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Summary		
<p>The RealDemo –project was a joint research project focused on enabling the commercialization of the solid oxide fuel cell (SOFC) technology. The project lasted from 2012 to 2014. The project's research partners were VTT, LUT and the Aalto University.</p> <p>The targets of the project were (i) to improve the reliability of SOFC systems, (ii) to simplify the system structure in order to bring down the investment and servicing costs and (iii) to identify the potential applications for the first SOFC system demonstrations.</p> <p>A systematic and formal methodology to extract high-fidelity measurement data for data-based model development was investigated with a complete 10 kW SOFC system. By utilizing the obtained experimental data, it was found that the reliability of the system can be improved by utilizing case-specific, data-based approaches for system diagnosis i.e. to identify sensor faults and abnormal operating conditions. Significant reduction of the systems' instrumentation as well as advanced control were also found possible with the data based methods.</p> <p>Several solutions simplifying the system structure were investigated and developed, including novel thermal insulation and supports, fuel recirculation and generation of system safety gases from fuel. Additionally, the results achieved in the power electronics research will lead to more efficient and reliable power conversion equipment for fuel cell systems in particular but also for other applications e.g. solar cells and battery packs.</p> <p>With improved efficiency of the power electronics, the electrical efficiency of the SOFC system can be increased to 54% and beyond. In total, over 10,000 operating hours were accumulated for the 10 kW SOFC demonstration unit by the end of the project.</p>		
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Preface

The RealDemo –project was a joint research project focused on enabling the commercialization of the SOFC technology. The project lasted from 1.3.2012 to 1.7.2014.

The project was led by VTT Technical Research Centre of Finland with Lappeenranta University of Technology and the Aalto University School of Engineering being two other research partners. The project was a part of the Fuel Cell Programme of the Finnish Funding Agency for Innovation, Tekes. The funding for the project came from Tekes, a group of industrial partners and the research partners themselves. The partners' funding effort is gratefully acknowledged.

The project's steering group is acknowledged for its active guidance and support during the project. Finally, the authors thank all the persons who worked for the project for their high-grade contribution which has been essential for accomplishing the project targets successfully.

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Authors

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1. Introduction

Solid oxide fuel cells (SOFCs) are electrochemical power generation devices operating at a high temperature. SOFCs have several benefits e.g., high efficiency, low emissions and fuel flexibility which make them an attractive technology for distributed generation, APUs and various other applications.

The SOFC technology is under intense development globally by various industrial companies and research organizations. Since 2010, SOFCs have started to progressively emerge to the market, mainly in Japan as small-scale (<1 kW_{el}) residential systems and in the USA as large (100+ kW_{el}) systems for distributed generation and prime power. In Europe, there are several SMEs working together with the heating appliance industry to realize large-scale field demonstrations of several hundreds of SOFC power units [1].

In Finland, an active group of companies and research organizations has been undertaking an effort to develop the SOFC system and stack technology towards market readiness for domestic use and for export. Among this group, VTT has actively promoted the development of SOFCs on a national level by coordinating and implementing several national jointly funded research projects [2-4]. Additionally, VTT has participated in, as well as coordinated, several EU-funded research projects in the same field [2]. This research report summarizes the main results of the RealDemo research project, which is the latest step in a 10-year effort on SOFC stack and system research in Finland.

The RealDemo research project was funded by the Fuel Cell Programme of Tekes, the Finnish Funding Agency for Innovation, by industrial companies and by the project's research partners. The project formed a direct continuation to earlier SOFC R&D efforts [2-4] and could thus fully utilize the existing research infrastructure, tools and the know-how accumulated in the preceding research projects. The general aim of the project was to increase the readiness of the SOFC system technology for market penetration by realizing improvements on system reliability and efficiency, and by identifying the potential applications for system demonstrations. The research parties in the project were VTT Technical Research Centre of Finland (VTT), Lappeenranta University of Technology (LUT) and the Aalto University School of Science and Technology (Aalto).

Only a summary of the main results of RealDemo is presented here. A more detailed and in-depth description of the project's results is available as publicly available publications listed at the end of this report.

2. Goal

The general purpose of the RealDemo project was to promote the demonstration and market penetration of power plants and products based on the SOFC technology. To this end, the project sought to develop technology, know-how, solutions and relevant up-to-date information, in order to support companies working on such fields as

- i) SOFC system integration and manufacturing
- ii) Balance-of-plant component supply and manufacturing
- iii) Fuel supply and power production

The need for the research project was evident since, despite the great potential of the SOFC technology, the actual operating time of state-of-the-art prototype systems has been too short for commercial applications. The short operational time is partly due to the limited operational experience of the various components and the stacks themselves in actual system conditions. The consequences manifest as too frequent disturbances and component failures which lead to operation interruptions. Additionally, though the operational characteristics of

individual components in SOFC systems are well understood, their interactions in real-world systems are less so. Identification between insignificant and critical patterns in system behaviour is typically done by experienced operators and designers of the prototype systems. In order to realize both autonomous and reliable operation of commercial SOFC systems, the monitoring and diagnosis of system behaviour needs to be automated. These challenges are addressed in the WP1 (Table 1).

In addition to methods and algorithms that enable identification and recovery of faults, the reliability of the actual hardware, i.e. both individual components and the system as a whole, has to be improved to a level which enables long enough servicing intervals. Concurrently, by utilizing novel designs for the systems' components and by optimizing its operating conditions, the targeted electrical efficiency of the SOFC systems should exceed 50% in order to create enough competitive edge for market penetration. WPs 2, 4 and 5 each provide solutions for complete systems, thermal integration of components and power conversion equipment, respectively, which help to enable required improvements of reliability and efficiency.

The investment cost for the first SOFC power plants is high compared to the technology that already exists on the market. This creates yet another barrier for the widespread market introduction of SOFCs. The challenges related to high costs can be alleviated by finding the most profitable applications and market segments for the first demonstration systems. WP3 addresses this challenge by firstly identifying applications where the advantageous features of the SOFCs, such as fuel flexibility, negligible emissions, high efficiency, modularity and low noise, can create added value for the customer, and secondly, by analysing which pre-requisites are the most critical on making the products more profitable compare to the competing technologies.

Table 1. Project's work packages, realizing partner and main targets

Work package		Partner	Target results
WP1	Diagnostics	VTT	Improved system reliability and lifetime by advanced diagnosis methods and algorithms
WP2	System	VTT	System experiments to develop diagnosis tools Improved reliability for BoP -components and structures Increased system electric efficiency
WP3	Applications	VTT	Applications and enablers for commercial demonstration of SOFCs
WP4	Thermal integration	Aalto	Novel and cost-efficient thermal insulation solutions
WP5	Power electronics	LUT	High efficiency power conversion equipment for fuel and solar cells

3. Results

3.1 WP1 Diagnostics

The main result of the Diagnostics work package is the adoption and validation of a new work paradigm based on formal experiment design and regression analysis of experimental data. Tangible outcomes of this result in the RealDemo project are the validated, data-based regression models for the fault diagnosis and monitoring of SOFC system components. An MLR-based fault diagnostics algorithm for the recycle flow meter was developed, implemented and verified in real operation and a similar model for the SOFC stack maximum temperature was applied in a real system for stack temperature control [3]. Advanced models for accurate monitoring and control of the stack temperature were developed and validated (Figure 1) [4].

