PROJECT FINAL REPORT

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1 Executive summary

On 1st January 2012, the research project DESTA started under the coordination of AVL List GmbH. The main project objective of the project was the demonstration of the first European Solid Oxide Fuel Cell (SOFC) Auxiliary Power Unit (APU) on board of a heavy duty truck. By gathering the project partners Eberspächer Climate Control Systems GmbH & Co. KG (Germany), AVL List GmbH (Austria), Volvo Group Trucks Technology (Sweden), Topsoe Fuel Cell (Denmark) and Forschungszentrum Jülich (Germany) into one consortium, a 100 % European value chain for a SOFC APU was established. With the aim to reduce pollutant emissions, noise and production costs, the end product shall have excellent export opportunities, creating new job opportunities in the field of high- & clean technology in Europe.

Figure 1: DESTA SOFC APU

From the start of the project detailed requirements for APU in a US type heavy duty truck were defined. In parallel a total of 6 APU systems were tested intensively by Eberspächer and AVL. In this laboratory testing process, total operating hours above 2,000 hours, electrical efficiencies of up to 30 % and operation on conventional road diesel (ULSD) were demonstrated. Based on the test results, the Eberspächer APU was selected for the truck integration. In a parallel exercise TOFC focused on testing of SOFC stacks towards thermal cycle-ability, sulfur tolerance and long term operation. Impressing results have been achieved especially towards thermal cycling with a power degradation of 1.5 % over 90 aggressive heat up cycles.

To prepare the truck integration Volvo designed the truck interfaces regarding mechanical, electrical and functional integration. A suitable DC/DC converter was developed to integrate the APU into the electrical grid of the truck. Major efforts were undertaken to develop the control software for operation of the APU within the truck system. Finally the Eberspächer APU was integrated and successfully tested within the truck environment. The truck was tested through regular operating according to US truck usage profiles including driving and idling periods. The truck and integrated APU went through a real life testing cycle including driving and stopping periods through day and night. More than 2,000 km of driving and 50 hours of APU power production during parking were demonstrated.

The final event of the DESTA project was held at Volvo Truck in Gothenburg on 9th of June 2015, assembling the entire project consortium and a representative from the Fuel Cells and Hydrogen Joint Undertaking. At this event, the 1st European SOFC Truck APU was successfully demonstrated. With the electrical net power class of 3 kW, the diesel-operated SOFC APU on board of a heavy-duty truck had its world premiere. The project was finished on June 30th 2015 and has reached every major project target.

Figure 2: Heavy duty truck with integrated DESTA SOFC APU

The SOFC APU technology developed within the project definitely shows great potential to reduce anti-idling pollutant emissions and costs for fuel consumption of heavy duty trucks. The technology furthermore improves the driver's comfort and has a positive impact on the surrounding environment due to a dramatic reduction of noise. A detailed cost analysis has also shown economic potential, however further measures have to be undertaken to bring this technology into the marketplace.

2 Project context and objectives

Idling of heavy duty trucks is a major concern within the industry. Typical US heavy duty trucks are idled up to 8 hrs per day especially during over-night stays on parking lots. During these breaks the driver consumes electric energy for various comfort functions like A/C, radio, TV & micro oven. Today this power demand is provided by idling of the main engine or by conventional engine based APU systems. Both solutions are not very efficient, emit a significant amount of emissions and produce major noise. Also from an economic point of view, idling - especially with the main engine - is quite expensive due to an idling fuel consumption of around 2.5-3 l/h. Due to the raising concerns various US states (Figure 3) have implemented idling regulations which more or less prohibit or at least limit idling of engines. At the moment a complete US wide idling ban is under discussion, which would significantly boost the sales of anti-idling solutions. Based on all these boundary conditions, AVL and Eberspächer, who already decided years ago to develop SOFC based APU systems for heavy duty trucks, teamed up in the DESTA project to accelerate the development of SOFC APU systems.

Motivation for SOFC based APU systems:

- Anti-idling regulations
- Fuel cost savings
- CO2 credits
- low noise
- 5 min idling ban

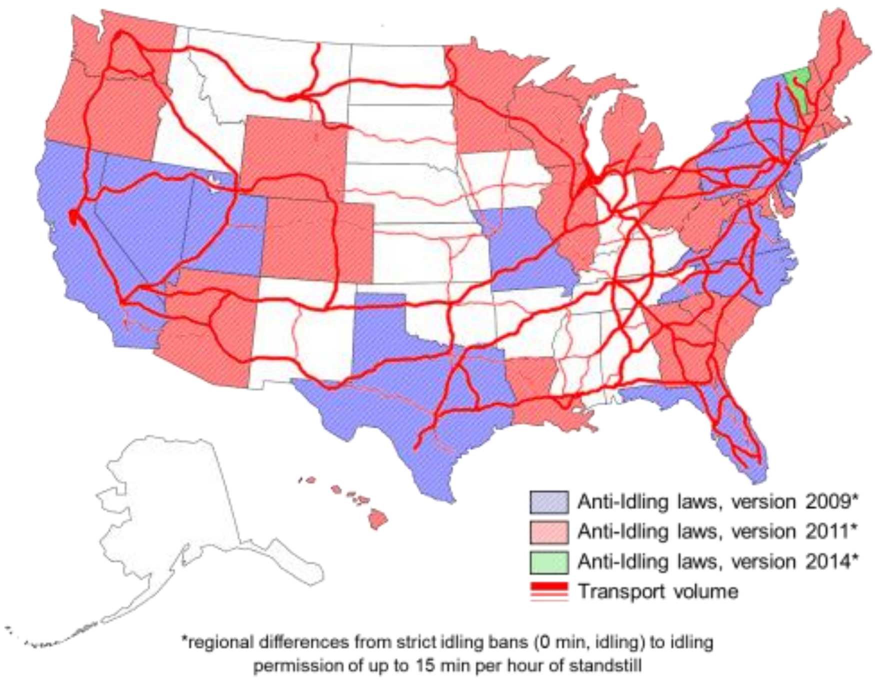

Figure 3: States with Anti-Idling regulations

Components of SOFC APU:

- **Reformer:** Synthesis of hydrogen-rich fuel out of diesel and ambient air (CPOX)
- **SOFC-Stack:** Electrochemical conversion of syngas and air
- **Off-gas Burner:** Conversion of unused fuel gas, reduction of emissions
- **Start-up burner:** Careful heating-up of the system

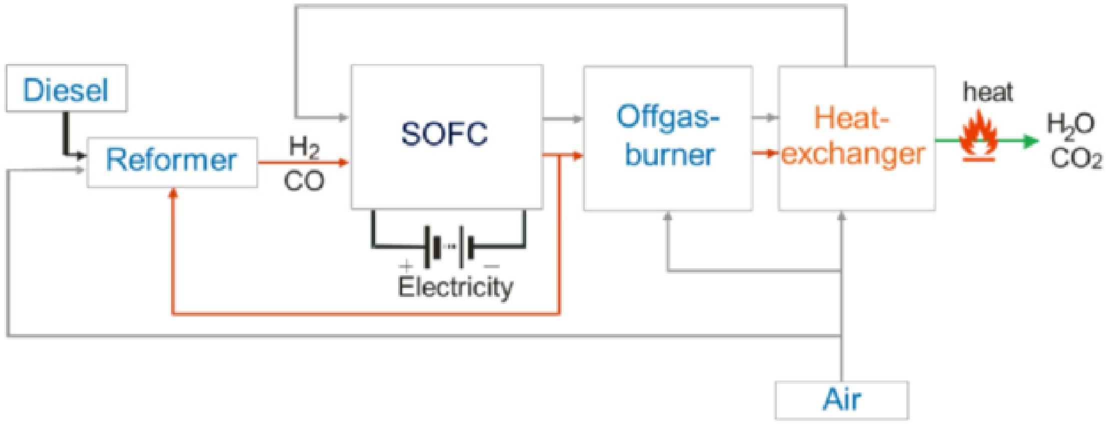

Figure 4: System Approach

The main objectives of the DESTA project were:

- ➔ 1 year thorough testing of SOFC APU prototypes from AVL and Eberspächer
- ➔ Development and assembly of the final DESTA SOFC APU system, merging the most promising approaches of AVL and Eberspächer SOFC APU concepts
- ➔ Off-vehicle tests of the final DESTA SOFC APU system regarding durability as well as reliability assessment under harsh operating conditions (e.g. vibration, salt spray)
- ➔ Long-term accelerated test of the final DESTA SOFC APU systems to assess the lifetime potential
- ➔ Truck integration and demonstration of a DESTA SOFC APU system on-board of a Volvo US type heavy duty truck

The project also defined very detailed technical objectives for APU systems to be demonstrated within the DESTA project:

- Maximum electrical power ≥ 3 kW
- Operation on conventional road diesel fuel (< 15 ppm S)
- Long-term tests: ~ 300 thermal cycles and ~ 3,000 operating hours
- System electrical net efficiency around 35 %
- System volume and weight below 150 l and 120 kg
- CO2 reduction of 75 % compared to engine idling of a heavy-duty truck
- Start-up time of ~ 30 min
- Noise level ~ 65 dB(A)
- Completely functional truck integration

3 Main scientific and technical results and foregrounds

3.1 Work Package 1: System Requirements & Test Conditions

The aim of WP1 was to identify the performance and design targets for the fuel cell based Auxiliary Power Unit (FC-APU) in an early phase of the project. The main aims were:

- Definition of complete vehicle integration specification.
- APU system testing requirements

The vehicle type is defined as a “Volvo VN” truck, which is the truck manufactured in US for the US and Mexico market. VN is short for “Volvo Normal” also called “Conventional cab” which is a truck with the cab positioned behind the engine, compared to the “cab-over-engine” type which is the most common in Europe.

Also the type of truck is defined as a “Tractor 6 *4”. The “Tractor” type truck is a truck designed to pull semi-trailers and is common for long hauler transports in the US. The “6*4” is short for 6 wheels thereof 4 driving. The nominal voltage of the electrical system in a US truck is 12 Volts (in comparison to 24 V in Europe). The test vehicle in the DESTA project shall have a 12 V system to represent the US-market.

The cab version is defined as a “sleeper cab version” since that type of cab is used for long-hauler transports. The sleeper cab is often equipped with one or two beds for the driver(s) and other electrical equipment that facilitates the life on the road.

The requirements for an SOFC-APU for vehicle integration has been developed by Volvo and in cooperation with the other partners - adapted to a suitable level for the DESTA project.

The FC-APU mounting position has been defined to be on the frame-rail beside fuel tank. The maximum dimensions for the FC-APU have been decided together with the partners. The maximum APU system mass has also been agreed to not exceed 150 kg. Requirements on air intake, fuel intake and exhaust have also been defined.

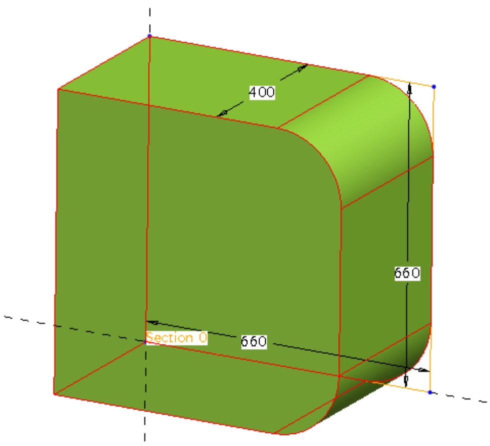

Figure 5: Maximum APU dimensions

Power requirements of the APU system have been defined. The maximum net power output has been set to 3 kW. Typical load profiles for a US truck driving mission when the driver lives in the cab has been assembled containing power consumption for different activities based on seasons.

The electrical APU system power architecture has been defined, using the vehicle DC/DC converter as a battery charger and the vehicle batteries as a power buffer and peak-load power provider.

