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Development of a SOFC/Battery-Hybrid System for Distributed Power Generation in India

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Abstract

In recent years India faces demanding challenges in covering an aggressively increasing electricity consumption through economic growth and progressive consumer requirements. Renewable sources and small distributed power generators have been identified as one of the options to establish a diversified power supply infrastructure. The present situation offers promising opportunities for fuel cell systems, as “grid-parity” is not the common measure of competitiveness, but rather the installation speed and availability of reliable power sources.

Contracted by the company h2e Power Systems Pvt. Ltd. based in Pune, India, Fraunhofer IKTS has developed a 1 kW(el) SOFC power generator during a three-year system engineering and technology transfer project. The fuel cell system is based on the CFY stack technology by Plansee SE and IKTS, incorporating state-of-the-art ESC with Scandia-doped Zirconia electrolytes. CFY-stacks have proven to be robust and reliable, showing power degradation rates below 0.6 % per 1.000 hours during endurance operation over 20.000 hours and a cyclization capability of more than 120 near-system cycles under full RedOx-conditions.

For the SOFC power generator a CFY stack is integrated with a pre-reformer, a tail-gas oxidizer and heat exchangers into a HotBox-module following a novel concept for least-space-demanding reactor integration and flow distribution. Aside from compactness, a simple and robust, yet highly efficient system concept was set as the primary development goal for the project. To meet these requirements, two major design decisions have been introduced in the process layout, i.e. a rated fuel utilization in the stack of 85 % as well as a POX-air pre-heater for reducing the reformer air flow to lowest possible values. This approach leads to a water-less SOFC system with a net electrical efficiency above 40 %.

In 2015, two Proof-of-Concept (PoC) prototype systems were commissioned and tested at IKTS. One of the PoC-prototypes was installed later at the customer’s laboratory in Pune, India, for test and demonstration purposes. In Project Phase II, three improved prototype systems were built at IKTS and shipped to India in May 2016 for initial demonstration projects and field trials. At the same time, the technology transfer to the customer was initiated, in order to enable for a local manufacturing and deployment of SOFC systems in India. By completion of the prototype delivery and technology transfer, the initial development project was successfully finished. Various follow-up activities are currently under negotiation between h2e Power Systems and Fraunhofer IKTS.

Introduction

The system development project was contracted at Fraunhofer IKTS by the company h2e Power Systems Pvt. Ltd., based in Pune, India, in 2013. Primary development goal was the provision of a Natural Gas fueled, 1 kW(el) SOFC power generator with optional exhaust heat utilization, to be integrated into a SOFC/Battery-hybrid system (see Fig. 1) for continuous and reliable on-site power generation within the unstable power distribution grid in India. The product shall be suitable for distributed, 24 x 7 power supplies in residential buildings and commercial facilities, like small manufacturing sites, clinics, etc. Due to the specific climate conditions and user demand profiles in India, conventional Fuel Cell micro-CHPs designed for the European or Japanese market are not sufficient for the intended use. It was rather required to develop a simple and robust system with very high electrical efficiency, and the option to use exhaust heat for hot water preparation – or to run the system as a pure power generator, only.

