTRA with political representatives in May 2022

In addition, the demonstration project includes the development of rules, regulations and laws for the use of hydrogen, high-power fuel cells and batteries on inland vessels, working closely with the authorities and classification societies.

Project partners

Anleg, Ballard Power Systems, Schiffswerft Hermann Barthel, BEHALA Berliner Hafen- und Lagerhausgesellschaft, EST Floattech, HGK Shipping, SER Schiffselektronik Rostock and TU Berlin – Fachgebiet Verkehrs- und Maschinensysteme

PROJECT PA-X-ELL2

Within the context of e4ships, the Pa-X-ell2 project is dedicated to the development of PEM fuel cell technology for use on ocean-going passenger ships with the aim of market introduction. The consortium, headed by MEYER WERFT, includes the project partners besecke, Carnival Maritime, DLR, DNV, EPEA, Fr. Lürssen Werft and Freudenberg Fuel Cell e-Power Systems.

© Grayling/Aida

The fuel cell system is installed on the AIDAnova

The focus is on integration of fuel cells into decentralised power grids or hybrid energy systems including energy storage systems on board passenger ships. Both energy concepts require the development of the maritime fuel cell system so it can meet the stringent requirements of passenger ships in terms of power, service life and reliability. Trials involving experimental fuel cell systems on board passenger ships are key stepping stones towards developing future-ready energy concepts as well as fuel cell technology in general, along with the relevant international rules and regulations.

The overall project can be subdivided into three areas of activity: The first area addresses fuel cell development, covering technology, system design and fuel cell pre-design, refinement as well as peripheral systems. These activities are accompanied by safety as well as ecological and economic analyses.

The scope of these efforts comprises NT-PEM system development by Freudenberg as well as pre-design by DLR to establish foundational technology for future large-scale HT-PEM systems. Specifically intended for use on board ships, an innovative NT-PEM system including a thermally highly integrated methanol reformer will be implemented by Freudenberg. The overall system design, comprising an NT-PEM fuel cell stack, the gas process transforming methanol to hydrogen, and a heat and water management system, will be an entirely new development for this project. This is necessary because the fluid mechanics and heat transfer processes are highly dependent on the required quantities.

Photo of the assembled demonstrator on the premises of Lürssen shipyard

© Lürssen Werft

Top view of the rendered CAD model incl. the room designation.

At the same time, the power and heat-related design must be entirely rethought for on-board applications to ensure high efficiency and a long service life.

Furthermore, DLR will examine and assess the potential performance and feasibility of large-surface HT-PEM fuel cell stacks within the Pa-X-ell2 project. An innovative design concept will be applied to allow the manufacture of large-surface membranes, which will boost the performance of the fuel cell stacks. The project intends to use a lab prototype to examine the feasibility of a large-scale HT-PEM system including a reformer, since higher temperatures will allow the heat energy to be used more efficiently on board.

© Freudenberg

Concept design of a large-scale fuel cell system from Freudenberg

The most substantial area of activity within the project is the development, design, construction and testing of the experimental systems which will be used to test the fuel cell system and to draw conclusions that are relevant for developing the energy management system as well as appropriate rules.

Fr. Lürssen Werft has integrated a 100 kW fuel cell system developed by Freudenberg into a demonstrator that includes all relevant systems and components of a yacht. From the bunkering process to running measured load profiles, all possible operating situations can be mapped as on a real yacht. From this, important knowledge for a later implementation on a yacht will be gained.

Furthermore, MEYER WERFT and AIDA Cruises will jointly develop a fuel cell system for installation on board the cruise vessel AIDAnova. The experiences gained with this innovative power generation technology will be useful for the development of decentralised energy networks. Furthermore, the operational learnings will play a key role in future technology assessments aiming to identify the potential of fuel cells, and to use this knowledge in further technology developments.

Both experimental installations not only require technology and system development work but also new safety concepts based on the international regulatory frameworks.

All resulting experiences and lessons learned will benefit the third area of activity which addresses integration development. The goal is to come up with an optimised integration concept for fuel cell systems on board passenger ships. This includes examining entirely new approaches, such as decentralised energy generation as well as energy management, to ensure efficient use of energy systems based on fuel cell technology.

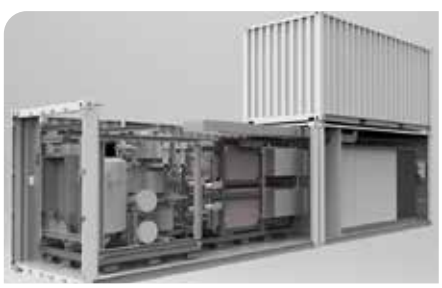
Project partners

besecke, Carnival Maritime, EPEA, DLR Deutsches Luft- und Raumfahrtzentrum, DNV, Freudenberg Fuel Cell e-Power Systems , Fr. Lürssen Werft and MEYER WERFT

PROJECT MULTISCHIBZ

16

The two-phased MultiSchIBZ project, managed by thyssenkrupp Marine Systems and OWI Science for Fuels, Aachen, comprised process optimisation and further development of the fuel cell system design from the SchIBZ2 project, aiming to enable commercialisation of the technology.