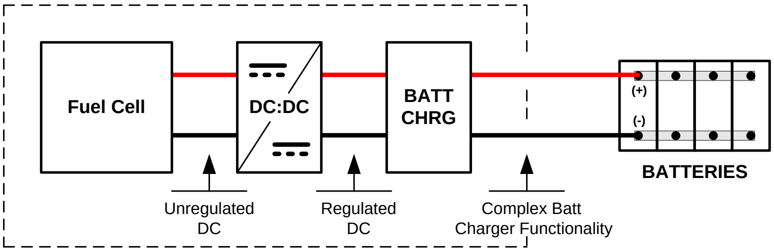

Figure 6: APU to vehicle power flow

The diesel to be used in the vehicle demonstration is of US type containing 15 ppm sulfur; ASTM D975, Grade No.2-D, S15.

The environmental requirements for the APU on a vehicle have also been described containing, e.g. operation temperatures, storage temperatures, humidity, altitude, thermal shock and sealing. The APU system is to withstand exposure to vibrations typical for a long distance smooth profile.

Operational requirements have also been addressed. e.g. requirements for noise level, EMC and maximum surface temperature has been stated and agreed.

Safety requirements have also been defined, such as emergency shut-down, internal shut-down mechanisms, galvanic isolation, personal safety etc.

In addition to the system requirements a test plan for the DESTA project has been developed by all partners with the purpose to verify requirements as well as ensure the functionality and performance of components and sub systems prior to vehicle integration.

A test matrix containing 95 tests in total covering sub-system, system and vehicle level has been defined. Responsibilities for all tests have been assigned to the project partners and corresponding work package.

A test plan for the APU benchmark test has been developed and agreed on by all partners. The benchmark test plan consists of three sections describing initial tests, load cycle tests and theoretical study. The report also specifies the evaluation criterion and corresponding points for evaluation.

The initial test section describes tests for start-up times, electrical start-up energy, start-up fuel, maximum/minimum electrical output power, rise/fall times and efficiency.

For the load cycle tests a load profile based on a typical power usage for a US truck during a summer time long-haul mission from the requirements report has been developed. The load profile represents a typical 5 days work week and shall be used during the load cycle test phase in the benchmark test.

The load cycle section describes tests for load cycle, lifetime, load following and efficiency.

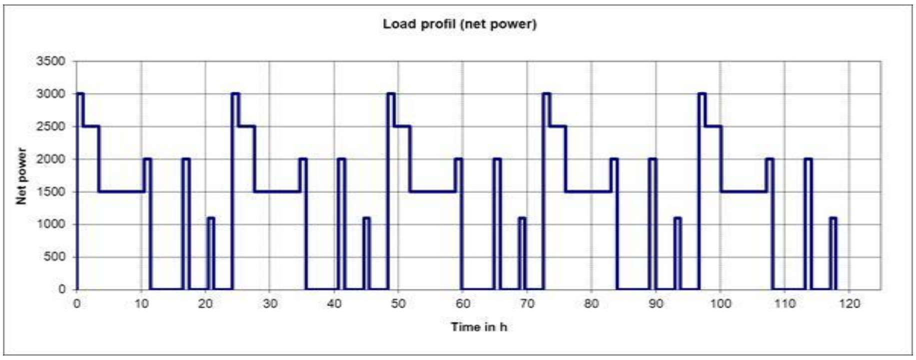

Figure 7: Load profile for load cycle test

The last part of the benchmark plan describes tests for packaging (APU dimensions) and APU weight and how those shall be compared.

The purpose of the test on an APU level is to make sure the APU is ready for vehicle integration. The basic functionality tests cover tests for e.g. start-up, load/thermo cycling, max output power, efficiency and lifetime. Electrical tests are also defined to ensure compatibility with the demonstration vehicle, including e.g. power supply, EMC, power consumption etc.

The environmental tests ensure that the APU will stand the environmental exposure during the on-vehicle tests, including tests for altitude, vibration, salt spray, noise, surface/exhaust temperature and emissions.

Additionally the mass and volume of the truck demonstrator APU were checked and a number of safety tests were performed.

The on-vehicle tests will address functionality as well as performance of the complete and integrated APU system. The basic functionality tests will cover the different operation modes and verify the functionality of the system prior to more intricate tests. A number of static tests will verify requirement fulfilment regarding noise, output power, surface temperature and CO_2 emissions.

A number of vehicle scenarios was tested to ensure compatibility of the APU system with the vehicle electrical system.

A driving mission schedule has also been defined in which the vehicle was operated in realistic conditions using the APU system for auxiliary power. The performance of the system will be measured to verify requirement fulfilment.

3.2 Work Package 2: SOFC-APU Benchmark

The goal of WP2 was to build up and test six SOFC APU systems, three from CCES and three from AVL. The test results of these six APU systems were benchmarked and afterwards the better APU system concept was identified, based on jointly elaborated assessment criteria. For both APU concepts industrialization studies should have been performed.

Eberspächer APU Testing

In the project DESTA, a new fuel cell laboratory was necessary, in which it was possible to operate maximum four fuel cell systems. As the company Eberspächer was planning some reorganization in combination with movements from one facility to another, a flexible and mobile kind of laboratory was foreseen, as shown in Figure 8.

Figure 8: New laboratory for fuel cell systems (Eberspächer)

Three SOFC APUs with start-up burner, reformer, off- gas burner, heat exchanger, stack, media supply, control unit and sensors in the form of an autonomous system were built. Basic tests were executed.

One-stack system:

In May 2012 the first autarkic system with one TOFC-stack was built up at Eberspächer. A picture of this system is shown in Figure 9.

Figure 9: First Eberspächer APU

In the first test an electrical gross power of 1.8 kW and an electrical net power of 1.6 kW at a reformer input of 6.6 kW were achieved. This corresponds to an efficiency of 24 %. The system output at a certain reformer power is shown in Figure 10. The system had successfully completed 8 cycles with ShellSol and 22 with US Diesel of ASTM-standard.

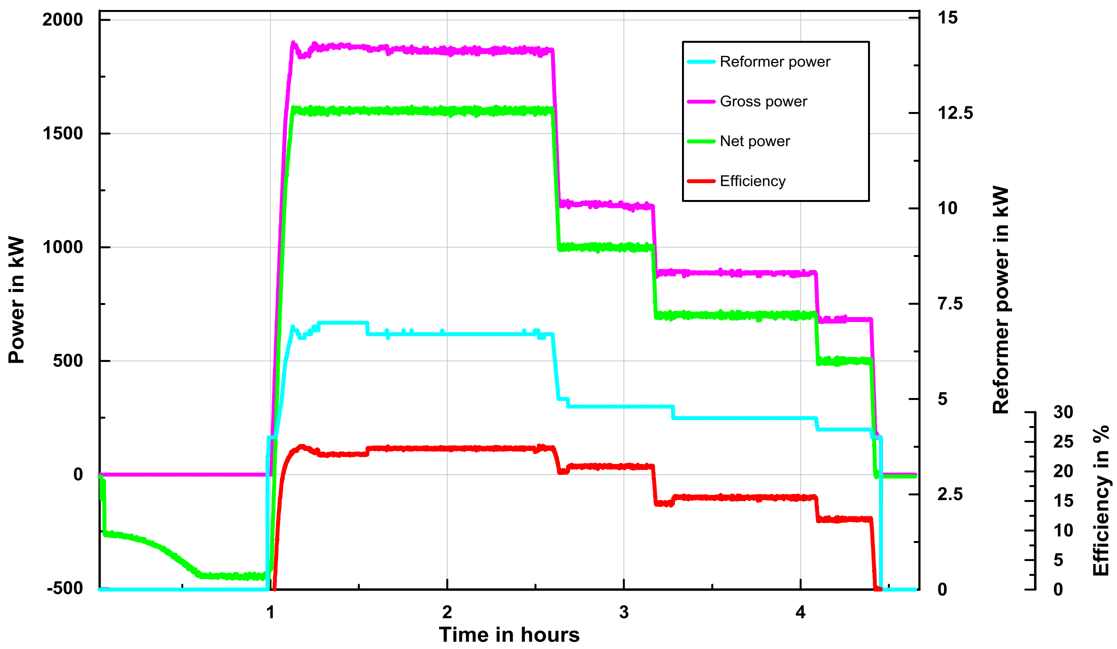

Figure 10: Reformer power vs. electrical power (net and gross)

In Figure 11 the best operation point of the one-stack system is shown. Additionally the system was operated with a diesel input of 8, 6.2 and 5 kW. The net power amounts to 1.7, 1.2 and 0.8 kW.

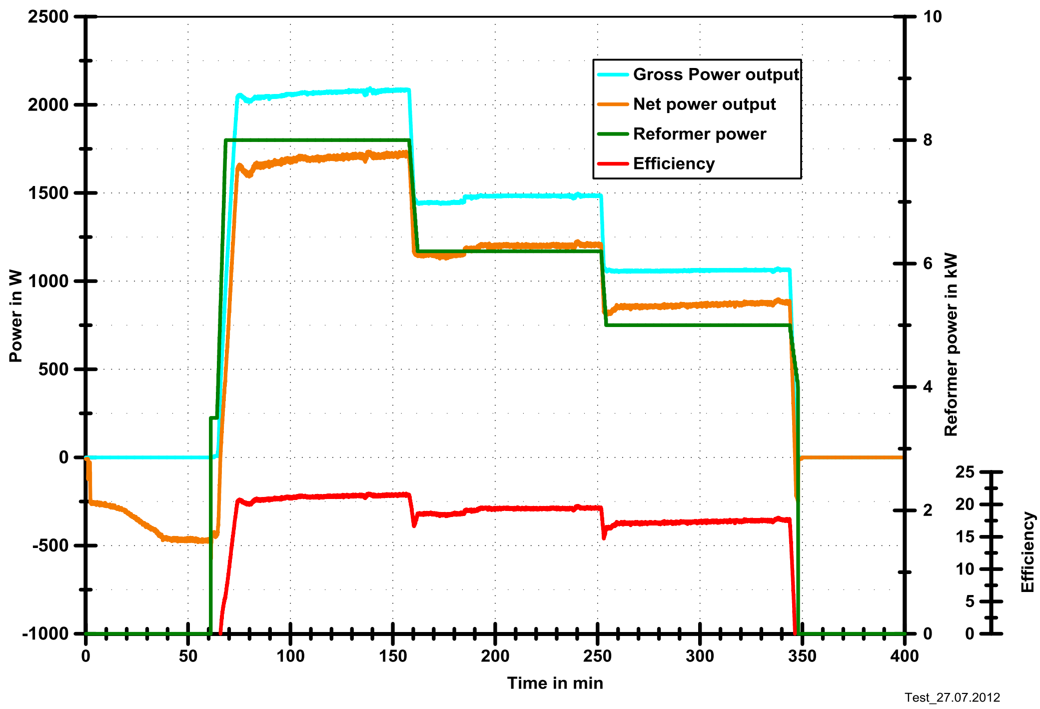

Figure 11: First results of Eberspächer APU

Two-stack system:

In WP1 it was determined that the SOFC APUs shall achieve an electrical net power of 3 kW. This led to the need for two stacks per system, which required design changes to integrate a manifold with the two stacks mounted in a boxer configuration. Hence it was necessary to develop a new stack module with a new isolation box. This also included a modification of the adapter plate. After the modification was conducted, the first system with two stacks could be operated in January 2013 for the first time.

The first two-stack system is shown in Figure 12 and Figure 13.