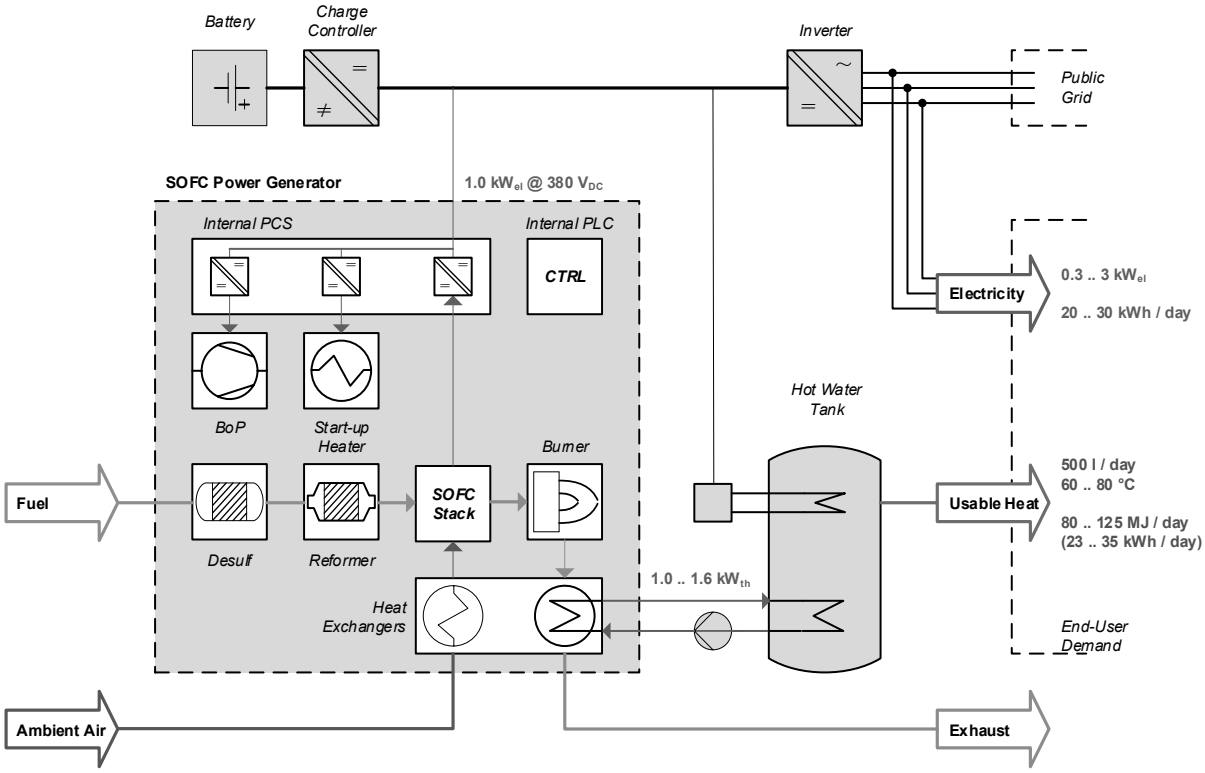

Fig. 1 Schematic representation of the SOFC/Battery-hybrid system.

1. Project Structure

The SOFC system development project was planned in two major phases. Phase I was aiming at the system concept definition and practical verification using two proof-of-concept prototype systems. During project phase II, the system design was to be optimized towards cost and manufacturability, and three improved prototype systems were to be delivered to the customer for on-site demonstrations and field trials. The project included a complete technology transfer for subsequent product development, local manufacturing and commercialization in sole responsibility of h2e Power Systems. The underlying project structure (see Fig. 2) followed the general concept for the development of application-specific system solutions, which is applied at Fraunhofer IKTS in numerous industry financed development projects.