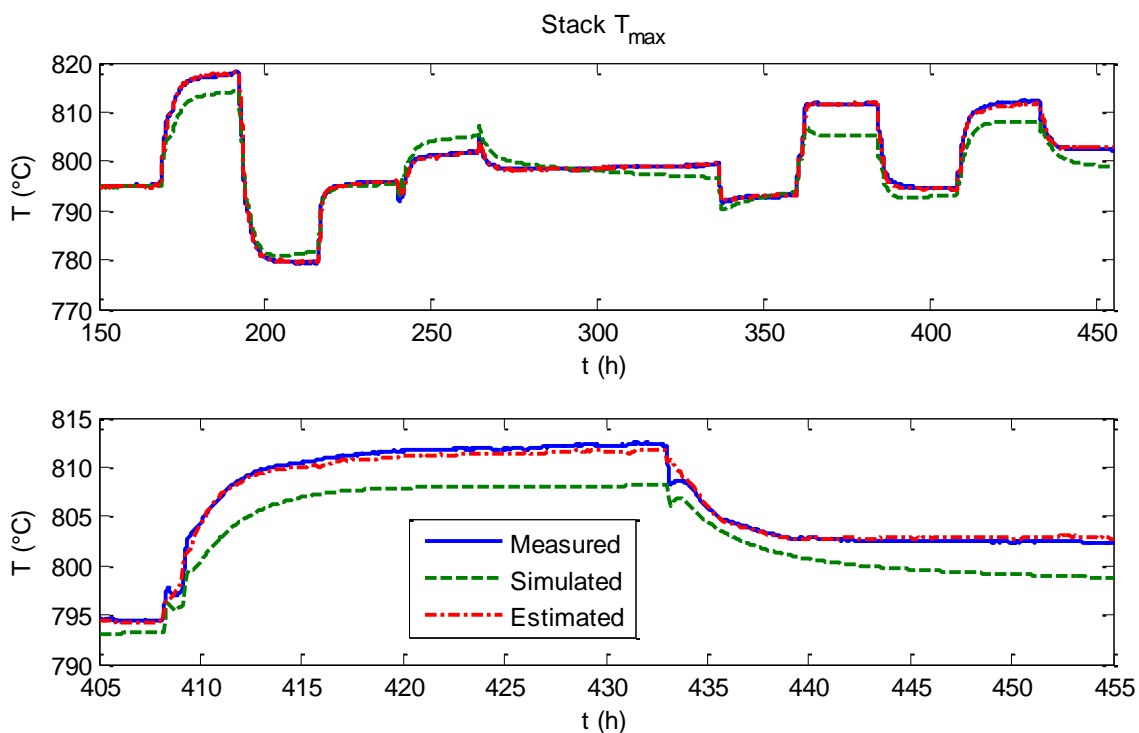


Figure 1 - An example of the stack temperature monitoring model performance. The estimate (red dashed line) remains within 1°C of the measured stack maximum temperature (blue solid line) also during transient operation. Bottom figure is zoomed in on the top figure.

The Diagnostics work package started with an empirical survey into potential computational methods of data analysis and modeling, applicable to SOFC system diagnostics purposes [5]. As a key result, it was observed that case-specific, data-based approaches fared significantly better than those based on physical modeling. Additionally, an algorithm for gas pipeline clogging detection and isolation was demonstrated and the MLR method was found especially efficient considering stack monitoring. Based on these results, the importance of experiment design issues and quality of data were recognized. This led to incorporating the design of experiments methodology as one part of the experimental and modeling work carried out in RealDemo [6]. The excellent SOFC stack temperature estimation tools obtained based on the RealDemo experiments speak clearly for the validity of the chosen approach [8-12].

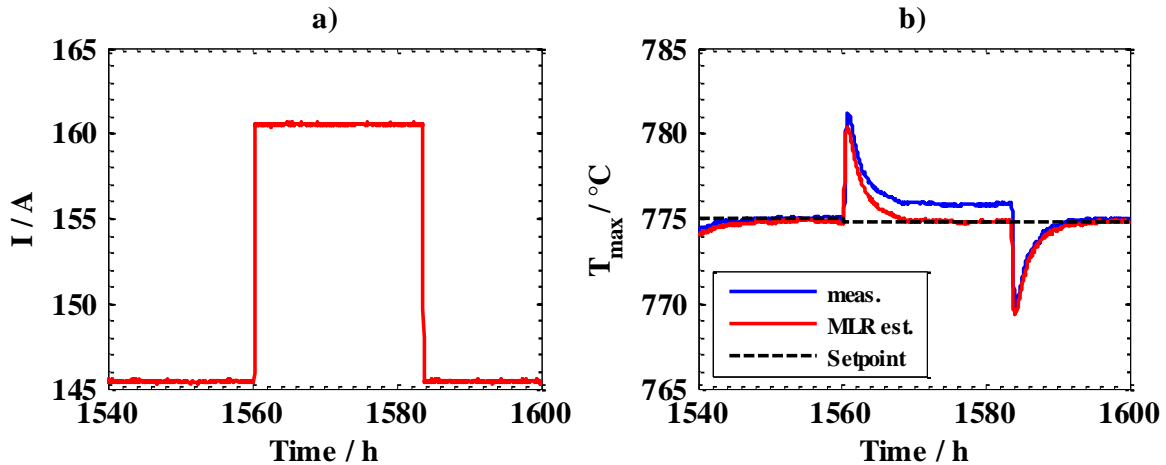


Figure 2 - Application of a model developed in WP1 for the closed loop-control of stack temperature during a load change. Subfigure a), the stack current and subfigure b) the measured, estimated and setpoint value of the stack maximum temperature.

The models developed in WP1 enables studying advanced, model-based control strategies for the SOFC system [7]. The simulated output in Figure 3 illustrates how, for instance, regulation of the SOFC stack maximum temperature could also be carried out if both air inlet temperature and air flow were simultaneously manipulated during the control maneuver. (In the case shown in Figure 2, only air temperature was manipulated.) The control algorithm is now based on a stack model and it is seen that a shorter settling time of the temperature can be obtained while still maintaining the system inputs within the operation envelope.

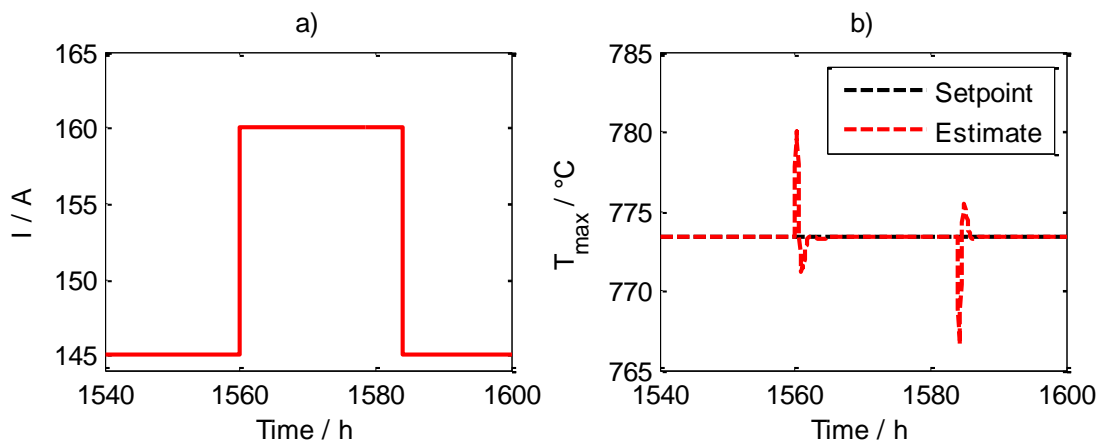


Figure 3 - Simulation of model-based control of the stack maximum temperature.