Figure 12: First Two-Stack system (left side)

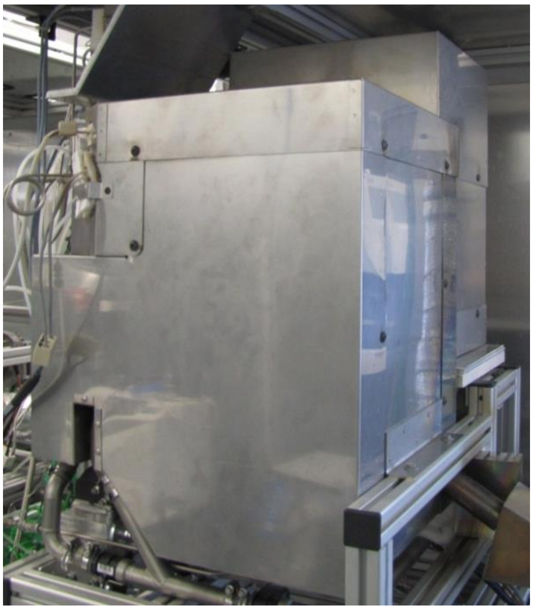

Figure 13: First Two-Stack system (right side)

The first tests of the two-stack system were performed with dummy stacks, like with the one-stack system before. The heating-up of two stacks is slightly different to the system with one stack. This resulted some changes in the control strategy.

The initial operation of the system with active stacks was done with support by two engineers of TOFC. The sulfur tolerance of the stacks was further enhanced and for that reason the tests could be done with US Diesel (ASTM D975) right from the beginning. The control strategy and automated operation was optimized for the first two-stack system.

After the successful operation the third two-stack system was built up until beginning of May 2013. The original system with one stack could be rebuilt for the operation with two stacks. On the one hand the system modification led to the fact that it could be rebuilt very fast to a two-stack system, but on the other hand unfortunately the volume requirement of Volvo could not be met.

Hence this system could not be integrated into the Volvo truck and it had to be redesigned in order to fit in the space available. The benchmark tests were then performed with three new designed systems. During the whole testing period an active data exchange and knowledge transfer between Eberspächer and TOFC led to the development of operating strategies and systems improvements.

AVL APU Testing

Test of 1-stack systems

The one-stack system was mainly used for implementing the two DESTA test cycles into the software and to get experience with functionalities like EAP (electronic anode oxidation protection) or power consumption measurement. For this initial phase sulfur free diesel fuel was used, as sulfur tolerant stacks were only introduced at a later stage of the project by TOFC.

Figure 14: AVL one-stack system on new test rig

Subsequently the fuel was changed to the ASTM D975 in order to check the sulfur resistance of the stack and the whole system. The stack used in this system was R-019. Figure 14 shows the system on the new APU test rig.

Figure 15 shows an initial test with the one-stack system. The heat up in this test was performed quite slowly, with only 50 % load of the startup burner. The maximum load point for this system was set at 2 kW for long term operation. For short periods it is possible to get up to 2.5 kW with one stack. The maximum power after heat up was held for 3.5 h instead of 0.5 h to check the temperature profile during stationary conditions.

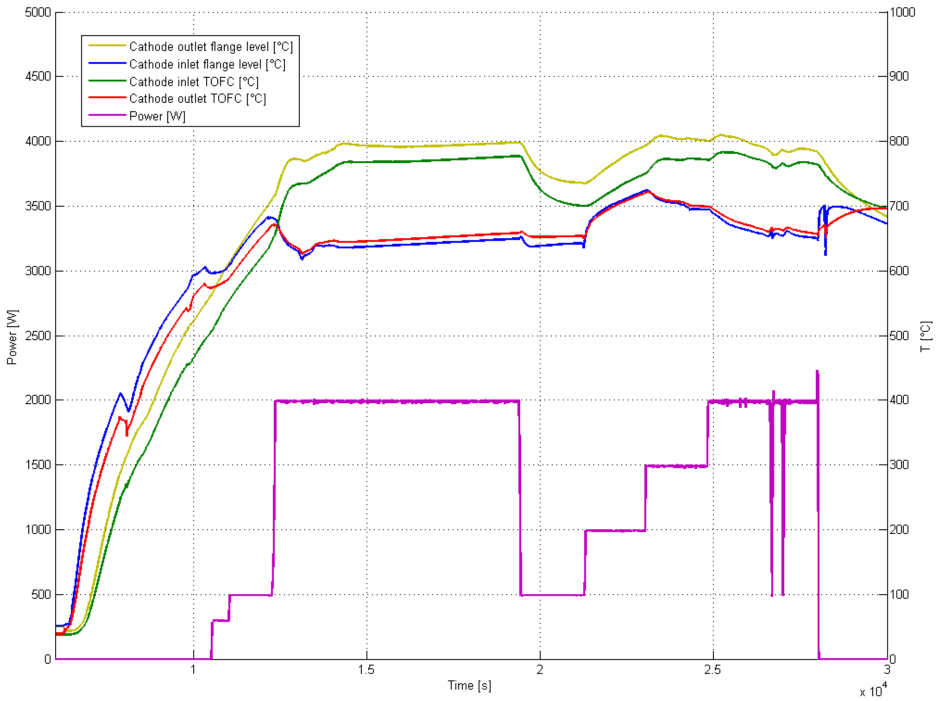

Figure 15: Initial test results with APU one-stack system

At the 2.2 kW_{gross} operation point (Figure 16) the internal power consumption of the system was around 400W with a fuel consumption of 6.4 $kW_{thermal}$ the electrical efficiency is around 28 %. The graph in Figure 16 shows the measurement data from the first test with the one-stack system. At this time, the load change rate was very low e.g. the change from 0.5 kW to 1 kW lasted around 1.75 min and the change from 1 kW to 1.5 kW lasted 3 min. After some tests and work on the controller side it was possible to decrease the load change rate to a few seconds as shown in the figure below. A good dynamic performance of the system depends mainly on the fuel supply on the anode side and has a slightly negative effect on the system efficiency, but not on the stack life time or the life time of all other components.

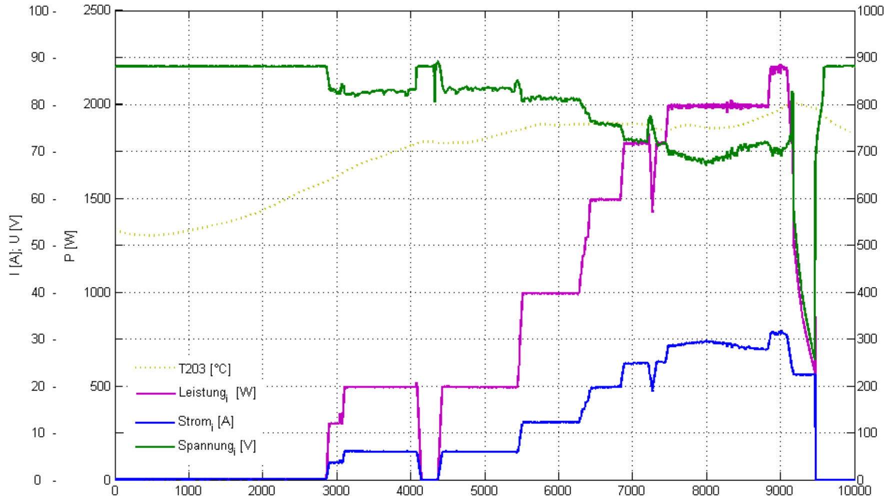

Figure 16: First test with the one-stack system up to 2.2 kW

In parallel to the re-design of the AVL APU system for two-stack integration, AVL has performed various tests with two one-stack APU systems. These two APU systems were based on the original DESTA GenII system design, but equipped with only one TOFC stack.

Load cycle tests of the complete stand-alone APU system were the focus of these tests. The APU system (Figure 17) was integrated with the developed power electronic unit (described above) and vehicle batteries to simulate real operation in heavy duty trucks. All APU consumers (blowers, valves,..) were also supplied via DC/DC converters from the battery bank.

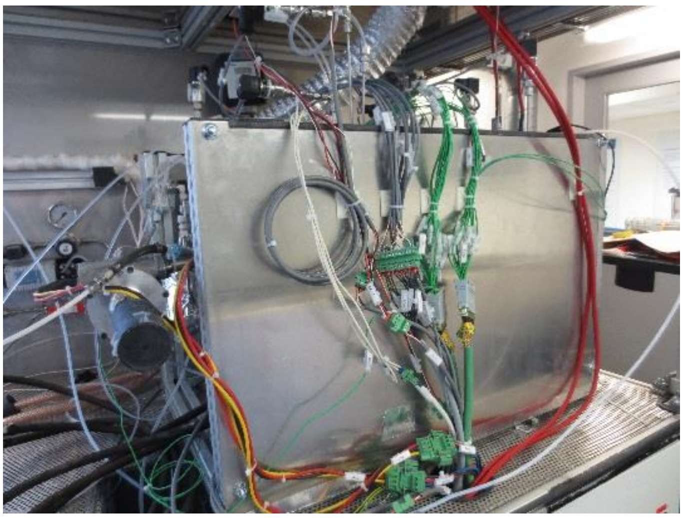

Figure 17: 1-stack APU system on the test rig

One exemplary complete load cycle test is shown in Figure 18. This test was performed with ULSD on an AVL APU test rig. The test consists of three phases, the start-up of the APU system, the operation/battery SOFC control and the shut-down. During the start-up phase, energy is consumed from the battery as can be seen from declining battery SOC (state-of-charge) in the beginning of this test. After two hours the APU system starts to produce electric energy and charges the battery. During operating hours 3-5 a typical load profile is applied to the battery by an external electrical load. During this timeframe the APU system provides the electrical energy to keep a constant SOC level of the battery. After five operating hours the external loads are stopped and the APU recharges the battery. After eight hours this test is stopped and the APU system is cooled down. In this test an active cool down has been applied, where the system is actively cooled by the air compressor, which can also be seen from the consumed electrical energy during the cool-down process. After 2 hours of cool-down the stack temperature falls below 200°C.

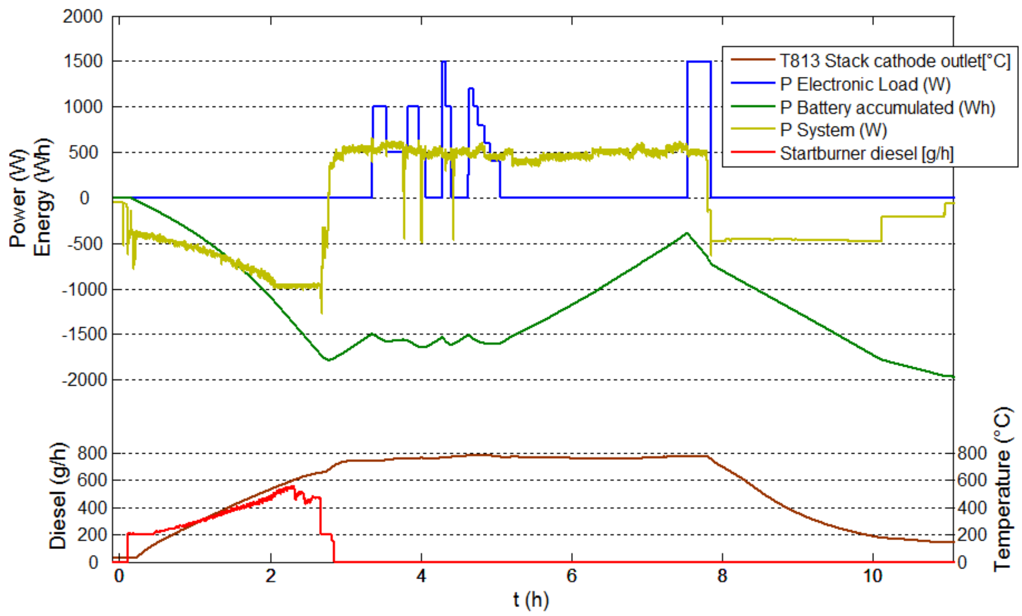

Figure 18: APU Load cycle test I

A detailed energy analysis of the complete load cycle shows a total electrical efficiency of around 24 %. The APU net electrical efficiency during operation was in the range of 28-34 %. The difference comes from the energy required for start-up and shut-down, which are included in the energy analysis. Additionally also the efficiency of the power electronics and battery lower the overall energy efficiency.