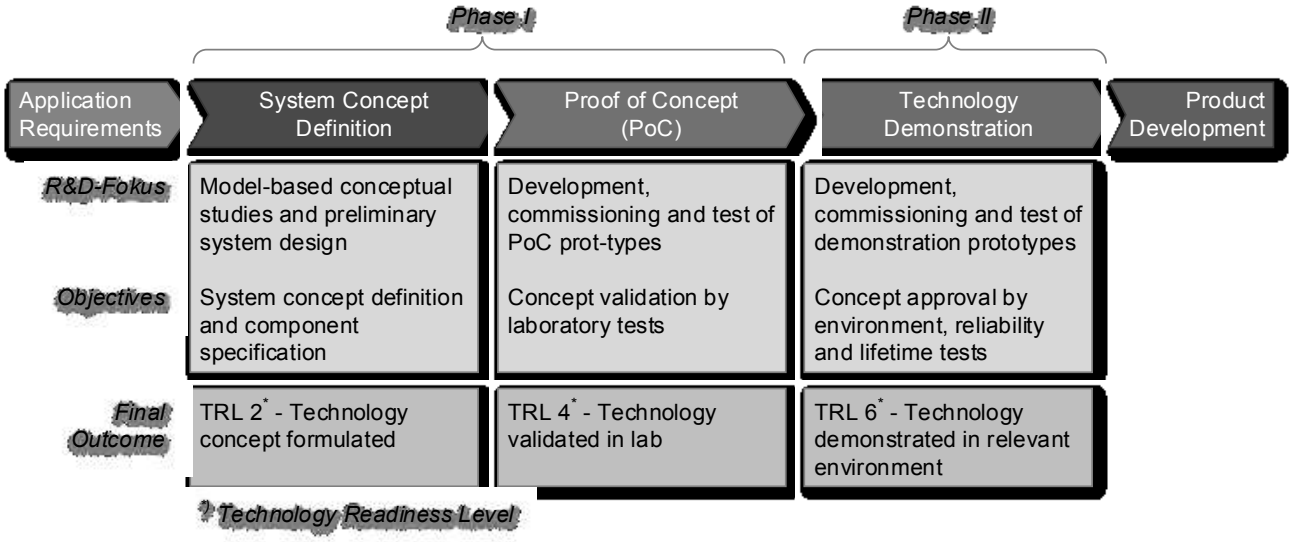

Fig. 2 Project structure for the development of application-specific systems.

2. HotBox Concept and Design Verification

The h2e® power generator incorporates CFY SOFC stacks, jointly developed by Fraunhofer IKTS and Plansee SE. The CFY stack technology is based on electrolyte-supported cells (ESC), which are characterized by their long-term durability and cyclization capability. Figure 3 shows an exploded view of the CFY stack configuration. The robustness of CFY stacks has been demonstrated in various tests over more than 20.000 hours and 120 start/stop-cycles, showing a power degradation rate below 0,7 % per 1.000 hours and 0,5 % per ten cycles, respectively [1-3]. CFY stacks have been adopted for system integration by various external research partners and companies, e.g. Convion Ltd. of Finland [4]. In 2015, the company MPower GmbH was formed for worldwide distribution and deployment of CFY stacks on a commercial basis.