3.2 WP2 System

The main results of the WP2 are coupled to the outcome of the WP1, as the 10 kW demonstration unit was used to provide the experimental data necessary to the research and development of the diagnosis tools. Furthermore, the demo unit provided a real-world test-bench for implementing and validating these tools. At the start of the project, several improvements were carried out on the 10 kW demo to expand its' operational envelope and so to enable the execution of the formally designed experiments [8]. After the refurbishments, the 10 kW demo was successfully utilized to (i) conduct several designed experiments, to (ii) obtain the experimental data for diagnosis tool development and finally to (iii) implement and validate the developed diagnosis tools in real-world system operation. [6,7,9-13].

Improvement of the SOFC demo unit electrical efficiency was recorded during the project and compared to the previous system generation (Figure 4). Electrical efficiencies of over 65% and 50% are possible for the stack and the complete system, respectively. Such improvements in the efficiency can be obtained by optimizing the stack operating conditions, which increases the stack gross efficiency, and by using more efficient power conversion equipment, which decreases the system parasitic losses.

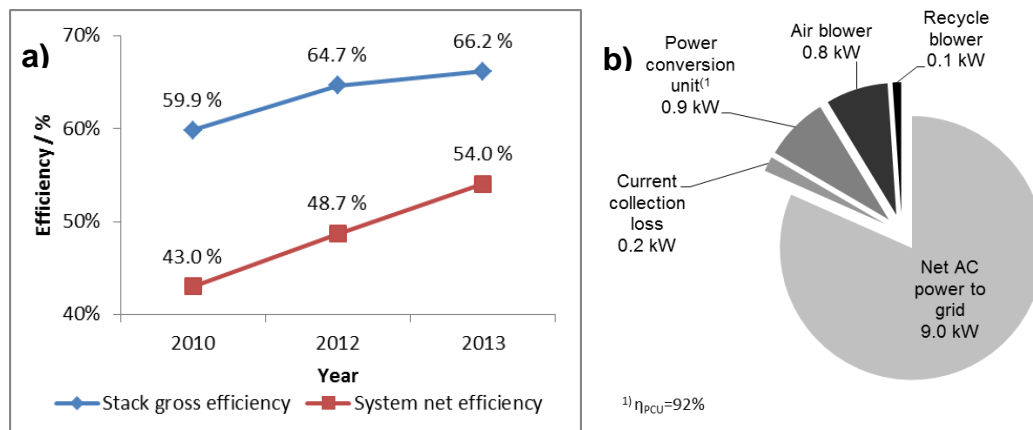


Figure 4. (a) Improvement of system efficiency and (b) system parasitic losses at nominal operating point

Over 10,000 hours of cumulative operating time was achieved for the SOFC unit by the end of the project (Figure 5). Several BoP-components, e.g. heat exchangers, blowers, insulation and supports have been used throughout that period without failures or detectable degradation in performance. More importantly, different modes of failure or degradation for several other BoP-components, e.g. recycling and fuel processing equipment, have been identified and solved during the project thus improving the reliability and lifetime of the system as a whole. Additionally, advanced analysis methods e.g. to detect failures due to increased stack leakages were developed and validated [9]. Tangible achievements on improved reliability and durability of the system are e.g.

- 5000-hour operation of the fuel reformer without performance degradation
- Recovery of the anode-off gas recycling equipment from sensor failures
- Improved afterburner design to prevent catalyst damage

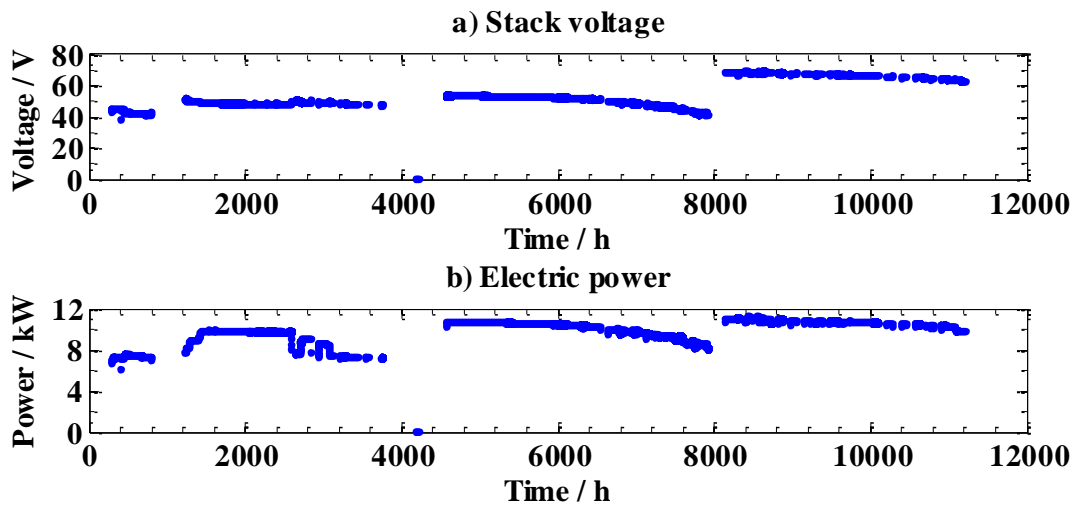


Figure 5. (a) Voltage and (b) electric power of the SOFC stacks during the operational history of the 10 kW demonstration unit at or near nominal operating conditions.

Novel solutions for SOFC system operation and process design, which can simplify the system design and system costs, were also investigated. The focus of this work was in the fuel processing subsystem. The results include:

- Establishment of operational constraints for an ejector-based anode off-gas recirculation subsystem. The ejector-based solution can replace a high-temperature recycle blower and thus simplify the recycling equipment [10].
- Elimination of the need for safety gases during system start-up. When no safety gas storage is necessary the investment and servicing costs as well as the physical system size decrease [11].
- Screening of alternative suppliers of precious-metal catalysts for reforming of natural gas and long-term evaluation of the performance and durability of catalysts available for SOFC use [12], [13].

3.3 WP3 Applications

The main goal of the Applications work package was to evaluate the possibilities for a commercial demonstration of SOFC technology in the most promising case applications. The case applications were identified based on the unique properties of SOFC systems, with a focus on domestic markets for SOFC units of up to 200 kW electric power capacity per unit. To support the techno-economic evaluation of the case applications, the performance of a state-of-the-art stationary SOFC system was estimated by systems modelling during the first funding period of the project [14]. The work and results from both of the project's funding periods are comprised in the final report of the work package [15].

In order to assess the profitability of SOFC investments in a set of applications, a flexible techno-economic spreadsheet model was developed. This model takes as inputs the key performance indicators derived from the SOFC demo unit's system model results [14], supplementary technical assumptions and economic assumptions on energy market price levels. The reference technologies, against which the SOFC units' economy is compared against, include reciprocating gas-fired CHP as well as back-up power generation and standard battery systems used in conventional uninterruptible power supply systems.

