Final report

1.1 Project details

Project title	SOFC mCHP Gamma II
Project identification (program abbrev. and file)	EUDP j.nr. 64010-0053
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Dantherm Power A/S Majsmarken 1 9800 Hobro
Project partners	Topsoe Fuel Cell A/S BSM A/S Kosan Gas A/S
CVR (central business register)	30804996
Date for submission	7/5-2015

1.2 Short description of project objective and results

In the Gamma II project next generation SOFC micro combined heat and power systems has been developed.
The project builds on experience from the Danish Micro Combined Heat and Power project and has been supporting the Phase III demonstration in the Danish Micro Combined Heat and Power project. The core system technology has been optimized and both test bench and real system have been built.
The fuel options were expected to be extending to include bottled LPG making systems independent of the natural gas grid, but with the significant challenges of making the core technology work as expected, the focus was directed to natural gas only during the project.

I SOFC Gamma II projektet er næste generations SOFC mikrokraftvarme system blevet udviklet.
Projektet bygger på erfaringer fra Dansk Mikorkraftvarme projektet og har understøttet Fase III demonstration i Dansk Mikrokraftvarme projektet. Kerneteknologien er blevet optimeret, og såvel testbænk som komplet system er blevet udviklet.
Fra starten var det forventet at brændstofvalget skulle omfatte såvel flaskegas (LPG) som naturgas, men på grund af væsentlige udfordringer med kerneteknologien blev det besluttet at fokusere på naurgas.

1.3 Executive summary

This project will build on results from a number of earlier projects and especially the efforts from Topsoe Fuel Cell were to a large extend offered to this project for free by leveraging on the EUDP project "Fuel cells put to work - market driven solutions for high performance power, J.nr. 64010-0052".

The long term goal was to reduce fuel consumption and lower/avoid CO2 emissions etc by introducing the highly efficient SOFC technology in broader use for generating electricity and heat in private households.

This project has been aiming at continuing the high pace on system development which was been established between the partners of this project based on the DKµCHP project. In order to secure fast progress it is important to prepare the phase IV systems in parallel to the phase III system builds and field trials.

The project has met some of the major milestones, and most of technical challenges that have come up have been solved. Test bench and full CE-marked systems have been developed and deployed, and critical mislestones and deliverables have been met (please refer to annex).

The project results from SOFC Gamma II cannot directly be utilized going forward as the Topsoe Fuel Cell business has been closed down and the availability of SOFC stacks and SOFC PowerCores thereby has stopped.

The learning at a fuel cell system level have been significant, and the full team that was dedicated to SOFC system development at Dantherm Power has been re-deployed to a new business segment.

The learnings from initial research and test using LPG fuel for the Gamma II fuel cell systems has been transferred to PEM fuel cell systems developed by Dantherm Power running on LPG.

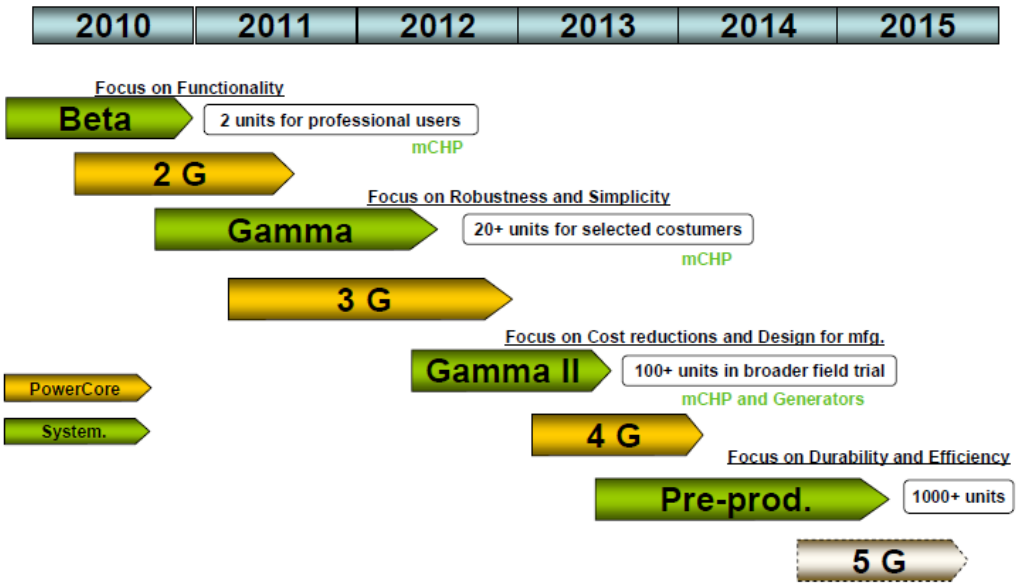
1.4 Project objectives

The partners behind this project, Topsoe Fuel Cell (TOFC), Dantherm Power (DTP), BSM (BSM) and Kosan Gas have a long history of close collaboration and have been working well together in the project. With a number of technical changes in the PowerCore design, it was decided that BSM should no longer do the PowerCore manufacturing for Topsoe, and for that reason BSM ended up as a passive partner in the project. With focus being directed to natural gas, Kosan Gas also ended up as a passive partner in the project, but has continued effort in other projects where LPG is used.