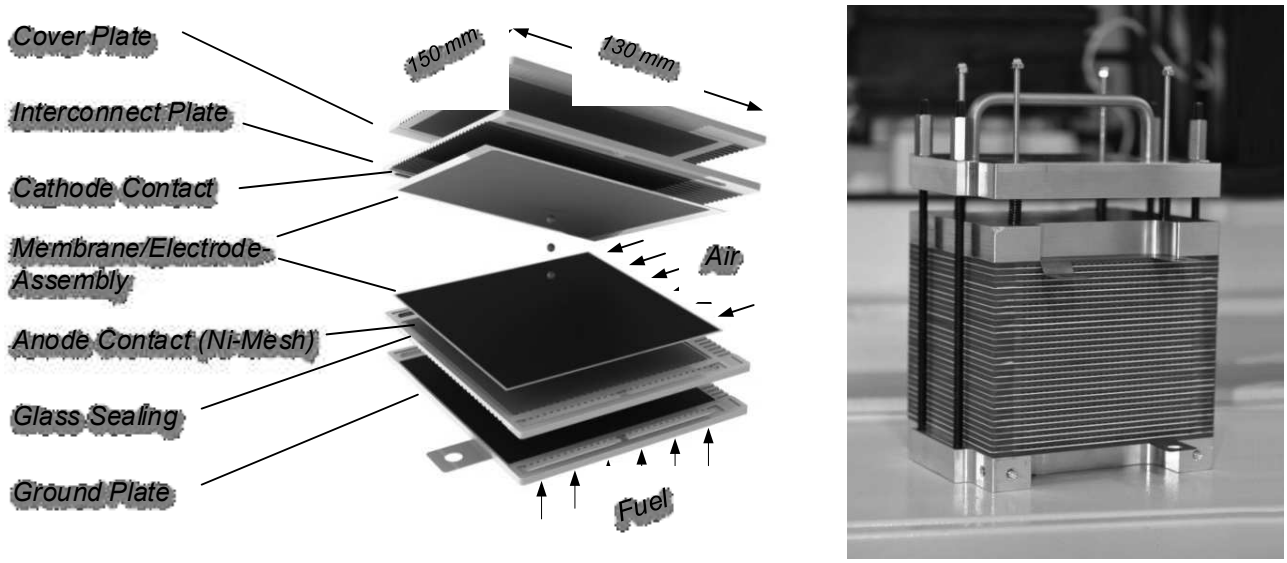

Fig. 3 Exploded view of CFY stack (left), 30-cell CFY stack in clamping device (right).

The h2e HotBox and system development was initiated with an in-depth requirements definition, based on intended application characteristics. With respect to the given technical boundary conditions, an appropriate system concept was derived, backed by a detailed process layout calculation including parameter studies and a system performance

estimation. With the created process design data, the detailed layout of required system components and sub-modules was initiated. The complete prototype system architecture was consolidated with a detailed 3-D CAD model, being the basis for actual component manufacturing and system assembly.
In order to achieve the desired net electrical efficiency of 35 to 40 % (LHV) with a very simple process design based on partial oxidation, a special arrangement of HotBox-components was required and demanding process parameters for the reformer and SOFC stack have been specified. A stoichiometric air ratio of 0,28 was determined for the POX-reformer and the anode-side fuel utilization in the SOFC stack was intended to reach 85 % at rated power output. For the approval of the initial component design and HotBox arrangement with specified process parameters, it was decided to execute a verification test with a preliminary HotBox prototype on a test-rig at IKTS. The prototype HotBox included the POX-reformer, SOFC stack, afterburner, supplemental parts and thermal insulation as designed for later system integration (see Figure 4 and 5).

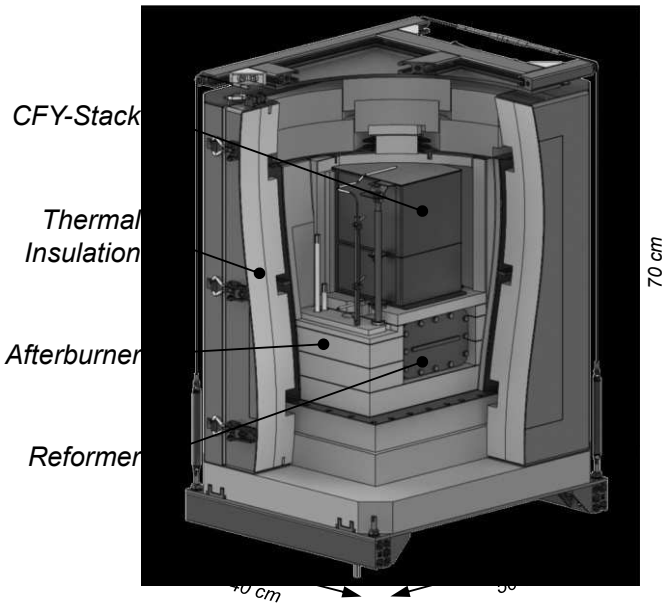

Fig. 4 Sectional view of the h2e® HotBox.