Out of seven discussed niche applications identified as promising for SOFC demonstrations, three applications were chosen for further case studies. These were:

1. Data Centre
2. Greenhouse
3. Hypermarket

The properties of the case studies are given in Table 2. Both the reference technologies and the demand profiles for power and heat differ strongly between the cases, giving a good basis for the overall evaluation of SOFC-technology's economic potential.

Table 2. Summary of assumed case properties.

	Data Centre	Greenhouse	Hypermarket	
Average electric power load	385	389	70	kWe
Required electricity	3 372 600	3 407 640	613 200	kWh/year
Peak power load	385	586	83	kW
Peak heat load	0	1 143	66	kW
Required heat	0	5 006 340	289 080	kWh, heat/year
System power sizing based on:	Average power load	Peak power load	Peak power load	
Other case properties:	UPS battery banks in reference system.	Heat pumps installed with SOFC system. CO ₂ demand at site.		

Each of the cases' economic profitability was assessed in situations where the investment was made in the SOFC units as an early mover (at a higher cost) or later on in the future as an n:th of a kind investment (at a lower cost). The economic life of investments was assumed to be 15 years. Table 3 summarises the economic and SOFC system related assumptions in the two market scenarios.

Table 3. The techno-economic assumptions in the “early mover” and “n:th of a kind” market scenarios.

Energy prices and main economic assumptions	Early mover	N:th of a kind	
Natural gas price	0,0675	0,0743	€/kWh
Price of purchased electricity (transferred at location)	0,1200	0,1320	€/kWh
Revenue from sold electricity	0,0200	0,0220	€/kWh
Price of purchased/sold heat	0,1000	0,1100	€/kWh
Annual trend in all prices		2 %	
Economic life		15	a
Interest rate (cost of capital)		5 %	/a
SOFC system performance			
Maximum unit size		200	kW
Electric efficiency (Beginning of Life)		55 %	
Allowed el. efficiency minimum	50 %	45 %	
Overall efficiency (CHP)	85 %	90 %	
Decrease of electric efficiency	0,40 %	0,20 %	/1 000 h
<i>Number of stack replacements in 15 years of operation</i>	9	2	times
SOFC system investment costs			
Stack unit	2 000 €	850 €	/kW
Total cost of system	4 250 €	2 000 €	/kW
Stack unit cost reduction trend		5 %	/a

Case 1: Data Centre. Data centres are highly energy intensive facilities, with a pronounced need for uninterruptible power supply. The conventional data centres deploy generator sets (GenSet) for self-sufficient power supply for critical systems during shortages in grid electricity. Typically, a GenSet consists of several smaller units to increase redundancy of the power supply. Additionally, a battery system is needed to provide the necessary power to the equipment during the start-up of the backup aggregates. SOFC units can replace the UPS batteries and GenSets, since they can operate in island mode and provide uninterrupted power during grid outages.

The results indicate that the SOFC investment is unprofitable for an early mover. This is mainly due to the assumed high investment cost for the system (4 250 €/kW) together with the mediocre stack life (<13 000 h). The payback times for SOFC data centre and other cases in both market scenarios are given in Figure 6. The profitability of an n:th of a kind SOFC investment in a data centre resulted in a positive net present value (NPV) over its economic life.

Case 2: Greenhouse. Of the three case examples, the greenhouse had an especially high system complexity due to strong differences between peak and average power and heat consumption, need for a constant CO₂ fertilization and an option to provide heat from an auxiliary natural gas firing boiler and from heat pumps on top of the SOFC units with heat recovery.

Again, the SOFC system investment in an early mover scenario resulted in substantial economic losses. The reasons for unprofitability were mainly the short stack replacement interval and the fact that the SOFC system was competing with technology that had a far lower initial investment cost. With the SOFC-related techno-economic assumptions and the market levels of the “n:th of a kind”-scenario, the SOFC-investment ended up slightly below break-even point during its economic lifetime. In the n:th of a kind SOFC application in a greenhouse, almost half of the heat was generated by SOFC-powered heat pumps. For the cumulative

NPVs of the SOFC and competing reference technology over the economic life, see Figure 6.

Case 3: Hypermarket. An average modern Finnish hypermarket of 3 000 m² has a peak power consumption of 83 kW electricity and 66 kW heat. The case hypermarket is connected to both natural gas and district heating networks. The reference technology option consists of only a backup generator set. The SOFC alternative runs in CHP mode and excess electricity is sold to grid. Similarly to the other case examples, with short stack life assumption (< 2 years), the SOFC investment is not economically feasible (see Figure 6).

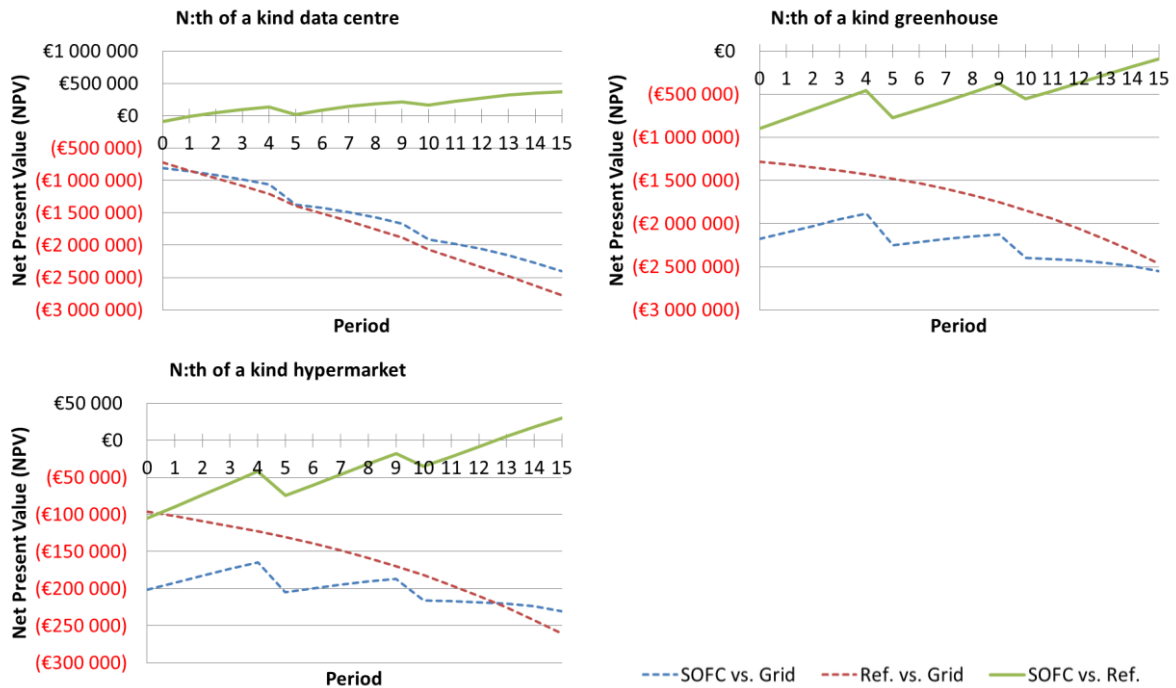


Figure 6. Payback times of the case SOFC applications compared to conventional heating and backup power in the assumed market scenarios.