Based on the Gamma field trial systems the focus in this next generation system development has been on:

- reliability
- efficiency,
- robustness,
- potential for cost reductions and
- fuel flexibility to include LPG as a fuel.

The Gamma II project builds on previous system developments, and the project can be seen as part of the roadmap seen on the picture below:



Achieving the objectives was intended to enable the partners to develop the Gamma II series for larger scale field trials. The Gamma II field trial systems supported the Phase III systems and should have been be the starting point for a possible Phase IV of the Danish µCHP project (DKmCHP, EUDP J.nr. 33001/33033-0333).

Specific objectives of each Work Package are found in the table below:

Work Package	**Objectives**
WP1 Test specification	· To define experimental program and establish optimal operation process
	· To identify the general capabilities of the PowerCore 3G
	· To demonstrate extended continuous operation
	· To validate operation on two different fuels
	· To validate operating performance of key system components
	· To demonstrate operation and system response under start-up, power cycling, thermal cycling, and normal and emergency shutdown conditions
WP2 PowerCore 3G activities	· Development of LPG based PowerCore 3G
	· Production of prototype PowerCore units for Gamma II systems
	· Characterization and demonstration of PowerCore 3G for both natural gas and LPG
WP3 Design of Gamma II Test benches and Test systems	· Specify, develop and produce two Test benches and two Test systems for WP4 PowerCore 3G verification
	· Risk assessment - Prepare to fulfil regulatory demands (CE certification)

	· Develop a manual and full automatic control and safety system
	· Enhance robustness, reliability, and lifetime on system- and component level
WP4 PowerCore 3G verification	· Characterization and demonstration of PowerCore 3G for both natural gas and LPG
	· Performance and durability evaluation under different operating and application conditions
WP5 Gamma II target specification	· Develop Gamma II target specification as input for Gamma II systems in DMKV Phase 4
	· PowerCore 3G optimization feedback to TOFC, as preparation for DMKV Phase 4

1.5 Project results and dissemination of results

In this section the results of each Work Package are briefly described. More details can be found in the annex as referred to.

WP1 Test specification

M1.1 Input from Market and Fuel Cell simulation model (DTP)

Dantherm Power has developed a Market and Fuel Cell simulation model a different project. This model has been fitted to the PowerCore S3 design and validated. Various simulations have been run and the outputs from the simulations are completed as input for M1.3. This corresponds to D1.1.

M1.2 PowerCore G3 specifications – Technical specification and operation procedures

TOFC have supplied DTP with a flow sheet calculation, a P&ID of the PowerCore, a general operation overview, a detailed description of how to control and calculate the anode recycle flow for safe operation, complete data sets from PowerCore start-up sequences, full operation and shut down. This corresponds to D1.2 and D2.1.

M1.3 Experimental program including technical specifications and operation procedures

Based on input from the market simulation model, a test specification has been developed for the PowerCore S3 to get a closer understanding of the general capabilities and limits of the unit. This Corresponds to D1.3

Furthermore specification of different LPG (Liquefied Propane Gas) compositions in Europe has been identified and captured to get a better understanding of markets demands and being able to specify the right system capabilities. The sulphur compounds in LPG are of interest, as the reforming catalyst is intolerant to this and will degrade rapidly if not removed before entering the PowerCore.

DTP has received input from Kosan gas on sulphur content in European LPG.

WP2 PowerCore 3G activities

In total more than twenty PowerCores have been manufactured and tested. The PowerCore has gone through a large number of testing programs including long term testing (3 PowerCores have more than 1500h test time), thermal cycles (>25), load cycles (>40), load modulation (20-110%), idle mode operation and more. Operation of the S3 Powercore has been described in details in the reports is Annex D2.1. The PowerCore design has proven to

be robust and operate in a reproducible matter. The PowerCore testing and verification is described in detail in deliverable D2.3. Please refer to Annex D2.3.

WP3 Design of Gamma II test benches and test systems

TOFC performed a two day hazop work shop and supplied the documentation to DTP in the early days of the project as a starting point for system design. After finalizing system design a HAZOP on PowerCore was finished between TOFC and DTP. This corresponds to D3.1. Please refer to Annex D3.1.

PowerCore hardware was delivered to Dantherm Power.