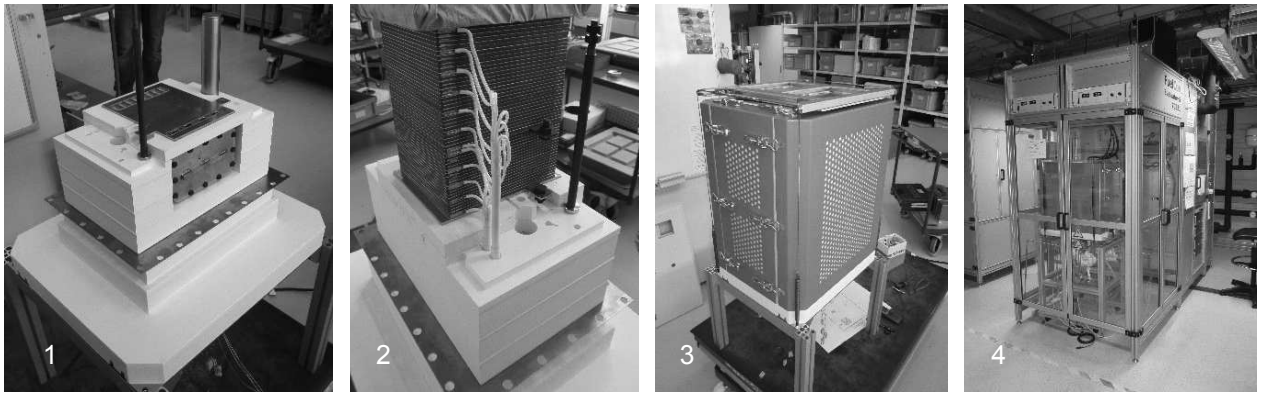

Fig. 5 Sample pictures of the h2e® HotBox assembly;
1) ceramic base plates with integrated reformer and afterburner; 2) 50 cell CFY stack mounted on baseplates; 3) assembled HotBox with thermal insulation; 4) prototype HotBox mounted in laboratory test-rig for verification test.

With the HotBox prototype installed in a laboratory test-rig, the start-up procedure intended for later system operation was implemented and tested. After successful commissioning and approval of the process parameters for rated power output, the HotBox was operated

under steady state conditions for 1.000 hours without any deviations. The endurance operation was followed by preliminary part-load tests, which indicated the possibility of a power modulation range between 400 and 1.400 W(el, gross). Finally, an automated start/stop-cyclization test was executed. It covered 38 full operating cycles including start-up, seven hours of full load operation, shutdown and passive cooling down to 500 °C stack temperature. Figure 6 below shows an overview of the design verification test with the h2e® HotBox prototype, installed in a laboratory test-rig.