Feed-in tariff is provided for installations that produce electricity to the grid from biogas in Finland. The price guarantee for such electricity amounts to 83.50 €/MWh. When the installation utilizes the produced heat to the point that the overall efficiency reaches at least 50%, a premium of 50€/MWh is added on top of the feed-in tariff. The feed-in tariff is paid until the end of 12th year of operation. The prerequisites seem to suit quite well on the case examples; the installation must be a complete new-build, and the power production capacity must be at least 100kVA after the installations own power consumption is accounted for. The feed-in tariff is not available if the investment of the installation was rewarded state support. Therefore these two subsidy instruments cannot co-exist for the case applications. The current Finnish subsidy scheme is summarised in Table 4.

Table 4: Subsidy scheme for biogas firing CHP plant in Finland (electric capacity >100kW and overall efficiency >50%)

Feed-in tariff		
Price guarantee	133.5	€/MWh
Annual decline of feed-in tariff	0	%
Availability of feed-in tariff	12	Years
Investment support		
Amount of support	8-30	% of investment

The effect of the current Finnish feed-in tariff for electricity from biogas was tested on the above case examples. The concluding result was that the NPVs of the SOFC investments were not considerably improved due to the support system. The case facilities consume most of the power they produce so the income from feed-in tariff remained limited, even if the heat premium was included. The investment support on the other hand only applies to the initial fixed costs; the burden from stack renewals is not mitigated by an investment support. The current subsidy instruments were only tested in the “early mover”-scenario with high investment cost and short stack lifetime. The final report of the WP3 includes a more detailed analysis of market price levels and subsidies. Also techno-economic assumptions of both the cases and SOFC units are further studied in the report in order to present break-even scenarios for the selected applications.

Judging by the NPVs, the data centre and hypermarket cases of the presented stationary SOFC power and CHP applications seem the most promising once the investment costs of the stack units come down. However, the differences between the results of the three cases in the “n:th of a kind”-scenario are not very large. Varying the purchase prices of gas and electricity would affect the results substantially.

The current price levels are hard to define, as the markets are driven mainly by subsidised early movers and the technology is on the learning curve. The effect of model parameter values to the early mover application is summarised in Figure 7. The stack unit costs with its anticipated future cost reduction trend are some of the most important parameters. The rate of electric efficiency decrease and its allowed minimum also play a major role in determining the each case’s profitability. The SOFC system dimensioning in the early mover applications should be made by Beginning-of-Life (BoL) electric output if possible to avoid over capacity. It should be taken into account that coping with the high stack unit cost is connected with research and development on lowering the rate of cell degradation and also the system design to allow for as much cell degradation within stack replacement cycle as possible without compromising the adequate performance of the system. This should be considered when investing on early demonstrations.

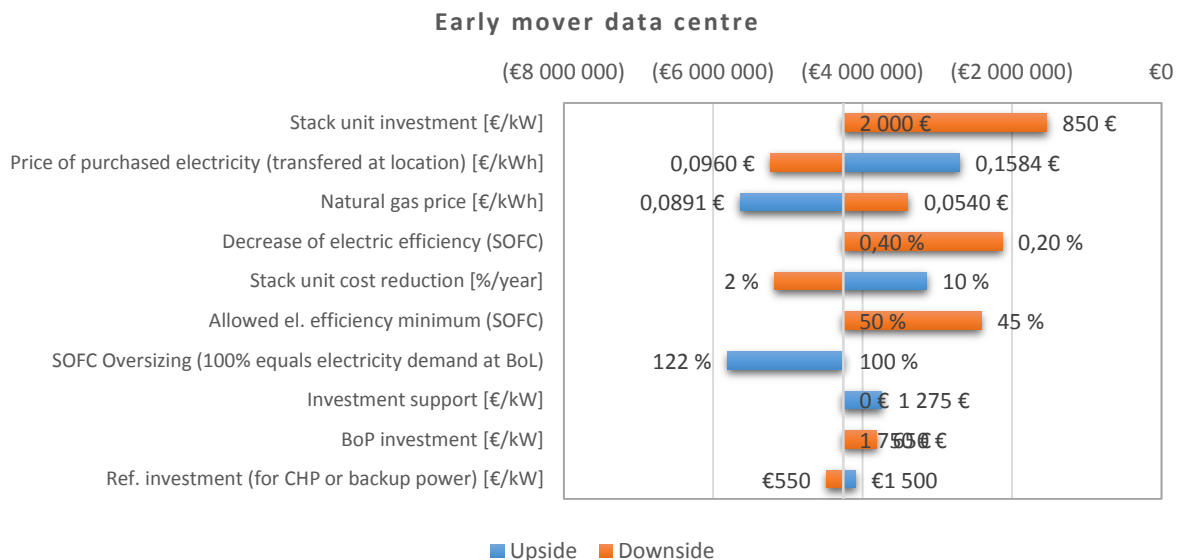


Figure 7. The most significant parameters contributing to the NPV of choosing SOFC over reference in the early mover scenario for a Data Centre.

3.4 WP4 Thermal integration

In WP4 research was done on two sub-topics: Thermal Insulation Concepts and Component Supports. These two functions are in close interaction and should be designed together. An experimental test-rig was designed and built to investigate and test new solutions in conditions that simulate SOFC systems in use.

3.4.1 Component support and system layout

Thermal expansion and thermal cycling of system structures cause stress and displacements in the structure and components. The most common solution to this problem has been the use of flexible metal bellows between rigidly supported components. In order to eliminate the need for costly bellows an alternative solution was researched: use of rigid support in a single location of the system while allowing free thermal expansion of the components to other directions from the single fixed location.

A new lead-through flange was designed, manufactured and tested (Figure 8). This specific lead-through enables overlapping thermal insulation material, thus reducing heat loss through gaps that can form in the insulation during the systems lifetime. In addition, thermal conduction is reduced by long thermal bridge and thin material. At the system level this lead-through flange works as a stationary thermal centre at the border between a hot system enclosure and the cooler exterior components and it is the only rigid support for the whole piping structure. Cool exterior components are attached to this point by hot piping that has thermal expansion. Thus, cool components were supported by linear bearings (Figure 9a) that allow low friction movement in the axial direction. In the radial direction the movement of this component was minimal, and it was compensated by flex in the support structure.

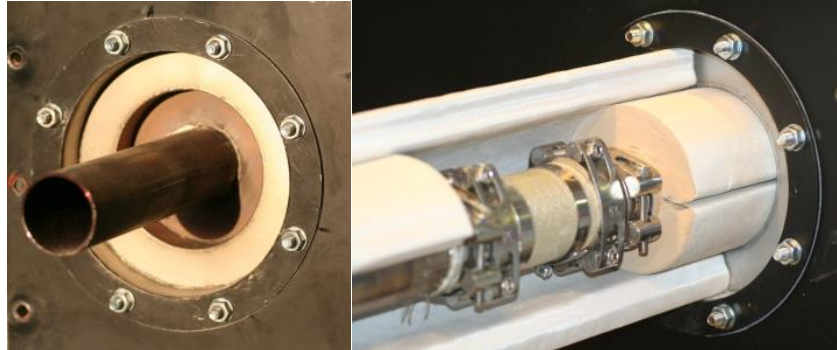


Figure 8 Stepped lead-through (316L, s=1 mm) for piping allows overlapping the thermal insulation at the connection of pipe and system enclosure. In this figure pipe sections are used on the outside that is visible in the picture, and panel or granular insulation is used on the inside for thermal insulation.