Test of 2 stack systems

During the first project period, a second stack has been integrated into the AVL APU system design to comply with the output power requirement of 3 kW. The AVL APU design (Figure 19) is based on three parts, the gas supply on top, the gas processing unit (containing reformer, afterburner & start-up burner) in the middle and the stack module on the lower part. The system is completely integrated to reach a high power density. The original design of the system was intended for integration of one stack and the AVL strategy for power upgrade has been to use one stack with a larger cell footprint. Due to decisions by TOFC an upscale of cell size was not possible and the chosen strategy for upscaling was the installation of a 2[nd] stack.

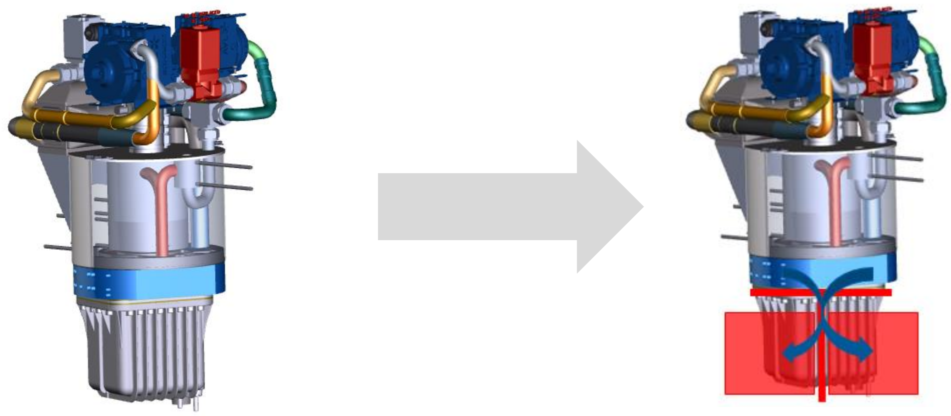

Figure 19: Integration approach of a second stack into the AVL APU system

AVL has built-up and tested one two-stack system based on the design shown above. During the commissioning of the system, various problems were identified: damages of the TOFC stacks (current collectors), impropriate sealing material and in general insufficient leak tightness of the stack/system interface. To solve all issues stacks have been partially repaired by TOFC, another sealing material has been applied and design changes of the stack/system interface have been performed. After these changes system operation was possible and as can be seen in Figure 20, 2.5 kW power output from the stacks has been reached.

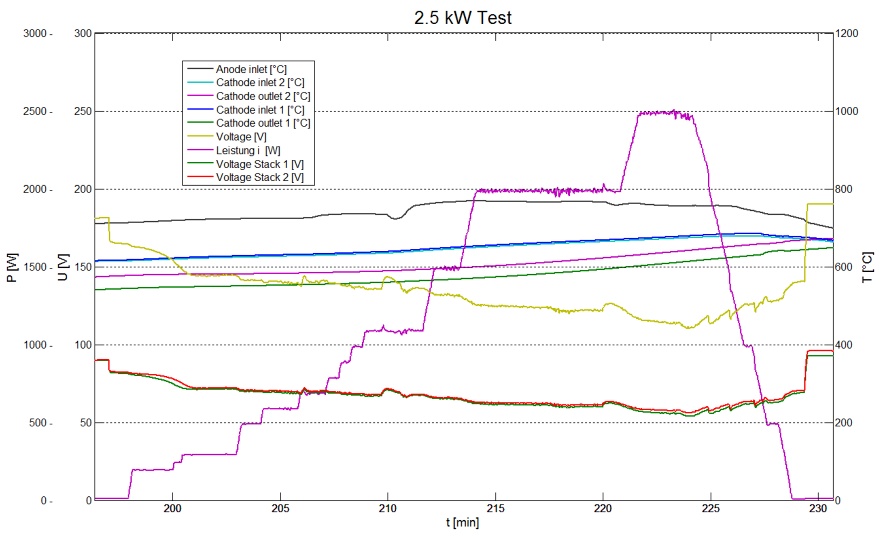

Figure 20: 2-Stack APU System test

Nevertheless this test had to be stopped as still a significant internal gas leakage has been experienced at the stack/system interface. This gas leakage allowed a small gas flow from anode to cathode side, which significantly influenced the performance.

Based on this test and further unsuccessful improvement measures AVL unfortunately had to conclude that the integration of a second stack into the AVL APU system was not possible in the current design. All performed intensive troubleshooting activities after M18 were unsuccessful. The major issues preventing a successful integration were:

- Sealing problems
- Pressure drops due to various gas redirections
- Mechanical fixation
- Integration of heat exchange into complex interface

In addition to the technical problems TOFC announced in mid of 2014 the closure of the company. Due to only one remaining stack pair, the non-availability of additional stacks from TOFC (even based on purchases) and the technical issues, AVL made the decision to stop troubleshooting with the two-stack TOFC system and investigate alternative stack suppliers. Based on this decision a new APU system platform has been designed with the following features:

- An open stack interface, to integrate stacks from various suppliers
- Massively reduced pressure drops to improve system efficiency
- Reduced volume & weight
- Reduced manufacturing cost and improved manufacturability

Within DESTA one additional APU system including TOFC stacks has been built up and assembled on an AVL test rig.

Figure 21: Re-Designed two-stack APU system during assembly

AVL still had one remaining stack pair from TOFC/HTAS available and these stacks were installed into the system. The complete APU system on the test rig can be seen in Figure 22.

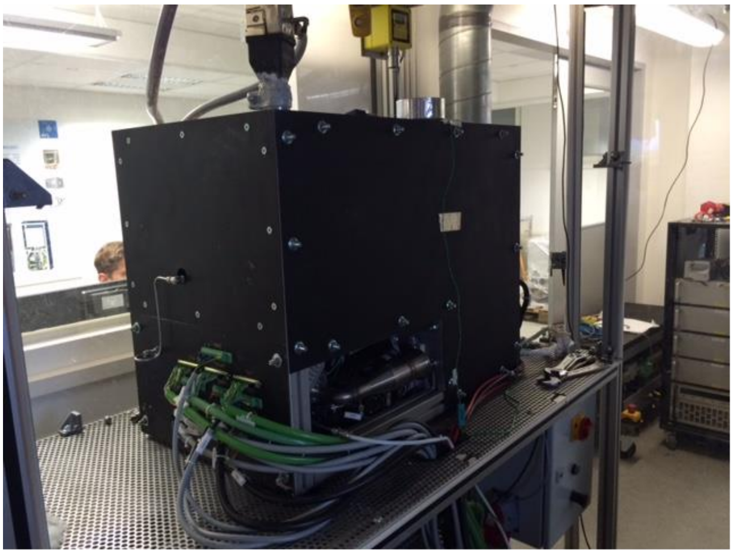

Figure 22: Re-design two-stack APU system on AVL test rig

The first tests of this new APU system haven't been finished within DESTA and were still ongoing at the end of the project.

Benchmark between the two systems from Eberspächer and AVL

At the end of the year 2012, test definitions for benchmark tests were determined together with Volvo, AVL, TOFC and Forschungszentrum Jülich in WP1. After the main criteria and their weighting for the benchmark were determined by Volvo, the necessary tests as well as a score system were defined by Forschungszentrum Jülich, AVL and Eberspächer.

The benchmark test consisted of a test part and a study part. Within the test part a total of three independent test campaigns had to be performed by AVL and Eberspächer (3 x AVL, 3 x Eberspächer).

Each test campaign was divided into two different test procedures, an initial test and a load cycle test. A new test campaign started, when stacks or reformers were changed. In the middle of May 2013 AVL suggested to extend the WP2 testing phase for 2 months till end of August 2013 because of technical problems.

The complete benchmark was split into different test protocols and an industrialization study.

Initial Test

The initial test was divided in two parts and is shown in Figure 23 and Figure 24.

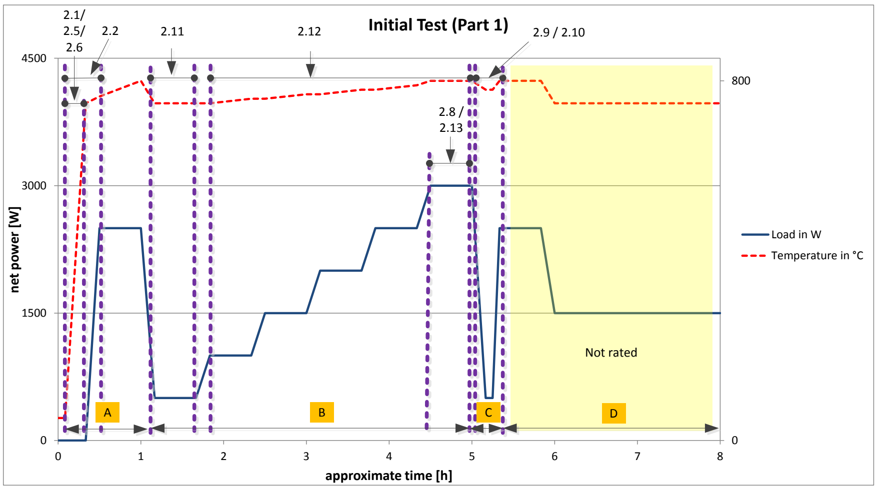

Figure 23: First part of initial test

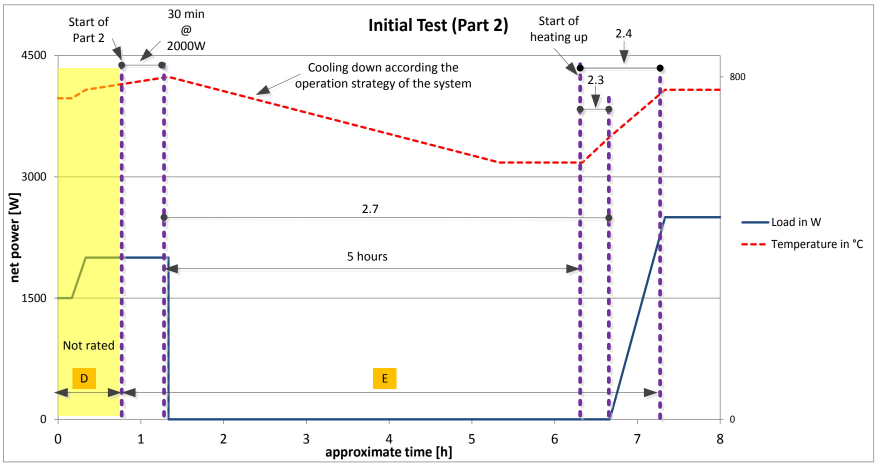

Figure 24: Second part of initial test

The following criteria were evaluated in the initial test:

- Start-up time from cold to net power [section A]
- Start-up time from cold to 2,500 W [section A]
- Electrical energy from cold conditions [section A]
- Fuel energy from cold conditions [section A]
- Max net electrical power [section B]
- Minimum load [section B]
- Width of efficiency region [section B]
- Efficiency at max power [section B]
- Fall time [section C]
- Rise time [section C]
- Start-up time according to weekly profile to net power Pnet > 0 W [section E]
- Start-up time according to weekly profile to max power Pnet = 2,500 W [section E]
- Fuel energy + electrical energy (from warm) [section E]

Load Cycle:

After the initial test each system was tested in a weekly profile. The week profile combined a cold start, warm starts, long cycle and short operation modes of the APU system. It was adapted from the load profiles of DESTA requirements. Total duration of a week cycle was 168 hours.