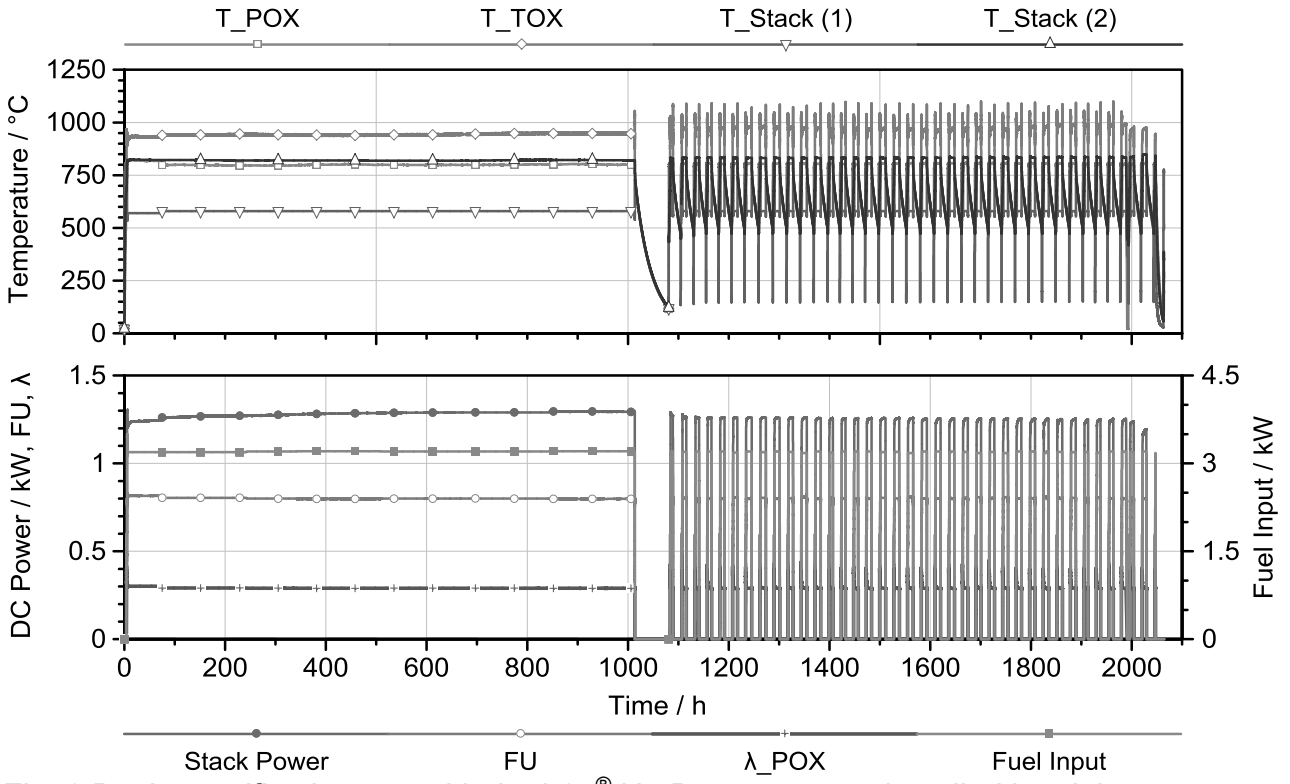

Fig. 6 Design verification test with the h2e® HotBox prototype, installed in a laboratory test-rig (1.000 hours endurance operation, followed by automated start/stop-cyclisation test, fueled by lab-grade methane during all tests).

3. Proof-of-Concept Prototype Development and Testing

Following the HotBox design verification, the assembly and commissioning of two Proof-of-Concept prototype systems was initiated, based on a slightly modified HotBox design. Figure 7 shows sample views of the prototype manufacturing. The prototypes were commissioned in IKTS' SOFC laboratory (cf. Figure 8) and passed a characterization test for process analysis, including part load operation. The procedures included steady state operation at rated power output and several scheduled sequences of part load operation. The system was operated manually or by script-based, automated control sequences. Intermittent shutdowns were required for updating the control software and for other minor maintenance jobs. Figure 9 below shows an overview of the initial characterization test with one of the h2e® Proof-of-Concept prototype systems.

Fig. 7 Sample views of h2e® Proof-of-Concept prototype systems during assembly.

Fig. 8 h2e® Proof-of-Concept prototype systems installed in IKTS' SOFC laboratory (left) and at customer's site in Pune, India (right).