© ThyssenKrupp Marine Systems

Schematic interior view of the demonstrator

© ThyssenKrupp Marine Systems

Completed land demonstrator in Kiel

When installed on board oceangoing ships, fuel cells can generate electricity and heat for auxiliary power units (APUs) as an alternative to shore power which is often economically critical. The system is designed to convert liquid fuels stored on board to high-hydrogen fuel gas, which is then transformed into electric energy using SOFC fuel cells. System operation is low in CO_2, pollutant and noise emissions as well as nearly vibration-free. Compared to conventional propulsion systems using marine gas oil, the system is expected to reduce nitrous oxide and particulate matter emissions by 99 %, and CO_2 emissions by 25 %. Using low-greenhouse gas fuels from renewable sources could further reduce the CO_2 emissions.

One of the key technical intentions of the project was to develop components allowing the well-established SOFC technology to be adapted for use in highly integrated, fully automated ship applications. Furthermore, the project was to address integration of the systems into the ship design including energy buffers in every fire zone, to do the groundwork for updates to applicable regulations, and to account for the requirements of operational procedures on board inland and other vessels. The lab demonstration units used SOFC fuel cell module prototypes with a total design output of 25 kWel. These are integrated into an overall system

complete with a process gas module, a hot exhaust gas afterburner, and a DC-AC converter. The process gas module converts liquid fuel to high-hydrogen fuel for the fuel cell module. When evaluating the demonstrator system, the researchers accounted for the operating points, load changes and the start-up behaviour. The emission values were found to be markedly lower than those of conventional engine-operated systems.

Developing the process gas module was a major accomplishment towards achieving full technology maturity. Key objectives along the way included implementing a robust pre-reforming process for diesel fuel including catalytic converter screening, as well as process optimisation simulations, development of methods to measure degradation, and the redesign and engineering work for the new diesel reformers. One of the core elements of the module is the catalytic converter whose service life is of paramount importance for the economic feasibility of the entire system. By optimising processes strategies, for example regarding the water temperature and mixing ratio, and by combining sulphur-free synthetic and biogenic fuels, an extended catalytic converter lifetime in excess of 10,000 h can be achieved. This means that economically feasible maintenance concepts are realistic. Furthermore, the project successfully implemented a closed-loop process water system by condensing the water and reconditioning it for use.

Residual gas recirculation systems using hot gas blowers are state-of-the-art for SOFC fuel cell systems; however, they are expensive, susceptible to malfunction, and have a negative impact on overall efficiency. For this reason, a passive anodic exhaust gas recirculation system was developed for this project. This technology keeps the hot anodic residual gas from the fuel cells within the system for further use, feeding it into an afterburner to generate heat which is then routed through a high-temperature heat exchanger to generate process steam for steam reforming. Passive anode gas recirculation serves the same purpose as a fan blower system but uses a hot steam jet instead. This unit was developed using CFD numeric simulations. It was manufactured in a 3D metal printing process which can produce compact devices requiring significantly less space within the system. Material tests were conducted to confirm the comparability of the additive manufacturing process with conventionally-manufactured components, and a proof of concept demonstrated the functionality of the recirculation system at all operating points, at system start-up, and in load change cases.

Process expertise for complex systems and smart manufacturing processes enabling compact, high power density components were key to the success of this project. The lab demonstrator unit has since been upscaled for implementation of a larger overall demonstrator system designed for a power output of 300 kWel, which will be implemented in a future follow-up project.

Fuel cell test bench at ZBT in Duisburg

Test bench with MultiSchIBZ solid oxide (SOFC) fuel cell system in the OWI laboratory

Project partners
DNV, Hülsenbusch Apparatebau, Leibniz Universität Hannover, OWI Science for Fuels, Rosswag, Sunfire, thyssenkrupp Marine Systems and ZBT Zentrum für BrennstoffzellenTechnik

PROJECT RIVERCELL

18

© MEYER WERFT

Digital closing event at NEPTUN WERFT

The RiverCell project focused on the development and testing of a modular hybrid energy system with fuel cells for river cruise ships.

Many European waterways pass through ecologically sensitive or densely populated areas, requiring major efforts to minimise exhaust gas and noise emissions. The passenger shipping segment in particular has been confronted with tougher sustainability requirements: It is especially present in the public eye because of its operational profile and its visibility primarily at inner-city jetties and popular tourist destinations where emission limits are already rather strict. Passengers and the general public increasingly expect visible measures to improve sustainability. Major challenges include exhaust gas as well as noise emissions along rivers. Efforts to optimise the established diesel engine propulsion technology to make it cleaner and quieter are reaching their economic and technical limits. There is an urgent need to develop and test alternative energy and propulsion concepts for inland vessels to meet future environmental requirements.

The completion of the RiverCell2 project resulted in a functional, safety-tested prototype of a fuel cell unit fit for use on board ships. Called Marine Fuel Cell Unit (MFCU), it was integrated into a hybrid energy system for inland passenger vessels in a shore-based testing and demonstration facility approximating on-board conditions.