A cradle type component support was used inside the hot thermally insulated enclosure (Figure 9b). One of the highlights of this solution is that it eliminates thermal bridges through the insulation due to support structures [16]. The support spreads the weight of the component and piping to a larger area over the thermal insulation board (Promalight 1000X) and the support is anchored to place with small spikes stabbed in the board. After the experiments the boards had no cracks or other deformation around the support. In addition, the support provides sliding contact in the axial direction where the thermal expansion displacement is greatest. In the radial direction the support centralizes the component and allows smaller displacements. The support is made of sheet metal (316L, s=2 mm). Manufacturing and assembly of this support does not need any welding and can be done economically by automated machines. In conclusion, the use of moving or flexing supports for cool and hot components instead of expensive and less durable pipe bellows is a feasible solution [16].

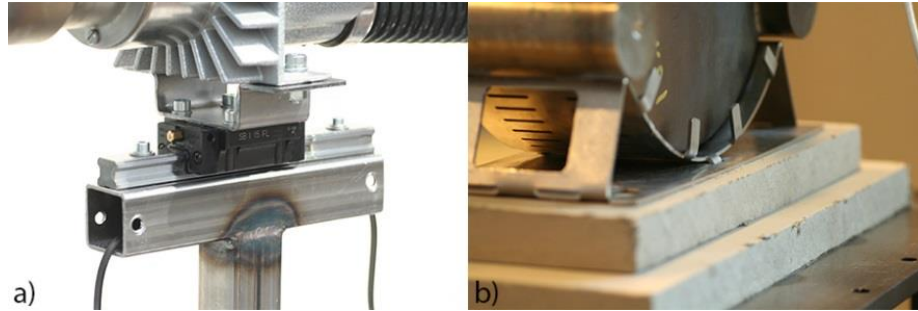


Figure 9 a) Cool component support that utilizes linear bearing between frame and component. b) Hot cradle-type component support that enables sliding contact between the component and the support structure in the axial direction.

3.4.2 Thermal insulation concepts

Selection of right thermal insulation concept is critical to realize an efficient SOFC system [17], [18]. Thus, it is relevant to evaluate alternative insulation concepts in their actual working environment. The test rig was used to investigate three concepts for the SOFC Balance of Plant: traditional box-type insulation and two novel concepts that are granular insulation and hybrid insulation (Figure 10).

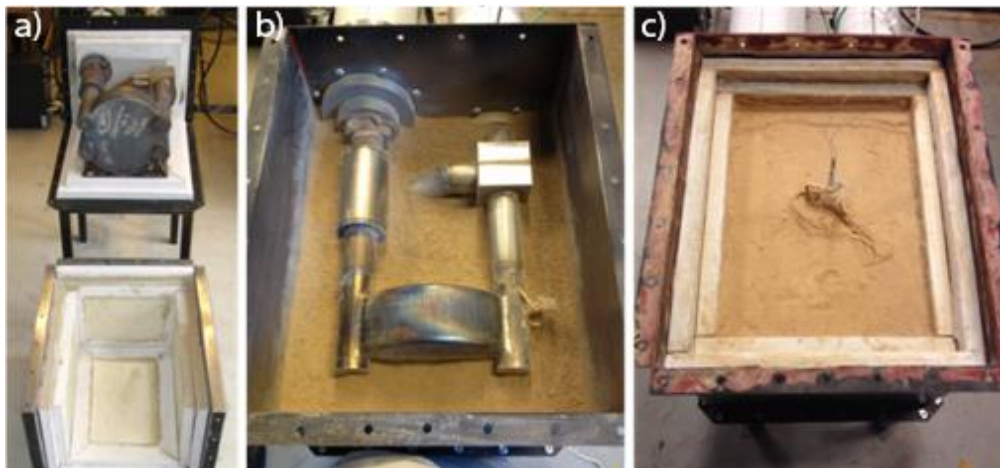


Figure 10 a) box-type insulation, b) granular insulation, c) hybrid insulation. Granular material is Promat FREEFLOW® 220 and panel is Promalight 1000X.

Main results from the experiments [19] were:

- i) Assembly time of the Granular insulation was 30 minutes which is significantly faster than assembly of the panel insulation that took 40 hours. The dusting of the insulation was roughly the same with both concepts, but with granular insulation the dust fallout was smaller due to shorter exposure time.
- ii) The material cost for granular insulation was 30 % less than for panel insulation.
- iii) Thermal loss of the system with the panel insulation was 150 W while Granular and Hybrid insulations reduced thermal loss to 110 W while steel structure remained the same [Figure 11]. One should note that thermal loss of the lead-through's is roughly 50–70 W of this amount, stating that performance of granular insulation is considerably better compared to panel insulation in this unit.

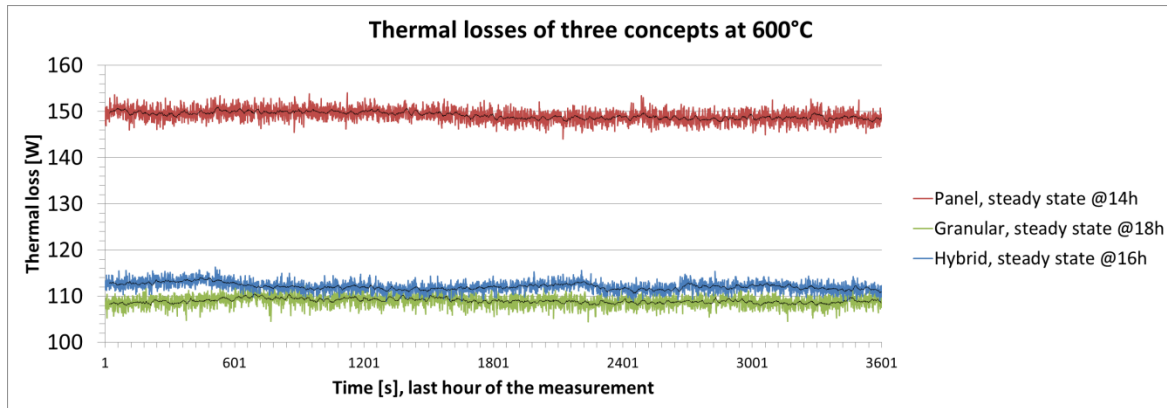


Figure 11 Thermal loss of the panel insulation was measured to be 150 W while granular and hybrid insulations resulted roughly 110 W of thermal loss.

As a conclusion, the granular insulation was the best solution in this investigation. Panel or Hybrid insulation had no advantages compared with pure Granular insulation in this unit. Disadvantages of the Hybrid insulation are greater cost and added assembly time when compared to pure Granular insulation. Secondary observations from the experiments were:

- iv) Microporous insulation can absorb 3–5 m% of water. Moisture in thermal insulation reduces thermal resistance and is otherwise harmful to the system accelerating corrosion and posing threats to high voltage conductors. Thus the use of moisture permeable layer on the outer surface of the thermal insulation is recommended.
- v) Granular insulation solidifies slightly in use. This can be seen beneficial, as it forms a block around the components (Figure 12) that seem to resist compaction in use. Inspection did not reveal any cracks in this block due to thermal cycling or thermal expansion.



Figure 12 Removal of the granular insulation by vacuuming after the experiments. Note how the granules have bonded together forming a uniform insulation block.