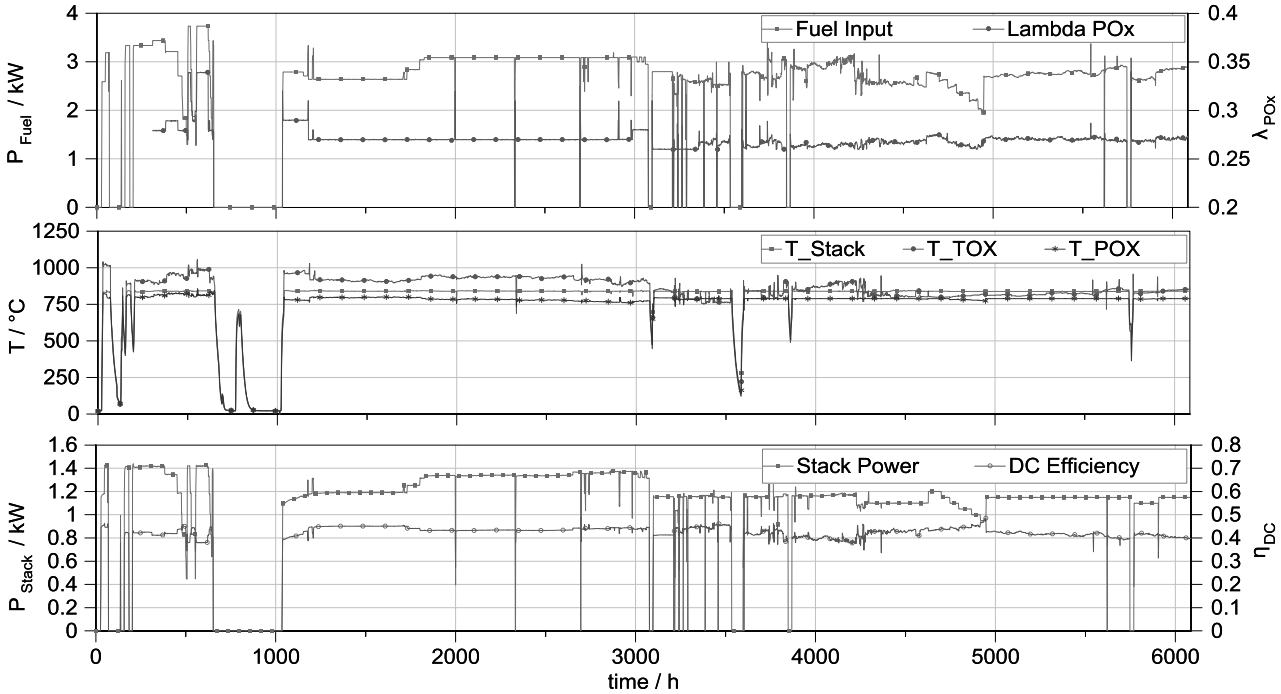

Fig. 9 Overview of the initial characterization test with one of the h2e® Proof-of-Concept prototype systems. Test procedure includes steady state operation at rated power output and scheduled part load operation for process analysis.

The part load characteristics of the h2e® Proof-of-concept prototype systems is summarized in Figure 10. During the system characterization tests, a power modulation range between 1.420 and 450 W(el, gross) was proven. The stack fuel utilization was kept constant at 80 % down to a power output of 820 W(el), and was reduced at lower power outputs in order to maintain the desired HotBox temperatures. The electrical efficiency showed, however, satisfying values, considering the fact that it is a water-less system based on dry partial oxidation. The balance of plant (BoP) power demand is dominated by the cathode air fan and the programmable logic con-troller (PLC). With a micro-controller based control unit and improved power conditioning system (PCS) in later system generations, an even higher net electrical efficiency can be expected.