Contrary to applications on oceangoing ships, space and weight considerations (tank weight) make liquefied gases more or less unviable as fuels for volume-critical vessels such as river cruise ships. Since liquid methanol has been shown to be a suitable alternative to diesel fuel for these kinds of vessels, a compact methanol tank and fuel supply

© MEYER WERFT

Fuel cell cabinet of the demonstrator

system has been developed for space-saving, safe integration on board inland vessels, and implemented in the demonstrator unit. The project was able to demonstrate that compact, double-walled tank systems integrated in the ship structure can be built and maintained with significantly lower effort than gas tank systems. Furthermore, it was demonstrated that on-board tanks can be refurbished for methanol, which means that this fuel is especially well-suited for the urgently needed conversion of the fleet in operation to sustainable fuel systems.

By implementing and trialling the prototype of a ship-ready MFCU fuel cell system, the solution concepts developed in the project were demonstrated to be viable. In particular, the safety concept was validated successfully and its high safety level confirmed. The voluminous operational data collected now form the basis for further development of the MFCU design and the fuel cell modules made by the project partner Advent Technologies. As the development of the MFCU continues, it will be important to focus on further optimising the power density, service life, manufacturing costs and control system. The project aims to increase power output to approximately 100 kW per rack of 2 or 3 modules.

The DC energy system used in the ship simulation demonstrator, comprising the MFCU, storage batteries, and diesel generator power input, was implemented and tested successfully. The interplay between the components of the hybrid system as well as the automation concept were thoroughly trialled in operation simulations applying realistic load profiles. Considering the high complexity of these energy systems, comprehensive automation and operational ergonomics are considered as key factors for successful market introduction.

The project members participating in the CESNI/PT/FC working group in a consultative role were able to contribute lessons learned from the construction and operation of the fuel cells and the methanol tank systems directly to the development of two new chapters of the construction rules for inland vessels (ES-TRIN). This resulted in a major step forward, enabling the requirements for fuel cell installations to be incorporated into the 2023 edition of ES-TRIN. Similarly, the chapter addressing storage of methanol fuel was completed shortly after the end of the project.

© MEYER WERFT

Land demonstrator of the fuel cell system in Rostock

Project partners

DNV, HADAG Seetouristik und Fährdienst, HELM Proman Methanol, MEYER WERFT, NEPTUN WERFT, Pella Sietas, Advent, TU Berlin and Viking Technical

Top left: Christian Allgeier, Claus Brandt, Dr. Martin Kröger, Peter Müller-Baum, Dr. Reinhard Lüken;
With e4ships-Logo: Bingbing Song, Christian Allgeier, Peter Lindlahr, Hermann-Josef Mammes,
Kurt-Christoph von Knobelsdorff, Achim Wehrmann, Dr. Ralf Sören Marquardt, Dr. Christopher Stanik

OUTLOOK

by Peter Lindlahr

You don't have to be a prophet to predict that the attention given to green hydrogen and its derivatives by the media, in politics and in the engineering world will not subside any time soon; on the contrary, it is bound to increase significantly.

Peter Lindlahr
Managing Director hySOLUTIONS GmbH

Whoever is inclined or under pressure to decarbonise must diversify. This diversification not only applies across all modes of traffic, including road, rail, water and air, but also, and especially so, to the questions how to integrate systems, what substances to use and in what physical form.

The e4ships innovation cluster has done valuable foundational work in the areas of regulatory development in the past while simultaneously delivering answers to key questions through specific demonstration projects. This dual structure has proven successful, enabling bountiful cross-stimulation.

The transformation process in the shipping industry has global dimensions. It therefore deserves a lively dialogue between stakeholders at all levels, along with political support and the undivided attention of the civil society. It is not only logical but, in view of the international competition, of critical importance to go beyond discussing the transformation of the shipping industry on the political stage by placing much greater emphasis on budgetary issues and financial support.

Provided that the Federal Government is willing to do so, this might result in a concerted effort, which would require the industry to take the initiative proactively and accept the responsibility to propose concrete application concepts.

This would put the shipping sector in a position to trigger a public-private partnership that could become a model for other industries.

As cluster manager for many years, hySOLUTIONS thanks all project partners for the joint journey, which must now be continued, because the motto „keep the ball rolling" also applies to e4ships: much remains to be done in the field between technological innovation, competitiveness and economic efficiency.

PARTNERS

hy SOLUTIONS
Innovative Antriebe für Hamburg

Leibniz Universität Hannover

LÜRSSEN

MEYER WERFT
PAPENBURG 1795

NEPTUN WERFT
ROSTOCK 1850

Science4Fuels
OWI
an der RWTH Aachen

ROSSWAG
engineering

Schiffswerft
HERMANN BARTHEL GMBH

SER
Schiffselektronik
Rostock
GmbH

sunfire

thyssenkrupp

VIKING

VSM

ZBT

e4ships
Fuel cells in marine applications

nip

e4ships
c/o hySOLUTIONS GmbH
Burchardstraße 21, 20095 Hamburg

info@e4ships.de

www.e4ships.de

September 2022

Funded by:
Federal Ministry for Digital and Transport

Coordinated by:
NOW GMBH.DE

Project management:
ptj Projektträger Jülich Forschungszentrum Jülich