3.5 WP5 Power electronics

The main emphasis on the power electronics research has been in phenomena related to soft switching DC/DC converters. The previous research efforts [17] have focused on low voltage, high current converters, where the soft switching techniques are not very beneficial [20]. In order to reduce conduction losses the fuel cell stacks can be designed to output voltages in excess of 150 VDC. The design approach for low voltage converters (fast and hard switching) may not be applicable to higher voltages, since the switching losses can become excessive and the high switching speed combined to the high voltage can cause destructive parasitic currents in the switching transistors. Therefore, in order to reduce switching losses and electromagnetic interference, the converter topology must be capable of soft switching.

3.5.1 Bi-directional converters

A bi-directional converter allows bi-directional power flow between the source and the load. A battery pack for example is a load which requires a bi-directional converter. The battery pack needs to be charged, but also discharged in a controlled manner.

A brief overview of recently published topologies and their operating principles is given and a bi-directional full bridge boost topology is presented in [21]. As was noted in the thesis, the topology is not very well suited for high voltage-low voltage conversion, but performs better in low voltage-high voltage conversion. The presented design and modelling principles are applicable to other bidirectional topologies as well.

The resonant push-pull topology previously presented in uni-directional operating mode [22] was modified to handle bi-directional power transformer in the ECCE publication [23]. The modification was made by replacing the passive secondary rectifiers with active switches and changing the way the transistors are controlled. The bi-directional capability enables the topology to be used also in applications where high voltage conversion ratio and two-way power transfer is required (like in high voltage DC link and battery interfacing).

3.5.2 Winding loss calculation methods

When designing a magnetic component, like a transformer, for a certain application, the number of possible alternatives is enormous. If the specifications for voltage and current levels are fixed, there are still a large number of changeable parameters affecting the transformer size and efficiency.

To make an economically feasible design, it is preferable to automate the design procedure to cover most, if not all, of the possible design alternatives. There are several commercial software that are capable of doing this kind of optimization, but sometimes the simplifications made to speed up the process can result in large calculation errors (and therefore expensive components that do not work as expected).

An example of a transformer optimization is presented with the parameters given in Table 5:

Table 5. Transformer design parameters.

Primary voltage	Output voltage	Duty cycle	Power ¹	Frequency
240 V	480 V	0.4	1 kW	100 kHz

¹primary RMS current 4.66 A, secondary RMS current 2.33 A

Table 6 illustrates the differences in calculation accuracy between a commercial Ansoft PExprt software (with the most detailed modeling method selected), MATLAB tools developed based on [20] and [24] and 2D finite element method (FEM) modelling.

Table 6. Example of resistance calculation accuracies between different methods.

	PExprt (1)	2D FEM (1)	MATLAB tool (2)	2D FEM (2)
Core	ETD49, N87	ETD49, N87	ETD49, N87	ETD49, N87
Primary winding	21 turns 1.65 mm ²	21 turns 1.65 mm ²	21 turns 1.5 mm ²	21 turns 1.5 mm ²
Secondary winding	42 turns 1.65 mm ²	42 turns 1.65 mm ²	42 turns 0.39 mm ²	42 turns 0.39 mm ²
Short circuit re- sistance referred to primary	58.7 mΩ	500 mΩ	214.5 mΩ	179.4 mΩ

It can be seen that the total AC resistance is about 8.5 times higher than the resistance given by PExprt. This would also mean 8.5 times higher losses, if the current is the same in both cases. The result of this kind of loss underestimation could be transformer overheating and failure.

The difference in the total AC resistance between MATLAB tool and 2D FEM is about 20% and the FEM actually produces smaller short circuit resistance than the analytical calculation. Small overestimation in resistances can be considered safer in practice than underestimation, since the lower resistances would generate less losses and heat than anticipated.

The calculation inaccuracies when using inductors is discussed in a publication prepared for EPE2014 conference [25]. The purpose of the paper is to illustrate how the magnetic core affects the winding resistance measurements, what kind of inaccuracies there are in the loss calculations of multi-layer inductor windings and how do the inductor air gaps affect the calculated (and measured) resistances.

3.5.3 Filter damping methods

Filters are needed in switching converters to filter out the unwanted frequency components. The problem of traditional filter self-resonance damping methods for example in LC-filters are the additional components, which in some cases can become quite bulky and lossy thus increasing the size and cost of equipment and decreasing the total efficiency. In the RealDemo project the research aim was to implement the damping into the main inductor without external components. This can be done by increasing the inductor AC resistance without affecting the DC resistance. This design approach will be presented in a publication prepared for EPE2014 conference [26]. The proposed approach can reduce the number of components, enable cheaper inductors and also improve overall filter efficiency.

3.5.4 Soft switching converters

Dual Active Bridge (DAB) topology is a DC/DC converter topology, which does not require other energy storage inductors than the inherent transformer leakage inductance. The leakage inductance is utilized in achieving Zero Voltage Switching (ZVS) for the primary and secondary transistors.

If using basic modulation methods e.g. Phase-Shift Modulation (PSM) with the DAB topology, the zero voltage switching range is quite narrow. When the operating point shifts away from the nominal design point, the zero voltage switching is lost and the efficiency is degraded. Various modulation methods have previously been presented in order to widen the ZVS range, but the methods are typically tied to a certain circuit configuration and the converter stability during the modulator changes is not discussed. During the RealDemo project a Variable Frequency Modulation (VFM) method based on variable switching frequency has been studied.

The VFM method is insensitive to DAB hardware configuration and can be utilized only with few equations on a digital signal processor. The efficiency improvement potential of the method is illustrated in Figure 13.

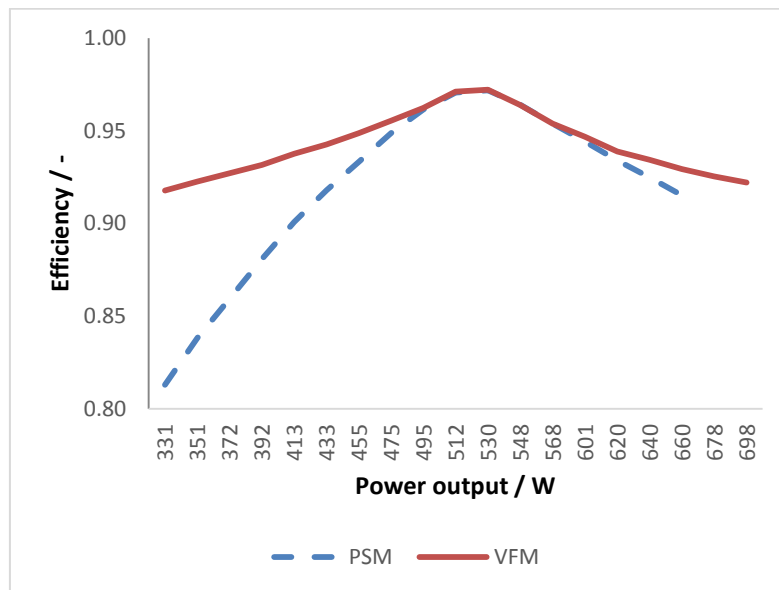


Figure 13. Efficiency comparison between basic phase-shift modulation (PSM) and variable frequency modulation (VFM). The input current reference is set at constant 4 A and the input voltage is changed.

It can be seen from Figure 13 that in PSM method the efficiency drops rapidly as the input voltage decreases and the converter becomes hard switched. The VFM method maintains the soft switching conditions and the efficiency curve remains almost flat and above 90% over the entire power range despite the increasing switching frequency. The VFM algorithm also decreases the current peaks of the transistors and the transformer, which results also in lower RMS currents and thus conduction losses. In VFM the dI/dt values are also lower, which reduces the possibility of voltage transients. An article is being written on the subject and it is planned to be published in an IEEE journal [27]. The modulation and control issues will be further discussed in the doctoral thesis currently prepared by Hiltunen [28].