The new Gamma II system was specified and a test bench system was designed.

P&ID was been finalized, all components were specified and the full BoM with all BoP components was purchased.

Control specification was finished and software was developed for the system.

A complete test bench system was built and verified. A PowerCore was installed in the test bench system and was running successfully for 3700 hours without interrupts.

To prepare for long-term testing on LPG, the first steps were taken for a permanent LPG storage tank installation at Dantherm Power including the necessary safety approvals for such installation. This work was stopped when the LPG activities were stopped.

M3.1 Test Bench HAZOP

A full Hazop has been conducted separately for both the test bench and the test systems as the test bench and the systems have a different integration level.

An issue of possible NI(CO)4 formation was analyzed/considered by DTP at an early stage when doing the test bench Hazop, and found to be safe, as the possibility for an eventual formation of NI(CO)4 from CO was low, and if any formation of NI(CO)4 should occur, the volume would be very low and contained in the piping, exhaust system and system enclosure, and eventual ventilated to the outside. Furthermore NI(CO)4 has a very low auto ignition temperature (60°C) and a very fast degradation rate at ambient temperature (below 60 sec), and though NI(CO)4 is extremely toxic, the hazard and risk was considered very low.

TOFC later finalized the Hazop, which conformed to the assumptions made when doing the test bench Hazop.

By the end of 2013, after finalizing the system Hazop, system and control design, programming, documen-tation and most of the system/programming debugging/FAT testing, TOFC raised the issue and concern of NI(CO)4 on the field test systems.

The outcome of TOFC's concern was of cause a reviewed Hazop. A steam purge procedure at shutdown was added. After heavy discussion concerning abnormal shutdown, a safety warning system in the event of abnormal shutdown or power outage was agreed upon. This is supported by a safety handling procedure if a safety warning is released for system attention.

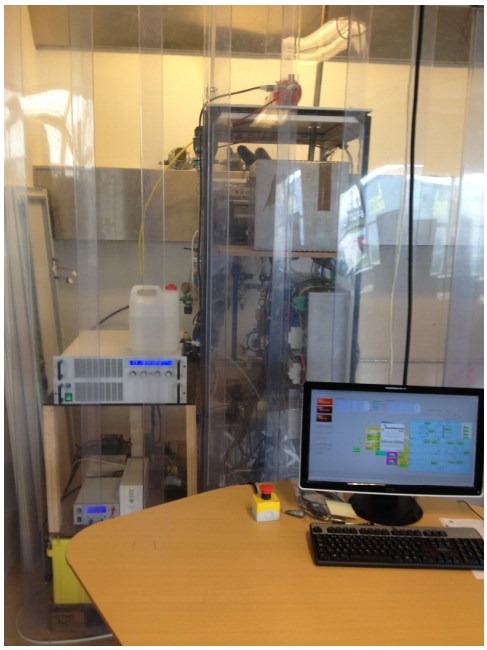
It must be emphasized that the safety warning system "fix", was (by Dantherm) only considered as temporary solution to get the system installed in field test within time. The proper and correct solution would be to add a catalytic mesh to the location on the stack enclosure in the PowerCore where it leaks.

M3.2 PowerCore 3G hardware delivery

Hazop on test bench was finalized as milestone M3.1.

A first PowerCore was delivered to DTP by TOFC. This corresponds to D3.2

A test bench was built for testing S3 PowerCore, controls and system components.



Test Bench System at Dantherm Power

Technical dossier has been built to support the unattended 24-7 operation of the test bench system in Dantherm Lab.

Running the test bench with PowerCore P149 showed that CO emission slipped over time as seen on the former S2 PowerCore, and a temporary solution with a post catalyst also needed to be fitted to the S3 PowerCore.

The PowerCore ran for 3700 hours and 15 thermal cycles in the Dantherm Power test bench system.

M3.3 PowerCore 3G hardware delivery

Updated 3G PowerCore, version 1.8 with new stack enclosure and insulation was delivered for heat management and air flow testing in the Dantherm Power test bench system in June 2013. The PowerCore had been used for testing at TOFC and was close to end of life. Results from former version 1.7 were re-produced except of heat recovery in cathode heat exchanger. This gave rise to an optimization using a by-pass valve on cathode air.

The 3G PowerCore version 1.8 for system integration was delivered in September 2013. D3.3 completed.

D 3.4 Finalized, report attached in Annex D3.4

Three test systems has been designed, build, FAT tested and CE marked/approved.

Technical dossier has been built to support the CE marking.

One test system was installed and running in Dantherm lab.

Test system for Dantherm Power Lab.
Picture from CE-testing at DGC.

Two test systems were built under the "Dansk Mikrokraftvarme" project and tested in two installations.