The electrical energy according to the load profile (Figure 25) had to be delivered within a certain time period. This approach reflects the energy demand of the driver and the buffer battery. An operation without any limitation of operation mode was possible. All energy consuming actions like heating-up, blower power, hot standby, load change and regeneration during the cycle operation were included.

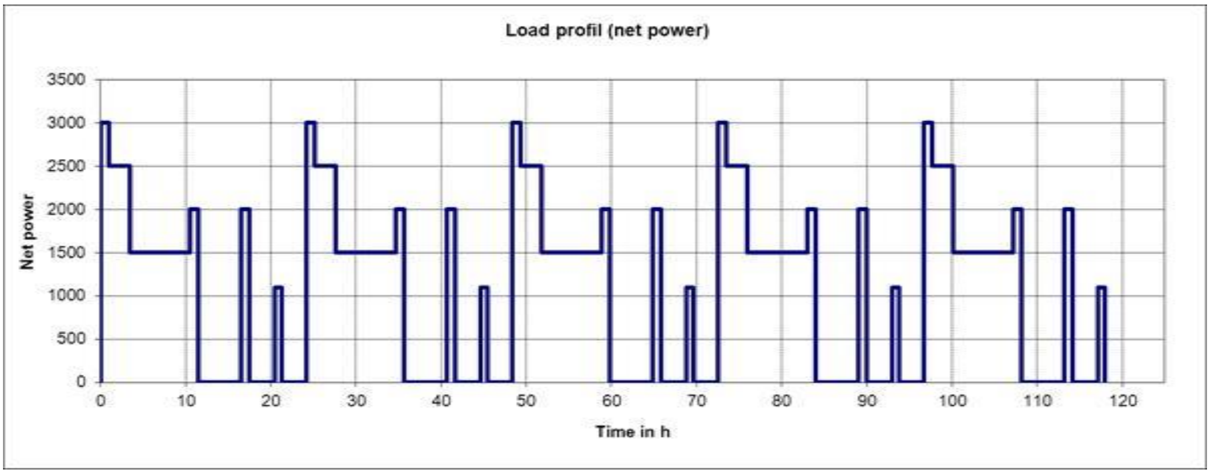

Figure 25: Weekly load profile (truck driver)

The start-up from cold conditions before the first delivery of power (3,000 W) had to be added before t_0. The time required for this start-up was part of the total 168 hours per weekly cycle. In the data recording, the operator defined where the weekly cycle starts (t_S) and where t_0 is, when the load profile started.

The following criteria were evaluated during the week load tests:

- Lifetime
- Load following
- Efficiency

Integration Study:

In the study part the following criteria were evaluated:

- Packaging
- Weight

Summary of the Initial Test

In total four data sets (3 x JE, 1 x AVL) were evaluated for the initial test. Although only one test campaign reached the max. net power of 3,000 W the evaluation was able to deliver valuable input for the further development of the truck APU system, e.g. for the dimensioning of the buffer battery and the layout of the control system. Details on the first part of the initial test can be observed in Figure 26.

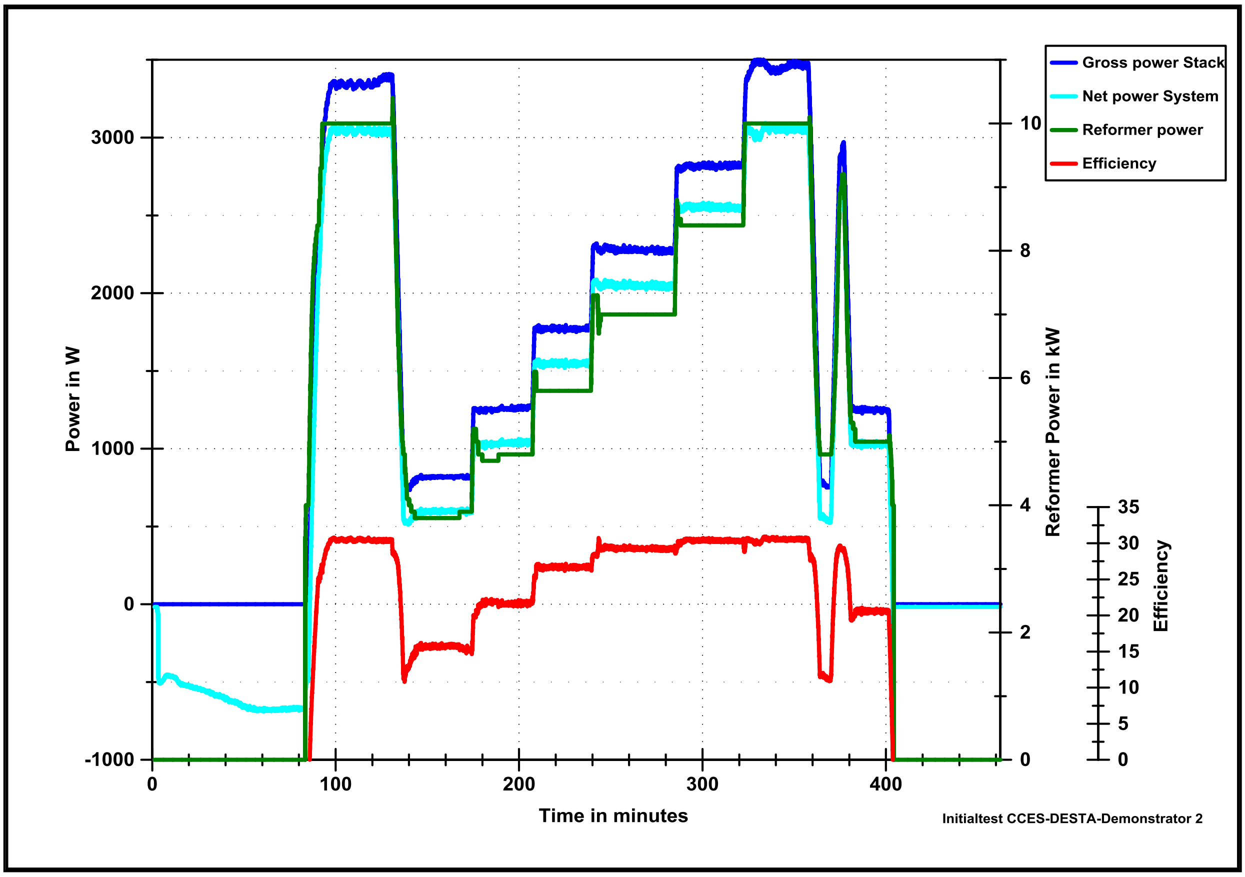

Figure 26: First part of initial test (SOFC APU, Eberspächer)

Summary of the Load Cycle Test

DESTA test cycle was specified as „electrical power demand of a trucker in one week“ with day breaks and a night break; including one cold start, 14 warm starts per week and five different load levels.

In Figure 27 the real load profile of an SOFC APU according to the demand of the truck driver (see Figure 25) and in Figure 28 a lifetime test are shown.

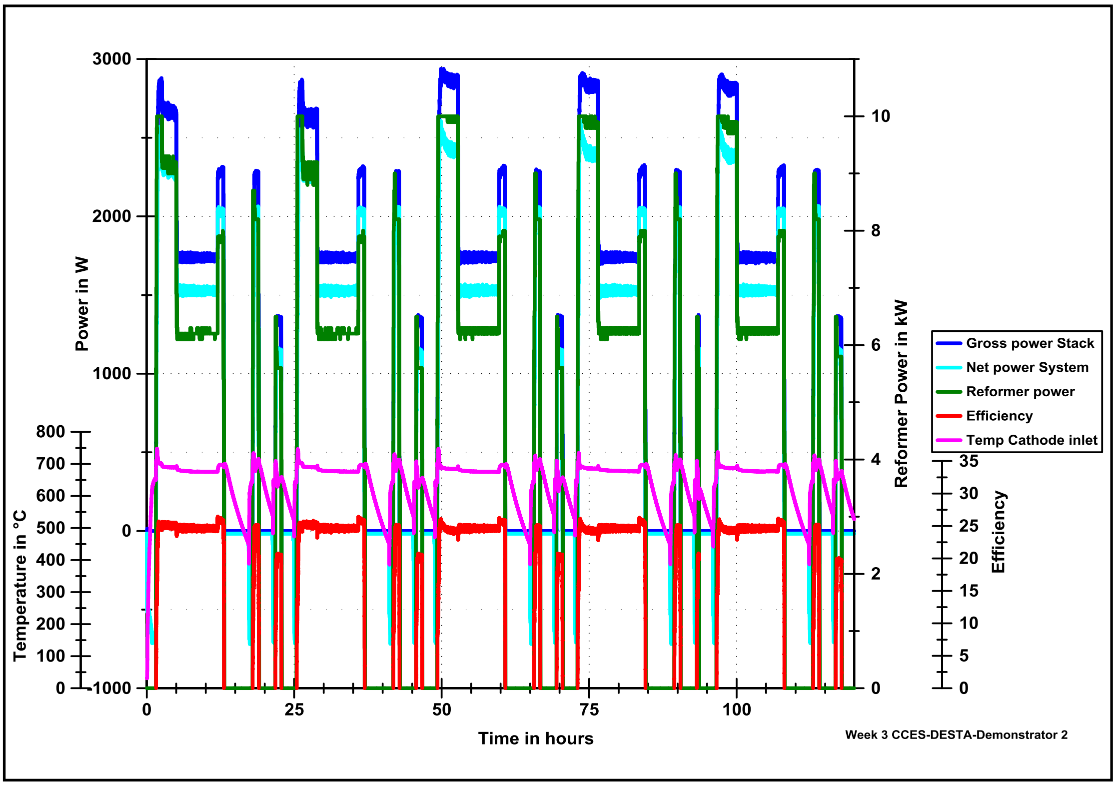

Figure 27: Real load profile of SOFC APU (Eberspächer)

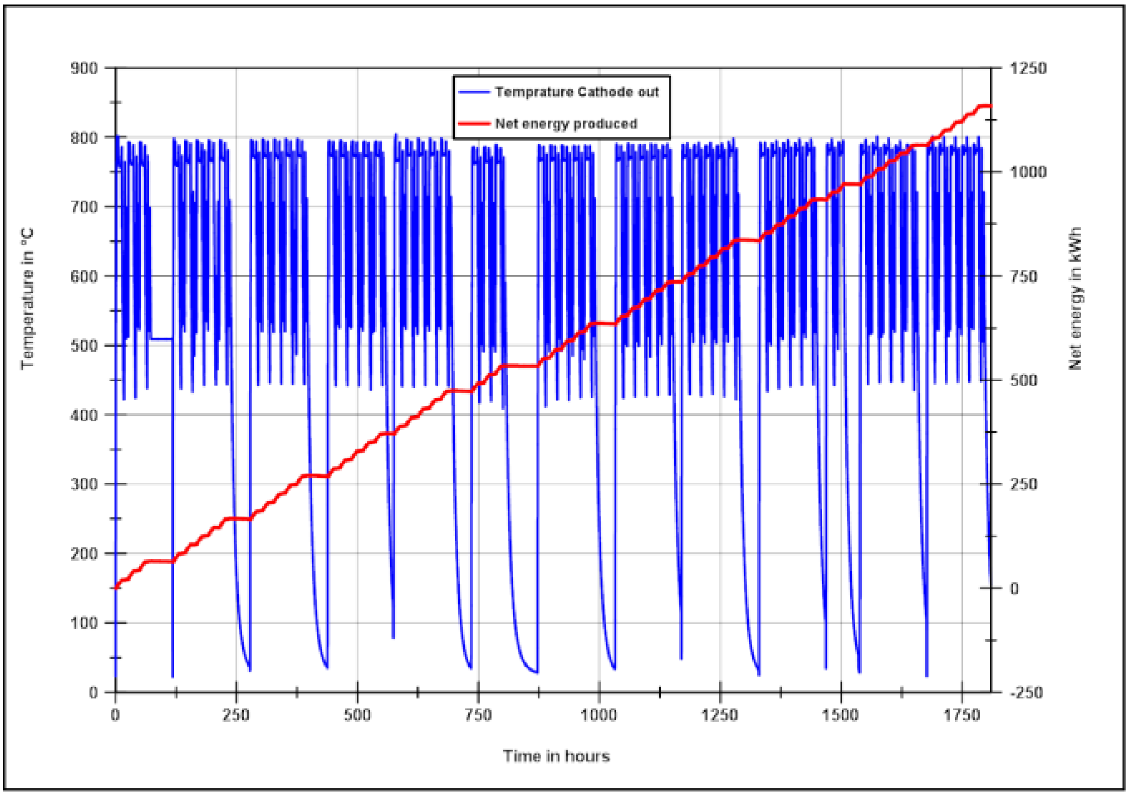

Figure 28: Lifetime test of SOFC APU (Eberspächer)

In total three data sets (3 x JE) were considered for the Load Cycle Test. A total of 19 weeks were evaluated. For lifetime and efficiency fourteen full 5-day-weeks were counted and for load following all nineteen weeks were accepted. The three systems of Eberspächer were operated 1,184 hours and produced 1,627 kWh of electricity.