4. International networking and dissemination

The project consortium has been active in maintaining and expanding its international relationship network. The project parties have participated in several FCH JU –funded projects, many of the RealDemo project results have been and are published in international scientific journals as well as conferences.

Bilateral research exchange has also been significant. The project enabled international long-term researcher exchange (total 2 person-years) from Lappeenranta University of Technology to Virginia Tech in USA and from École polytechnique fédérale de Lausanne (EPFL) in Switzerland to VTT. Additionally, shorter term (1-3 person-months) researcher exchange took place between VTT and EPFL, CEA (France) and POLITO (Italy).

During the RealDemo -project, VTT has participated in nine and coordinated two SOFC related FCH JU –funded projects (ASSENT, Cation, Genius, DeSign, SOFC-Life, SOFCom, DIAMOND, NELLHI, StageSOFC) [2]. Additionally, LUT is currently participating in StageSOFC project funded by the FCH JU. Until recently, VTT held a position in the IEA Advanced Fuel Cells Annex, a global workshop of the fuel cell community.

The results of the project are published extensively on the international scientific forum. In total, 16 publications [6,7,10-13,15,17,22-24,28-32] were prepared during the project. 13 public presentations, listed in Section 6, regarding the projects results were given.

5. Summary and conclusions

The targets of the project were (i) to improve the reliability of SOFC system, (ii) to simplify the system structure to bring down the investment and servicing costs and (iii) to identify the potential applications for first SOFC system demonstrations.

In the project, a systematic and formal methodology to extract high-fidelity measurement data for data based model development was investigated with the VTT 10 kW SOFC system. By utilizing the resulted experimental data, it was found that the reliability of the system can be improved by utilizing case-specific, data-based approaches for system diagnosis i.e. to identify sensor faults and abnormal operating conditions. Additionally, individual balance of components' reliability and lifetime was improved by correcting design and dimensioning flaws that realize only after extended operation in system environment. In total, over 10,000 operating hours was accumulated for the 10 kW demo unit by the end of the project.

Significant reduction of the systems' instrumentation was also found possible with the data based methods. Here, application of regression models enables accurate and reliable estimation and control of the internal temperature of the stack with simple and cheap system instrumentation, thus eliminating the need for costly and complex internal temperature sensor arrangements for the stacks. More advanced model-based control strategies for the SOFC system were investigated as well, which can be used in the future to optimize the system operating conditions for maximum efficiency and lifetime.

Solutions simplifying system structure were developed for thermal insulation and supports, where a novel granular insulation was found feasible for SOFC system use. Granular insulation provides both shorter assembly times and better insulation properties. Additionally, novel solutions for fuel subsystem i.e. ejectors for fuel recycling and generation of safety gases from fuel were investigated and developed, which provide simpler and cheaper system.

Results achieved in the power electronics research will lead to more efficient and reliable power conversion equipment for fuel cell systems in particular but also for other applications e.g. solar cells and battery packs. In particular, the active modulation methods can improve converter efficiency ($90\% \leq \eta \leq 99$) in a wide load range and especially at light loads, where the traditional methods perform poorly. With improved efficiency for the power electronics, the electrical efficiency of the SOFC system can be increased to 54% and beyond.

Redundant power production in a data centre, a greenhouse and a hypermarket were chosen for case profitability studies after promising applications for demonstration of SOFC technology were screened during the study. Out of the three case applications, the data centre had the shortest payback time, when system investment of 2 000 €/kW (stack 850 €/kW) was assumed. The application additionally benefitted from a capital intensive reference technology, making the data centre stand out as the most promising future demonstration for SOFCs. As a side-product of the study, a flexible spreadsheet model was developed. The model has potential uses in the future for pre-feasibility concept evaluations.

6. Public presentations

- 1) M. Halinen, A. Pohjoranta, J. Pennanen, and J. Kiviaho, "*Application of Multivariable Regression Model for SOFC Stack Temperature Estimation in System Environment*" 11th European SOFC and SOE Forum 2014, Lucerne, 2014.
- 2) M. Halinen, A. Pohjoranta, J. Pennanen, and J. Kiviaho, "*Stack temperature estimation in system environment by utilizing the design of experiments methodology*" 13th International Symposium on Solid Oxide Fuel Cells (SOFC-XIII), Okinawa, Oct. 6-11, 2013.
- 3) Pohjoranta, M. Halinen, J. Pennanen, and J. Kiviaho, "*Dynamic SOFC Temperature Modeling with Designed Experiments and Time-Series Model Identification*", 11th European SOFC and SOE Forum, Lucerne, 2014.
- 4) Pohjoranta, M. Halinen, J. Pennanen, and J. Kiviaho, "*Simple data-based methods for SOFC stack temperature estimation in system environment*", EERA Workshop, Rome, Dec. 10th, 2013
- 5) M. Halinen, "*Solid Oxide Fuel Cell Systems - Efficient electricity production from natural gas*", Gasumin kaasurahaston seminaari, Helsinki, Dec. 10th, 2013
- 6) J. Hiltunen, V. Väisänen ja P. Silventoinen, "*A bidirectional current-fed resonant push-pull converter for low voltage, high current applications*", Energy Conversion Congress and Exposition (ECCE), 2013.
- 7) V. Väisänen, J. Hiltunen, J. Nerg ja P. Silventoinen, "*AC resistance calculation methods and practical design considerations when using litz wire*", 39th Annual Conference of the IEEE Industrial Electronics Society (IECON), 2013.
- 8) J. Hiltunen, "*High power density DC/DC converter for energy storage applications*", Fuel Cell Annual Seminar, 2013.
- 9) V. Väisänen, "*Galvanically isolated DC/DC converters in fuel cell applications*", 6th Fuel Cell systems Workshop, Brugge, 2013.
- 10) V. Väisänen, "*Electrical conversion and connection: DC/DC and DC/AC converters in grid interfacing*", SOFC Summer School, Crete, 2012.
- 11) V. Väisänen, "*Grid connection of distributed generation*", SOFC Summer School, Crete, 2012.
- 12) J. Hiltunen, "*Benefits of latest semiconductor technologies for fuel cell power electronics*", 7th Fuel Cell Systems Workshop, Brugge, 2014
- 13) P. Salminen et al., "*Evaluation of Thermal Insulation Concepts for the Balance of Plant of a Solid Oxide Fuel Cell System*", in 13th International Symposium, Topical problems in the field of electrical and power engineering, Pärnu, 2013, pp. 323-329.

7. Theses

- 1) H. Järvisalo, "*Kaksisuuntaisen DC/DC hakkurin virtasäätö polttokennosovelluksessa, Master's Thesis, Lappeenranta*", Lappeenranta University of Technology, 2013.
- 2) J. Tallgren, "*Reforming of Natural Gas for Solid Oxide Fuel Cells*", Master's Thesis, Aalto University School of Science, 2013
- 3) J. Hiltunen, Doctoral thesis, "*Improving Power Conversion Efficiency and Reliability by Means of Modulation*", (unpublished, in preparation).
- 4) M. Halinen, Doctoral thesis, "*Design and Operation of Solid Oxide Fuel Cell Systems with Anode Off-Gas Recycling*", (unpublished, in preparation).

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