Installation: Kellberg VVS *Rideskole*

WP4 PowerCore 3G verification

PowerCore 3G has been verified with good results. Report is attached as part of M4.3 – please see below.

M4.1 Validation and mapping of the PowerCore 3G Natural Gas

The PowerCore 3G has been validated and mapped in the Dantherm Power test bench system running on natural gas, and results of the testing were positive. A durability test was initiated and with a 3700 hour operation period with 15 thermal cycles the results looks promising. The test data are collected in M4.3.

The new updated PowerCore ver1.8 has been tested in the Dantherm Power bench test system for thermal integration, and a new by-pass cathode air supply will be implemented to mitigate possible challenges on air temperature.

M4.2 Validation and mapping of the PowerCore 3G LPG

Due to the challenges in on PowerCore development for LPG (D2.5), the LPG PowerCore has not been validated and mapped.

M4.3 PowerCore 3G testing report natural gas

The PowerCore 3G test bench system test results are attached in Annex D4.1.

M4.4 PowerCore 3G testing report LPG

Due to the challenges in on PowerCore development for LPG (D2.5), the LPG PowerCore has not been tested.

WP5 Gamma II target specification

Test results from WP4 have been used to define the target specifications for the Gamma II systems.

M5.1 Gamma II target specification

The Gamma II target specifications have been continuously updated. With technical challenges on the core technology, the specification has been an iterative process between the possible technical solutions and the market needs. This has been be an ongoing task in the project.

Data on LPG gas composition from relevant European countries has been collected, and the relevant certification requirements have been determined as part of the requirements specification.

M5.2 PowerCore 3G optimization specification

This activities behind optimization of the PowerCore 3G have been ongoing since first test in the Dantherm Power bench test system as reported in under previous WP's above.

WP6 Commercial milestones

M6.2 Deployment of DKmCHP Phase III systems

It was decided to use the Gamma II 3G PowerCores for the DKmCHP demonstration in order to have the latest and most robust technology going in to the demonstration. The new stack module was integrated in a PowerCore and demonstrated in the systems in the "Dansk Mikrokraftvarme" project.

TOFC changed their strategic focus towards large CHP systems, hence no agreement was signed between the different partners in the project, and eventually Topsoe Fuel Cell was shut down shortly before the project was finalized.

Dissemination

Dissemination of results have been limited to sharing with other partners in the Danish fuel cell industry, as broader dissemination initiatives were not taken further after shutting down Topsoe Fuel Cell.

1.6 Utilization of project results

The project results from SOFC Gamma II cannot directly be utilized going forward as the Topsoe Fuel Cell business has been closed down and the availability of SOFC stacks and SOFC PowerCores thereby has stopped.
The learning at a fuel cell system level have been significant, and the full team that was dedicated to SOFC system development at Dantherm Power has been re-deployed to a new business segment where the PEM fuel cell technology for Fork Lift Trucks etc from H2Logic in Herning is being taken on towards it's early market by Dantherm Power.
The learnings from initial research and test using LPG fuel for the Gamma II fuel cell systems has been transferred to PEM fuel cell systems developed by Dantherm Power running on LPG. As such all the LPG knowledge built in this project is helping out in other activities, which are are partly supported by EUDP in the projects USDan and Simba.

1.7 Project conclusion and perspective

The SOFC Gamma II project was severely hurt by several delays on SOFC Hotbox developments and results. As such the project was re-defined twice and ambitions were reduced to make sure that the basic concept was functional and proven before taking on more challenges.
After fairly successful demonstration of complete SOFC system in 2012 with 2000 hours of successful runtime the project was looking promising, but withmore challenges on the following generation of PowerCores and the decision by Topsoe to shut down Topsoe Fuel Cells in the summer of 2014, the project suffered further. Dantherm Power decided to finalize the project and get the best possible outcome to capture the full learnings and to support the final demonstration of SOFC systems in the project "Dansk Mikorkraftvarme".
The perspectives of directly utilizing the resultsof this project going forward are vague as the core component – the PowerCore – is no longer available.
Dantherm Power is continuously monitoring progress within SOFC development, and can, if a breakthrough is seen with other developers of SOFC technology, quickly jump on to continuing the system development efforts.
Until then the learnings are used for Fork Lift Truck Fuel Cell Systems and for LPG driven PEM Fuel Cell Systems.

Annex

1 Milestones and Deliverables

D2.1 PowerCore G3 technical specifications on NG and operation procedures (TOFC)

D2.3 PowerCore 3G testing report natural gas (TOFC)

D2.5 PowerCore 3G testing report alternative fuel (TOFC)

D3.1 PowerCore G3 Hazop (TOFC)

D3.4 N-Gas Testbench (DTO)

D4.1 Reporting_Validation and Mapping of 3G PwC_S3