Overall Benchmark Result

The overall result of the Benchmark, based on the evaluation of Initial test, Load Cycle tests and Study is shown in Table 1. AVL was not able to bring 3 kW systems into operation during the foreseen benchmark test duration. Only test results of a single one-stack system were evaluated.

Table 1: Overall Benchmark Results for JE and AVL

	Results (total points)	
Eberspächer (JE)	6,568	73,0 %
AVL	1,795	19,9 %

Summary Benchmark

Within this benchmark Eberspächer was able to provide data sets of three test campaigns for Initial Test and Load Cycle Test, as well as for the study. AVL supplied data of one test campaign for the Initial Test and for the study.

Eberspächer reached 73 % and AVL about 20 % of the maximum available benchmark points. The results of the evaluation showed clearly that the Eberspächer collected more points due to contributions from three evaluated systems. AVL collected only points from one system. In the industrialization packging/weight evaluation the AVL system has clear benefits and collected more points.

In the Initial Test part a large amount of performance data (e.g. start-up time, efficiency etc.) could be collected. These data provided an important input for the further development in the following work packages. The desired maximum net Power of 3,000 W could be reached only by one test campaign.

The Load Cycle Test in total 19 weeks of operation could be demonstrated by Eberspächer within three test campaigns. The week efficiency for the given load profile is 15.4 % (mean value of three test campaigns). The study part was provided by AVL, as well as by Eberspächer. The result was that both manufactures will meet the goals defined in the System Requirement Report.

During a telephone conference mid of September 2013 it was decided, that the Eberspächer lab system is chosen as a basis for the truck demonstrator.

3.3 Work Package 3: Stack Optimization

The objectives of this work package were to design, manufacture/produce, test, ship, and integrate SOFC stacks optimized for diesel applications and the fully integrated mobile APU system and its durability and performance objectives.

TOFC stacks are based on planar anode supported cells with metallic interconnects. The stack design used for APU applications has a side air manifold and internal fuel manifolding and is integrated into a stack module. Figure 29 shows the stack module and the boxer configuration with electric terminals and the air and fuel inlets/outlets.

Figure 29: Stack module and boxer configuration with electric terminals, air and fuel inlets/outlets

This includes a cast casing containing

- A high temperature compression system, that holds the stack itself in place, ensures mechanical integrity and secures tightness of the gaskets inside the module.
- A flat interface allowing for bolting onto the system, either as a single stack, or – for the systems described here – in a twin/flat configuration.
- Electrical isolation of both terminals of the stack itself, so that the casing can be connected to vehicle ground and allowing for galvanic isolation of the high voltage part of the system.
- Power outlet feedthroughs.
- Voltage probe feedthroughs, connecting to some of the interconnects in the stack. These allow for diagnostics during development.

Performance and robustness testing

The stacks are tested under a number of operating conditions to ensure their performance and mechanical integrity under harsh thermomechanical stresses. Two gases are used: One composition resembles the real fuel, the other one is a reforming fuel based on CH_4, which will subject the stack to thermomechanical stresses due to the cooling effect when CH_4 and water is reformed inside the stack to form CO and H_2.

Figure 30 shows a typical short time test track of the stacks. Stack voltage is unchanged after 10 cycles in H2 based fuel and 10 cycles in reforming fuel.

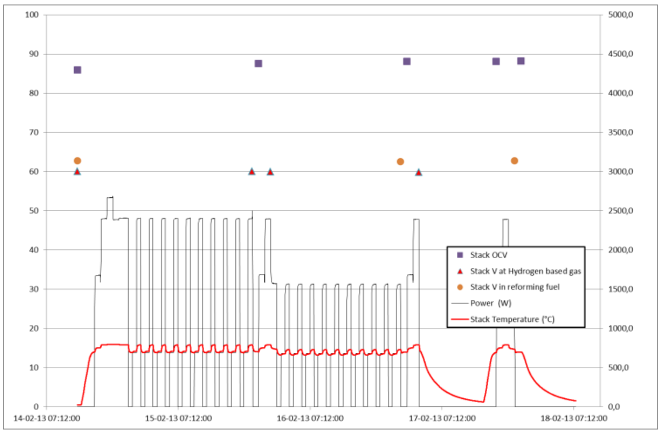

Figure 30: Typical short time test track of the stacks

To verify that the stacks are fit for the application including a weekly full cool-down and heat-up, an accelerated test method has been developed so that a full thermal cycle can be completed in less than four hours. The test results show that the stacks can withstand more than 100 thermal cycles without any damage.

Sulfur testing

To accept the Sulfur levels of ULSD, the anodes have been modified. These modifications have been tested on stacks with 10-25 cells. Figure 31 shows the performance of the cells with and without anode modification and how the anode modification greatly improves performance and Sulfur tolerance at system relevant conditions. The anode modification has been implemented and verified in some of the full size stacks used for developing the two APU systems.

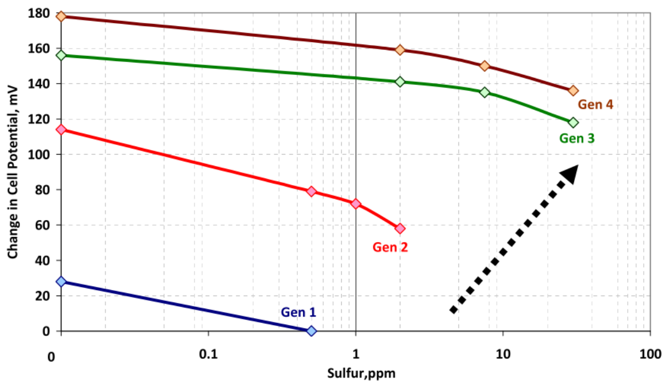

Figure 31: Sulfur tolerance at system after anode modification

In the first project half, a total of 16 stacks were delivered for one-stack systems and benchmark systems. A change of interconnect was implemented in March 2013. The new interconnect had been developed for TOFC's stationary applications in other projects and had shown good results. Within the second period a total of 12 stacks were delivered to Eberspächer for integration into the truck demonstrators. In August 2014, it became known that Haldor Topsoe A/S will close Topsoe Fuel Cell A/S (TOFC). Thus, TOFC was terminated from the DESTA project as of 15th of October 2014. Since the project was already advanced very far and enough stacks were available, the decision was made to continue and close the project with the remaining consortium.

3.4 Work Package 4: Optimization SOFC-APU & Test

The goal of WP4 was to develop, assemble and test the final DESTA SOFC APU systems. Based on the recommendations from the benchmark study, the most promising approaches from the AVL and Eberspächer SOFC systems were identified and combined to the final DESTA SOFC APU system. A new system architecture was devised by selecting the best performing components or subsystems. A new control system was developed, including control algorithms for all relevant operating modes. On a component level (e.g. fuel processor or blowers) various optimization tasks were performed to improve the system performance, lifetime and reliability. A detailed production cost study and design-to-cost analysis was performed. Finally, five DESTA SOFC APU systems were assembled, of which one went into the truck demonstration tests in WP5 and four into laboratory tests comprising a cycling & lifetime test, a vibration test and a salt spray test.

After finishing the benchmark phase within WP2, Eberspächer saw its mechanical APU design and control strategy mature enough to go into a next design generation. One major advantage of the Eberspächer systems was the ability to transfer the basic APU layout without changing the functionality of the system. To meet the numerous requirements that were defined by Volvo Technology, an overall evaluation of the current APU was necessary. To fulfill the volume requirement was just as challenging as putting system control and power electronics into the same, very limited space. At the end, the APU had to fit into the given space as shown in Figure 32 and offer all necessary interfaces like power supply and data communication.

Figure 32: SOFC APU concept in a Truck (Eberspächer)

Figure 33 shows the overall system layout with its major sub components and the fundamental functionalities. Besides meeting the Volvo system requirements and basic function, aspects like production costs and manufacturability were major design targets during the APU development phase.

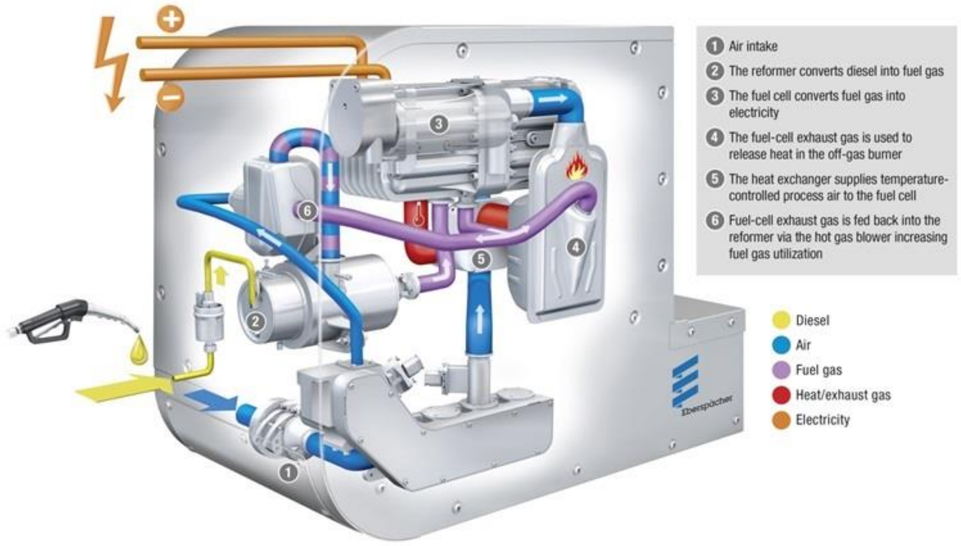

Figure 33: APU system layout (Eberspächer)

The original intention to merge AVL and Eberspächer APU technologies into one superior system did not work out. The lack of system maturity and at the same time the absence of reliable test data was key aspects to develop the truck APU on the basis of the Eberspächer system only. In September 2013, the APU design for truck integration was frozen and the first built-up of one lab system, internally called the TDL1, was initiated, see Figure 34.

Figure 34: APU Design (Eberspächer)

Between October 2013 and March 2015, a total of 4 lab systems were built with continuous development regarding manufacturability and function. Testing and system optimization started right after the first system was built and ready for operation. Since sub-components were shifted around within the APU in comparison to the previous Eberspächer APU generation, their thermal behavior had to be redefined and the system control had to be adapted. Once this had been done, first basic lab tests including heating-up, normal operation and cool down were carried out.