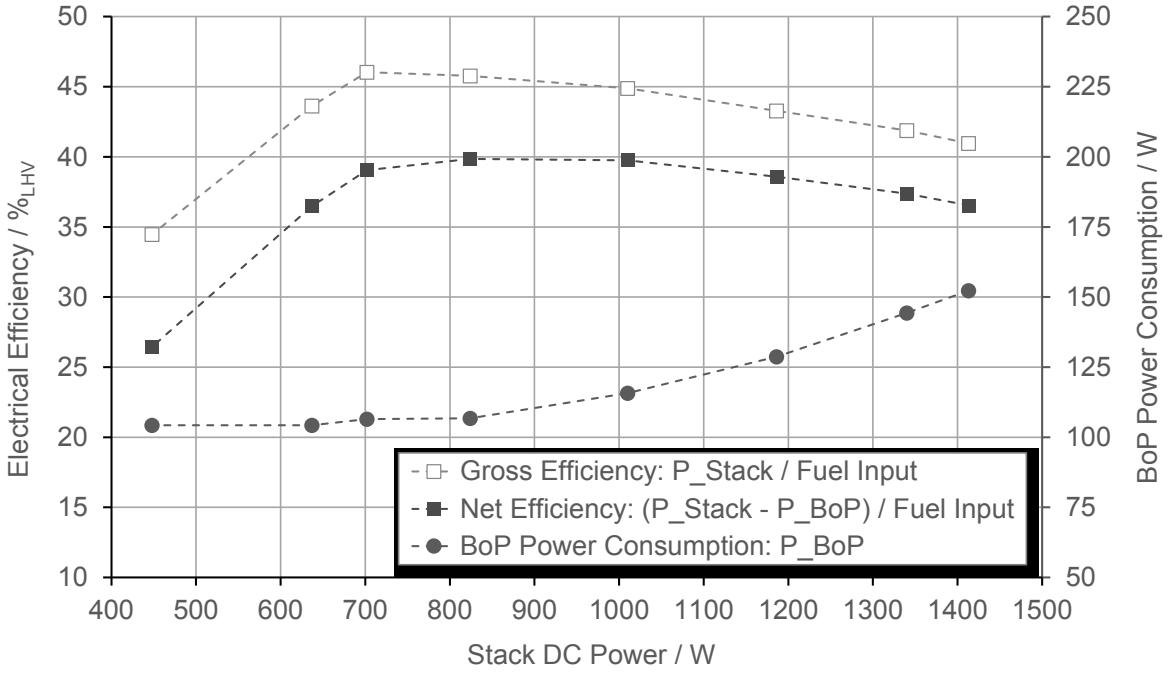

Fig. 10 Part load characteristics of the h2e® Proof-of-Concept prototype system. Stack fuel utilization was kept constant at 80 % between 1.400 W(el) and 800 W(el), and was reduced at lower power outputs to maintain desired HotBox temperatures.

Following the successful system commissioning and acceptance test, one of the h2e® Proof-of-Concept prototype systems was shipped to Pune, India, and installed in a laboratory owned by the customer for test, training and demonstration activities (cf. Figure 8). The second prototype system is remaining at IKTS for further technical development, i.e. process automation and parameter tuning, followed by endurance operation mimicking real-world conditions.

4. Demonstration Prototypes

The commissioning of the Proof-of-Concept prototype systems marked the completion of project phase I according to the contracted work plan. Afterwards, project phase II was initiated, which included a system design review towards cost and manufacturability. Based on the operational experience with the Proof-of-Concept prototype systems, it was decided to reconfigure the exhaust heat exchangers for cathode air pre-heating and hot water preparation, using improved heat exchangers made by alternative suppliers. Furthermore, the electric air pre-heater for system start-up was integrated into the HotBox, leading to a significant reduction in volume. The CFY stack configuration was reduced to a single 40-cell stack, providing sufficient power output for the intended application.

Additional design changes aimed at the reduction of system-internal losses, facilitated system assembly and maintenance, as well as simplified process instrumentation for reliable and robust process controls. Major activities during project phase II were dedicated to the process automation and safety concept implementation. Based on a state machine with sub-ordinated control loops, all routines for fully automated system operation including start-ups, steady-state operation with changing fuel compositions, load changes, and shutdowns have been implemented. A machine safety concept based on a risk assessment according to DIN EN ISO 12100 was applied in terms of organizational and technical measures of hazard prevention, including an independent safety control unit.

Fig. 11 Demonstration prototype systems during assembly (left); finished prototype unit with detached laboratory PCS and control unit (right).

Three demonstration prototypes were assembled and commissioned at IKTS (cf. Figure 11). For acceptance testing, a laboratory power conditioning system (PCS) and control unit was used, which is detached from the SOFC power generator. After shipment of the prototype units to the customer, a near-product PCS with integrated micro-controller will be used for system operation. This PCS, which is built to purpose by Pune-based company Magnaflux Systems Pvt. Ltd., is designed to provide higher AC/DC and DC/DC conversion efficiencies, and will serve as the master control unit for SOFC system operation, storage battery integration, and inclusion of additional DC sources (e.g. PV modules).
In parallel to the demonstration prototype development at IKTS, the knowledge transfer, vendor sourcing and infrastructure development for local manufacturing and commercialization of h2e® systems in sole responsibility of the customer was initiated. It is expected that h2e Power Systems Pvt. Ltd. will start in 2017 with the commercial deployment of SOFC power generators in India.

References

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