Laboratory tests ("Off-vehicle")

Depending on the temperature of the system the heating–up time varies between 30 and 75 minutes. Thereby the heating-up strategy was improved with the knowledge gathered in WP2, to be more stack preserving.

The maximum gross power reached with that system was around 3.3 kW with a net power of 2.8 kW.

As the build-up of more systems continued, the testing plan was extended. At the end of the DESTA-project the following tests were carried out:

- Basic functionality including warm and cold cycling
- Salt-spray testing
- Vibration testing under APU operation
- Water spray treatment under APU operation

As the Eberspächer APU had proven its maturity, the final build-up of the truck systems was started.

From an outside view, the Eberspächer APUs for truck demonstration fairly similar to the lab systems. Nevertheless, they have gone through multiple hard- and software loops in order to make them ready for truck integration. To prepare the Eberspächer APUs for truck demonstration and for integration they underwent different pre-test scenarios as shown in Figure 35.

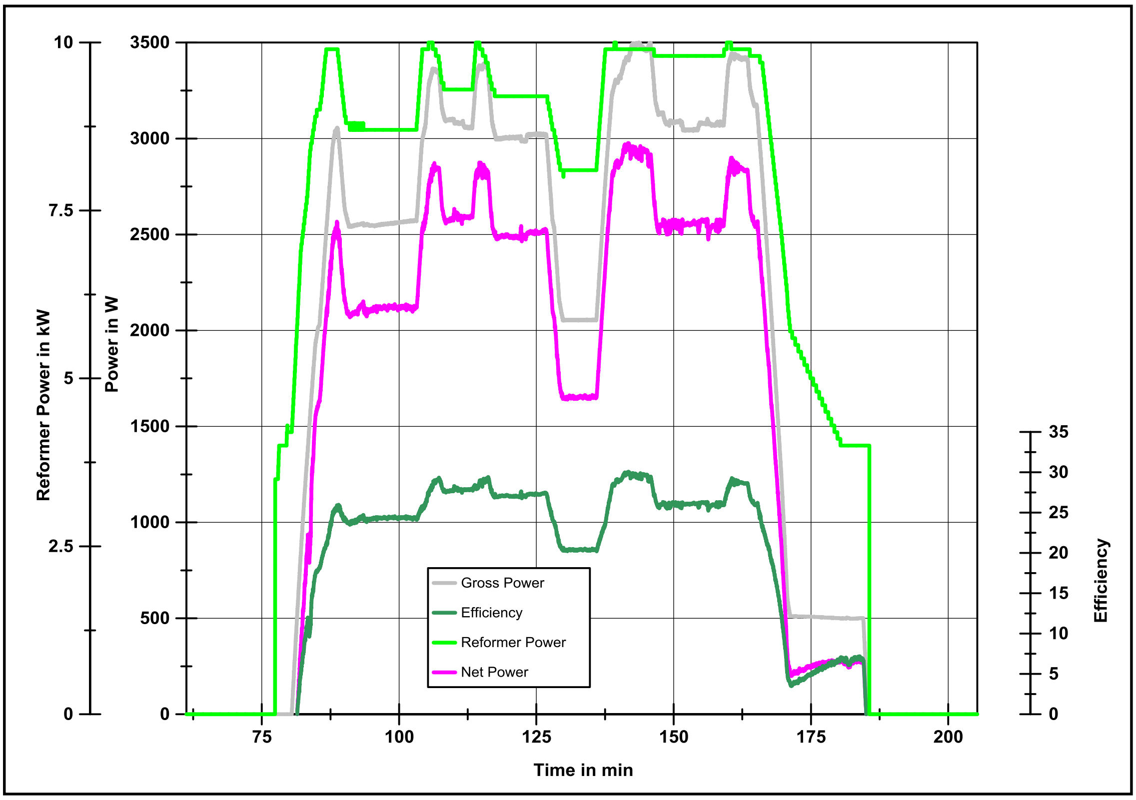

Figure 35: Truck Demonstrator pre-test (Eberspächer)

The maximum power output of 3.0 kW is shown in Figure 35. Besides ramping up to maximum power, load changes and smaller power levels were tested. One very fundamental step was to validate the vehicle communication. Once the APU is mounted on the truck, operation requests are mainly given by the vehicle and not directly through the APU itself. This made adaption in the controlling necessary.

Figure 36 shows the TD1 system in the Eberspächer lab during pre-testing. Along with the APU, Eberspächer engineers were present at Volvo test facilities to accompany and if necessary, help the Volvo staff with their test procedures.

Figure 36: Truck Demonstrator during pre-test in the lab

A total of four lab APU systems were built and taken into operation. They have shown magnificent test results during basic operation on the one hand, and during environmental testing on the other hand.

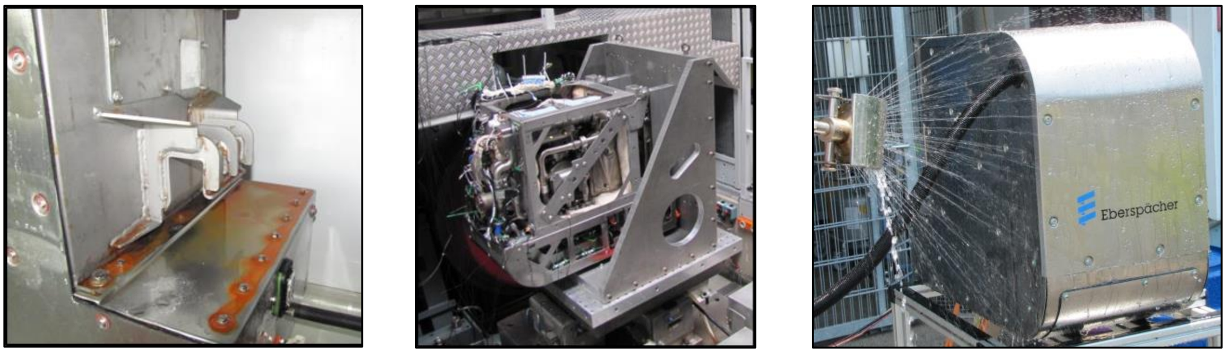

Figure 37: Truck Demonstrators during salt spray, vibration and water spray testing in the lab

Except for some minor requirements, the Eberspächer APU was able to fulfill the complete list of demands that were given by Volvo Technology.

3.5 Work package 5: Vehicle Integration & Field Demonstration

This work package aimed at preparing the final on-vehicle installation of the developed and in laboratory demonstrated SOFC-APU system as well as the conduction of the final system testing and reporting of the results. The main aims are:

- Definition and development of vehicle interface design
- FC-APU integration on vehicle
- Field demonstration and data collection
- Data analysis and assessment of the results versus the project targets

Vehicle interface design

The overall electrical architecture has been developed and the interaction between system components and the vehicle architecture has been defined. The following main components will be used: APU unit, DC/DC converter, vehicle batteries, system control ECU, external control panels.

To be able to utilise the APU electrical power, a DC/DC converter is needed to convert the voltage to a level which is suitable for the vehicle system, i.e. 12 V nominal. The secondary side of the converter is connected directly to the batteries in parallel. With this set-up the APU system can provide batteries with charging current and power to load at the same time. Also the power source to all loads can seamlessly change between alternator, batteries and APU. The source with the highest voltage will supply the rest of the system. The batteries, which act as an energy buffer, can both supply power and be a load, depending on voltage and state of charge.

A lot of efforts have been spent on detailing the APU vehicle mechanical and electrical Interface specification which describes the interface between APU and vehicle in detail and is the fundament for continues integration. The electrical interface has in detail been defined including e.g. power supply (voltages, power consumption, protections, connector etc.), power output (hazardous voltage requirements, voltage and current levels, protection, connector and relay function etc.), potential equalization and signal interface. Also the mechanical interface has been defined with dimension restrictions, frame hole pattern etc. Details about the media interface, for e.g. air intake, fuel intake and exhaust are described as well. A lot of efforts have also been put in defining the communication interface with CAN-messages (Controller Area Network), communication scenarios and functional descriptions. All needed communication scenarios has been defined together with Eberspächer: start-up, normal operation, shut-down, regeneration, emergency shut-down and service mode.

To be able to convert the unregulated voltage supply from the SOFC-stack into voltage usable for charging the vehicle batteries, a DC/DC converter has been developed. The role of the converter is not only to charge the batteries, but also to load the SOFC-stack in a controlled and constant manner. The DC/DC is built of eight 500 W modules working in parallel with the capability of delivering 3,750 W output. The architecture is a low noise ZCS/ZVS (Zero Voltage Switching/Zero Current Switching) with an isolated and in-rush limited high voltage side. It is air cooled with a heat sink and cooling fans. Control and monitoring of (e.g. primary/secondary voltages/currents) is done via a CAN interface.

For the overall system control a software platform has been developed and deployed in a Volvo ECU (Electronic Control Unit) and is built on an automotive standard open source-based software platform.

A number of device drivers and software components have been developed in order to abstract the low level details for the top layer application components and providing control, status monitoring and diagnostics of the whole system.

A control panel for a wireless android tablet has been developed to facilitate driver’s control over the system such as start or stop of the system as well as monitoring of the status.

An overall system controller (APU Controller) has been designed and implemented in the ECU. The system controller gathers information from other nodes such as user interface, APU, vehicle DC/DC converter, vehicle batteries and vehicle. Based on the information received from these nodes it sends back commands and status information.

A typical scenario is that the user requests APU start from the user interface. The controller then wakes up the APU and DC/DC, initiates the APU heat up process, waits for the APU to be ready and the vehicle to be immobilized before starting the reforming process. It then tries to balance the energy flow from the APU, through the DC/DC to maintain a healthy charge level in the batteries while keeping all nodes within their operational limits.

APU Installation

A Volvo US heavy-duty truck has been imported to Sweden from the USA to serve as a demonstration vehicle for the DESTA project. An US type truck is chosen because the primary market for an SOFC APU is the US market.

Figure 38: Demonstration vehicle with installed SOFC APU

The complete electrical architecture of the DESTA system have been built up and installed into the demonstrator vehicle. The key components are: Vehicle DC/DC converter, electrical junction box, batteries and battery state of charge sensor, control panel and wireless router, isolation monitor, keypad and vehicle ECU. Also wiring harness for power distribution, signal harness, power relays etc. had to be installed to connect every component.

The SOFC APU delivered by Eberspächer has been installed on the left hand side of the chassis frame of the vehicle. Also all necessary external components as air intake and filer, exhaust pipe, fuel intake from diesel tank, electrical power supply, power output to vehicle DC/DC converter and signal wiring harness have been installed.

Figure 39: The SOFC APU installed on the chassis frame of the vehicle

To be able to test the APU system in an efficient manner, a lot of test equipment had to be installed in the vehicle as well. E.g. computer and screen for data logging and system monitoring, electric load for load simulation, current sensors, battery charger, 230 V inverters for usage of realistic loads such as coffee maker, microwave oven and water boiler and APU cell monitor measurement units.

Test of integrated APU System

To be able to reach the ultimate goal of having a functional APU system integrated on vehicle, several integration tests had to be performed during the development work. Both the APU and the vehicle system were developed in parallel and for each integration test more and more hardware and functionality were introduced. In total one workshop and two integration tests have been held at Eberspächer in Germany and two complete weeks of integration tests in the lab at Volvo, Sweden with the complete APU system.

Once the APU system interface and functionality had been verified in the lab, it was installed on vehicle and the on vehicle tests could start according to the defined test plan. In total five full weeks of intensive and joint testing of the APU system have been performed by Volvo and Eberspächer.

Almost all tests defined in the test plan for the in-vehicle tests could be performed except when not considered as relevant any more.

The test period started with basic tests including e.g. start-up from cold, load changes, realistic loads, shut down, 10h of operation, start-up from warm and safety tests.

Then some static tests were performed as noise measurements, maximum power and fuel consumption and CO2 emissions.

Also a number of vehicle scenarios were tested such as start-up while driving, engine crank while APU operational, shut-down while vehicle driving etc.

When the APU system had passed all tests, realistic driving mission profiles were also performed, using the vehicle and APU in a realistic scenario (24 h). The APU was operational during night and the vehicle was driving on public roads during daytime and APU started for lunch break.

Also one extra week was spent on driving on roads to expose the APU to vibrations and other environmental impacts (>2,500 km in total).

The following key test results have been demonstrated in vehicle:

- APU integrated and functional in the vehicle electrical system
- Fully automated control of APU and system overall control
- Start-up time of <70 minutes from cold and 30 minutes from warm (after ~3 h cool down).
- Max Electrical output power from APU: 2.9 kW
- APU efficiency: 29 %
- Diesel consumption: 0.95 liters/hour @Max power)
- Volume of 178 liters, (40 cm wide) and weight of 160 kg including 20 kg brackets.
- Noise level of 58 dB(A)
- CO2 reduction of 73 % compared to idling engine
- Operating on conventional US Diesel
- Successfully used realistic electrical loads such as coffee maker and microwave oven
- Driving on roads while start-up and cool down of the APU.
- Environmental impact on installed APU from >2,500 km of driving on public roads.
- Environmental impacts from outdoor testing and driving such as rain, ambient temperatures, water splash and gravel etc. from the roads
- No vibrations or emissions from APU

So the goal of demonstrating the first Europeans SOFC APU on a heavy-duty truck has been achieved.

Figure 40: The DESTA consortium at the Final Event Live Demonstration

3.6 Summary of all technical objectives

The table below summarizes planed and achieved technical objectives in DESTA.

Table 2: Technical objectives (planed and achieved)

Technical objectives	Unit	Planed	Achieved	Status
Max. start-up time	min	30	< 70	
Max. Electric power (net)	kW	3.0	2.9	
System electrical net efficiency (approx.)	%	35	29	
Diesel consumption (3 kW, net)	l/h	0.86	0.95	
Volume	l	186	178	
Weight	kg	150	160	
Noise level	dB(A)	65	58	
CO_2 reduction compared to engine idling of a heavy-duty truck	%	75	73.5	
Operation on conventional road diesel fuel (US Diesel)				

The 1st European SOFC Truck APU was successfully demonstrated.

4 Potential impact

After the successful demonstration of a SOFC APU on a heavy-duty truck, it has been proven that the technology is mature enough to function as an on board power source for the anti-idling use case during a typical long-haul transport mission.

It has also been demonstrated that there is great fuel saving potential with an SOFC APU compared to an idling truck engine. The fuel savings could result in cost savings for the vehicle owner as well as reduced CO_2 emissions. For the truck owners perspective the anti-engine idling will also reduce engine hours, engine maintenance and service cost.

Even though not quantified in vehicle, the environmental impact could most probably also be lowered since there are very little emissions of NOx and particles from the SOFC APU compared to a truck engine or diesel generator APUs.

Using an SOFC APU will have driver comfort benefits since it is vibration free, but also reduces noise levels (~58 dB(A)) compared to an engine or diesel generator APU which is not only great benefit for the driver bus also the surroundings of the parked truck.

However, the higher production costs are a very great challenge at the moment. The main cost driver is the fuel cell. Moreover, the cost projections of truck manufacturers are very ambitious.

5 Exploitation of results

The successful achievement of most of the DESTA targets provides a good baseline for further exploitation of the results. Nevertheless, the project showed also some existing bottlenecks especially towards the addressed application on heavy-duty trucks.

The exploitation plan includes:

- The market potential and addressable market have been in depth analyzed within the DESTA project by AVL and Eberspächer. SOFC APUs represent an improved product for an existing market. The existing market of truck APUs only in the US represents a sales volume of about 50,000 units per year. The existing products are based on small diesel engines and battery based solutions. Absolutely dominant market leader in this field is ThermoKing.
- Dissemination of the DESTA achievements with the truck industry in the US and EU (including OEMs and large fleet operators)
- Preparation of additional demonstration projects with truck OEMs and fleet operators to raise the awareness for this technology at critical decision makers
- Further analyses of the business case compared to existing solutions and updated by regulatory changes for anti-idling.
- Continuation of the development to improve key performance indicators and reduce cost:
    - Improve the efficiency to around 40 %
    - Improve the robustness and lifetime to 5,000 hrs
    - Further reduce the system cost by DtC and DtM measures
    - Investigate the application of new metal-supported SOFC stack technology which offers a significantly reduced cost potential than in DESTA used ASC technology.
    - Reduce the start-up time to below 45 min by system improvements and/or alternative stack technology (MSC)

- Dissemination of the results to policy makers (e.g. Department of Energy, US) to show the CO2 reduction potential of this technology and to elaborate tax credit incentives and CO2 bonus systems to support market introduction.
- Investigation of early markets for this technology like special purpose vehicles. This vehicle category is not as cost sensitive as the commercial heavy duty truck industry and therefore market entry is much easier and bears less risk. Successful roll-out of a commercial product in this market will also accelerate the heavy duty mass-market. Discussions with first OEMs have already been started and especially AVL is at the moment performing more than five demonstration projects within this market segment.
- The consortium believes that a commercial product for special purpose vehicles might be available in the timeframe of 2017-18. Depending on market entry support (CO_2 credit system, tax incentive system,…) commercial roll-out to the heavy duty truck market might start in the timeframe 2018-2020.
- Evaluation of the possibility to place a larger field-test of APU systems installed in heavy duty trucks and/or busses under the FCH JU 2.
- Investigation of smaller APU systems (<2 kW) with OEMs for the US and European market for anti-idling and night-city logistic vehicles.
- Due to the successful demonstration and prove of concept of the SOFC APU Volvo will start to develop technology road maps for future fuel cell activities. Volvo will also in closely monitor any other technology improvements within the fuel cell area.
- For a market introduction of a SOFC APU and acceptance of the end customer, the investment cost is of great importance and Volvo is following this in order to evaluate the business case.
- The clean and efficient performance of the SOFC fuel cell APU as an on-board electric power source is a technology that might be of interest for other applications than an APU for anti-idling.
- The results of the DESTA project will be disseminated internally within Volvo to managers, product planning and engineers to spread the results and transfer technology know-how to increase the awareness of the state of art technology and facilitate future initiatives within the fuel cell area.

6 Main dissemination activities

The following table gives an overview over the dissemination activities performed by the project consortium throughout the project.

Table 3: Main Dissemination Activities

Title	Date	Event	Type
DESTA Website	01.01.2012	The DESTA Website, featuring information on the project, results, events, dissemination activities and public deliverables is available at www.desta-project.eu.	Website
DESTA Press Release	01.02.2012	DESTA press release at project start. Published on DESTA homepage, provided to FCH-JU.	Press Release
DESTA Project to Develop Fuel Cell Auxiliary Power for Volvo Trucks	26.03.2012	Article on DESTA (based on press release) in Fuel Cell Today.	Article
European Fuel Cell Forum	27.06.2012	Presentation held at the 10th EUROPEAN SOFC FORUM.	Presentation
Fuel Cell Seminar and Exposition	05.11.2012	DESTA and the AVL SOFC APU have been presented at the Fuel Cell Seminar and Exposition, an international Fuel Cell & Hydrogen conference.	Presentation
FCH-JU Programme Review Day	28.11.2012	Jürgen Rechberger presented DESTA and the current achievements at the FCH-JU Programme Review Day in Brussels.	Presentation
Thermal Cycling of SOFC Stacks for Mobile Applications	06.11.2012	At the 2012 Fuel Cell Seminar and Exposition, Niels Erikstrup presented the state of development of the TOFC APU stacks.	Presentation
WHTC 2013, Shanghai	23.-29.9.2013	International networking and DESTA update	Presentation
SAE COMVEC Chicago	30.9.-4.10.2015	Presentation of the DESTA SAE Paper	Presentation
SOFC XIII Conference, Okinawa	5.-17.10.2013	International networking and DESTA update	Presentation
Fuel-Cell-Seminar Columbus, USA	19.-26.10.2013	Presentation of “Technical progress and commercialization of the AVL SOFC APU system”	Presentation
Programme Review Days 2013	10.-13.11.2013	Presentation about the actual status of DESTA	Presentation
FC EXPO Tokyo	23.2.-5.3.2014	International networking and supplier meetings	Presentation
Hannover Fair 2014	6.-9.4.2014	Exhibition of an SOFC APU system	Presentation

7th workshop 2014 - Progress in fuel cell systems	19.-21.5.2014	Workshop Series: Fuel Cell Systems. Presentation of the actual DESTA status and overall discussions about SOFC Systems.	Workshop
EFCF 2014, Lucerne	1.-5.7.2014	Presentation of “DESTA: SOFC APUs for Heavy Duty Truck Idling – a Progress Report”	Presentation
Asian SOFC Symposium Korea	15.-27.9.2014	International networking and DESTA update	Presentation
65. IAA 2014	25.9.-2.10.2014	Eberspächer presented their SOFC APU at the IAA 2014.	Presentation/ Showcase
World of Energy Solutions	6.-8.10.2014	Presentation of “DESTA: SOFC fuel cell as APU for trucks”	Presentation
Fuel Cell Seminar, Los Angeles	6.-17.11.2014	International networking and DESTA update, exhibition of an SOFC APU system	Presentation
Programme Review Days 2014	10.11.2014	Presentation about the actual status of DESTA	Presentation
39th International Conference and Expo on Advanced Ceramics and Composites , Daytona	25.1.-6.2.2015	International networking and DESTA update	Presentation
Hannover Fair 2015	12.-15.5.2015	Exhibition of an SOFC APU system	Presentation
Live Demonstration DESTA system - Volvo	19.5.2015	Live demonstration of running DESTA system on truck at Volvo. Posters, movies and live demo for product planning, engineers and managers and others within the Volvo group.	Presentation
DESTA Final Event: Demonstration of first SOFC APU on truck	9.6.2015	Live demonstration of the DESTA system integrated in truck for the DESTA Final event, including posters, video, truck and presentation.	Presentation
DESTA Press Release	15.6.2015	A press release on the project results is available on the DESTA website.	Press Release
DESTA Video	15.6.2015	The video presented at the final event is also available on the DESTA homepage	Media
Advanced Technology and Research town hall tech show, Gothenburg	2.9.2015	The DESTA results were presented at the Presentation about the actual status of DESTA Advanced Technology and Research town hall tech show.	Exhibition
Programme Review Days 2015	11/2015	Presentation about the actual status of DESTA	Presentation
6th Transport Research Arena	04/2016	Submission of Paper „Demonstration of the first European SOFC APU on a Heavy Duty Truck”	Paper

7 General Project Information

Project Acronym	DESTA
Project Long Name	Demonstration of 1st European SOFC Truck APU
Call topic	SP1-JTI-FCH.2010.1.5: Auxiliary Power Units for Transportation Applications
Start-date	01th January 2012
End-date	30th June 2015
Total budget	€ 10.441.619
FCH JU contribution	€ 3.874.272

Project Consortium:

AVL List GmbH, Graz (AVL)	Austria
Eberspächer Climate Control Systems GmbH & Co. KG, Esslingen (CCES)	Germany
Topsoe Fuel Cell A/S, Lyngby (TOFC)*	Denmark
Volvo Technology AB, Gothenburg (Volvo)	Sweden
Forschungszentrum Jülich GmbH, Jülich (FZJ)	Germany

* terminated from the project in October 2014

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Project website: www.desta-project.eu

Project Logo:

Photos illustrating the work of the project (© Jonas Hagerskans):

DESTA truck with SOFC APU (without fairing):

DESTA SOFC APU: