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Residential fuel cell systems - a future option of distributed CHP generation?

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Residential Fuel Cell Systems – a future option of distributed CHP generation?

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1 Introduction

For several years, stationary Fuel Cell applications have been an object of the research activities at the chair of energy systems engineering and heat economy of the Technische Universität Dresden. Besides the scientific attendance of a number field trials, advanced principles for the assessment of stationary Fuel Cell use are worked out in the context of energy-economical expertises and model supported analyses.
Since the end of 1997 the installation and operation of an ONSI-PAFC system within a hospital in the German city of Kamenz was supported. The 250 kW_{el} Fuel Cell was a part of a complex solar supported combined heat, power and air conditioning system. In the year 2005 the Fuel Cell stack accomplished 40.000 hours of operation. In addition, since 2001, the chair is one of the contractors in the field-trial programme "DemoCell" of the German gas supplier Verbundnetz Gas AG (VNG), where in total eight residential Fuel Cell systems in the power range up to 4,7 kW_{el} have been operated in real world conditions.
Besides a huge set of high-resolution measurement data covering energy demand and system operation, a manifold expert knowledge on the technical boundary conditions of the Fuel Cell use in various practical applications arose from the continuous collaboration in those projects.

2 Development pathways of the Fuel Cell technology

Figure 1 shows a general sketch of the current development pathways of the Fuel Cell technology. The further descriptions will cover stationary applications, only.
Apart from the Fuel Cell use for grid independent electricity generation, e.g. in communications technology or as backup-power supplies, there are three main development lines of stationary Fuel Cells, differing in the power range and the announced field of operation [3]:

- Residential Fuel Cell systems (up to 10 kW_{el}),
- Block-type Fuel Cell systems (10 kW_{el} .. 1 MW_{el}),
- Fuel Cell power plants and combined cycles.

From the multitude of the theoretically possible configurations of electrochemical converters almost only the PEFC, the PAFC, the MCFC and the SOFC have emanated as the technologies of choice for stationary applications. If fossil fuels are used, a fundamental technical advantage may be attributed to the high-temperature Fuel Cells (MCFC and SOFC), resulting in various options for system simplifications, in higher electrical efficiencies as well as in the possibility of using the higher exergy content of the exhaust gases for further electricity generation.

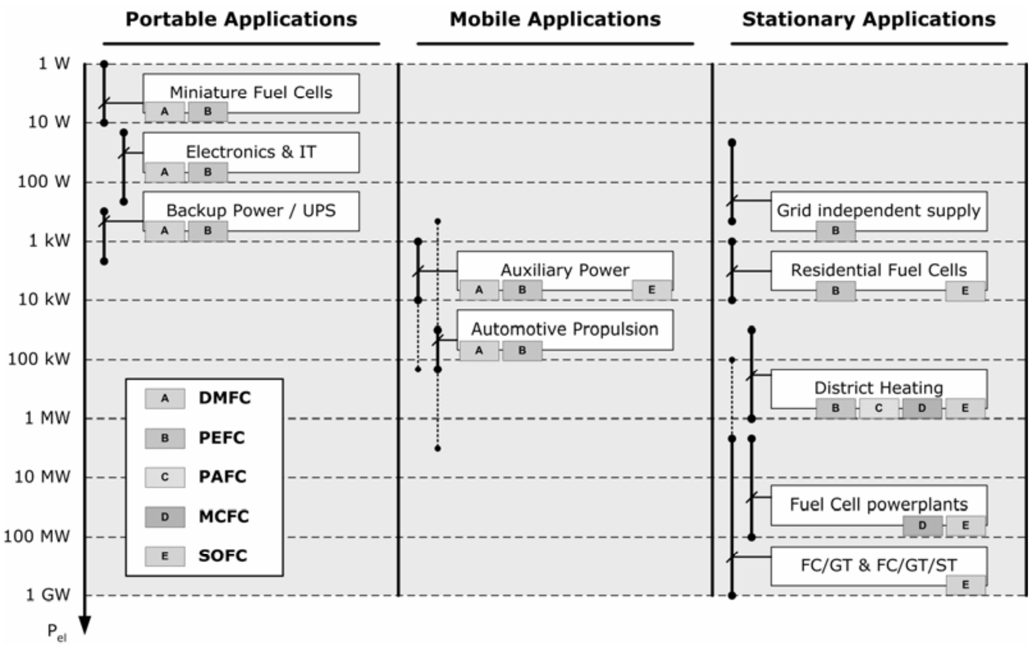

Figure 1: Development pathways of the Fuel Cell technology

Stationary Fuel Cell systems are developed and tested in various power ranges since around 1970. At the end of the year 2004 the total number of stationary Fuel Cells ever installed - in terms of research projects, prototypes and small production series - was approx. 3200. First in 1992, a larger growth in the power range above 10 kW_{el} was to notice, indicating the increasing general interest in Fuel Cell applications. Fuel Cell systems in the range below 10 kW_{el} were increasingly developed after the year 2000, only [1, 2]. Today, for the Fuel Cell systems currently in operation in the power range up to 10 kW_{el}, including backup-power systems and grid independent applications, a total number of approx. 2000 units worldwide can be assumed. The number of larger systems up to 1 MW_{el} is around 250 units worldwide. The total installed (and available) Fuel Cell power capacity adds up to approx. 50 MW_{el}.

2.1 Residential Fuel Cell systems

With the development of small stationary Fuel Cells for the electricity and heat generation in single or multiple family homes it is primarily aimed to substitute the conventional (separated) energy supply to individual customers with decentralized CHP generation, at least partially. Due to the continuously tightened energy conservation regulations a declining heat demand of residential buildings is expected in the future, why predominantly gas suppliers are currently interested in the development of decentralized CHP-systems.

It can be assessed, that by far the largest share of all the worldwide development activities in the field of stationary Fuel Cells is concentrated in the power range below 10 kW_{el} and mainly focused on the PEFC-technology. With respect to certain circumstances and from an energy-economic point of view, these developments may be judged critically as it will be discussed in section 3.

2.2 Block-type Fuel Cell systems

The development of stationary Fuel Cells was pushed in the 1990s mainly by the U.S. company ONSI (today UTC) with the production of a 200 kW_{el} PAFC-system. In the following years PEFC-, MCFC- and SOFC-systems in the same power range have been presented by other companies as well. Due to remaining technical barriers and limited cost reduction potentials, several development projects have been interrupted in between (e.g. ONSI, Siemens Westinghouse) or stopped completely, meanwhile (Ballard). Nevertheless, with a stack lifetime above the 40.000 hours and electrical efficiencies between 35% and 40%, those block-type Fuel Cells approved their technical competitiveness compared to conventional decentralized CHP-systems like IC-engines or micro turbines.
As it is the case for conventional block-type CHP-units, the profitability of stationary Fuel Cells for decentralized electricity generation and district heating is hardly to achieve under the present monetary conditions of the liberalized energy market. Subject to a compulsory reduction of the specific investment cost, the future domain of block-type Fuel Cell systems may be expected in smaller industrial CHP-applications as well as in combined electricity, heat and air conditioning systems for larger commercial buildings.

2.3 Fuel Cell power plants and combined cycles

In the 1990s already, the first Fuel Cell systems with an electrical power output in the range of several MW_{el} have been presented by the Japanese companies Toshiba and Fuji - primarily in terms of connecting a number of smaller units in parallel. This concept is currently followed by the U.S. company Fuel Cell Energy, which develops power plant units up to 2 MW_{el} by arranging several 250 kW_{el} MCFC-modules around a central fuel and air processing unit. But even with opening up larger power capacities, the electrical efficiencies of Fuel Cell systems will remain below the level of modern power plant processes, why the use of Fuel Cells for electricity generation only is just restrictedly to be legitimated.
The better application of Fuel Cells with respect to thermodynamic and especially exergetic considerations is to see in the combination with a Joule- and/or Clausius-Rankine-cycle. The proof of concept for those combined cycles was shown by the company Siemens Westinghouse, which unveiled a pressurized SOFC & gas turbine system with a power output of 220 kW_{el} and a nominal electrical efficiency of 52% in the year 2000 [4]. However, the adaptation of those system concepts for power plants of larger capacities is right at the beginnings at present - and the number of companies and research institutes currently active in this field of application is very limited. New impulses for the Fuel Cell use in a central power plant scale are to be expected by publicly founded research projects, e.g. the contract between General Electric and the U.S. Department of Energy (signed in August 2005, [5]) for the demonstration of a 100 MW_{el} SOFC & gas turbine power plant with integrated coal gasification having a development budget of 86 million US$ for a period of 10 years.
Conceptual analyses have shown however, that even with highly integrated processes and the consecutive connection of a SOFC, a Joule process and a Clausius-Rankine process a much higher efficiency level compared to conventional combined cycle power plants (gas & steam) is hardly to achieve [6].

3 Decentralized CHP generation by residential Fuel Cell systems

Almost all European heating equipment manufacturers and a large number of utilities (mainly gas suppliers) as well as research institutes, universities and medium-sized enterprises are involved in development projects and field trials of stationary Fuel Cells for residential CHP generation in single and multi family homes or in smaller commercial applications. By substituting a growing share of conventional boilers with Fuel Cells in the power range up to 10 kW_{el}, the opening up of a potential mass market for Fuel Cells and other CHP technologies is expected - culminating in the vision of "Virtual Power Plants" consisting of thousands of networked residential CHP systems. However, first practical experiences and model supported examinations show that the potential use of small stationary Fuel Cells could be limited by the technical and economic conditions of the present energy supply structures - and of course by unavoidable scale-down effects.
From an energy-economic point of view, the current challenges of residential Fuel Cells may be addressed by the following keywords:

- primary energy consumption and efficiency numbers,
- characteristics of the electricity an heat demand of individual consumers,
- investment cost and operational profitability,
- marketing strategies and the "business case".

In the next sections some of the relevant aspects are briefly discussed.

3.1 Primary energy consumption and efficiency numbers

As it is the case for all the known electricity generation processes, smaller Fuel Cells will only achieve lower conversion efficiencies than comparable units in the power plant scale. In addition to the expectable scale-down effects and the higher share of thermal losses and auxiliary power consumption, especially the fuel preparation for the Fuel Cell process as well as the DC/AC-conversion show a significantly decreasing efficiency at a smaller system sizes. In contrast to that, with CHP generation the lower electrical efficiency is partially compensated by the use of the thermal losses for room heating and hot water preparation purposes.
The acceptable efficiency level of a decentralized CHP unit is limited by the primary energy demand for a comparable amount of electricity and heat (e.g. the annual consumption of an individual customer) delivered within the conventional energy supply structures by a central power plant and a heating system at the customer site. From a simplified approach for this comparison (schematically shown in Figure 2) the following equations of the minimum electrical and total utilization ratios of decentralized CHP-units can be derived:

$$\zeta_{el,eq} = \left(\frac{1}{\chi \cdot \zeta_{PPLT} \cdot \zeta_G} + \frac{1-\psi}{\sigma_a \cdot \zeta_H} \right)^{-1} \quad \text{and} \quad \zeta_{tot,eq} = \zeta_{el,eq} \cdot \left(1 + \frac{1-\psi}{\sigma_a} \right).$$

The symbols in those equations denote the following dimensionless numbers (to be calculated for instance on an annual basis):

- $\zeta_{el,eq}$ Electrical utilization ratio of the CHP-unit for equivalent PE-consumption
- $\zeta_{tot,eq}$ Total utilization ratio of the CHP-unit for equivalent PE-consumption
- ζ_{PPLT} Utilization ratio of the electricity generation process (comparison basis)
- ζ_G Average efficiency of the electricity distribution grid

- ζ_H Thermal utilization ratio of the local heating system (comparison basis)
- χ Demand coverage of the decentralized electricity generation (0..100%)
- σ_a Cogeneration index of the CHP-unit (electricity to heat ratio)
- ψ Share of the electricity generation in non-CHP-operation (0..100%)

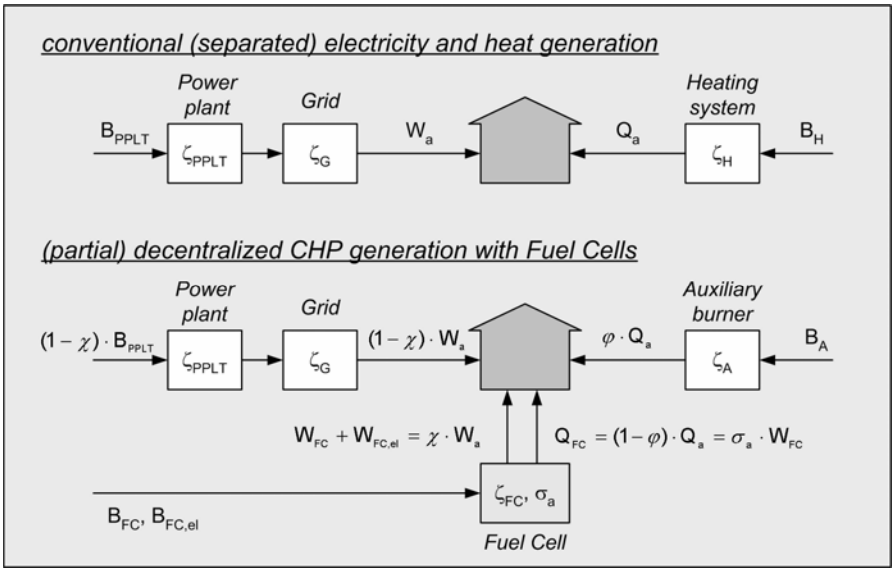

Figure 2: Simplified approach for the comparison of the PE consumption

The results of the given equations are shown in Figure 3 as a function of ζ_{PPLT} and σ_a using the following assumptions: χ = 0,75; ζ_G = 0,95; ζ_H = 0,75 and ψ = 0.

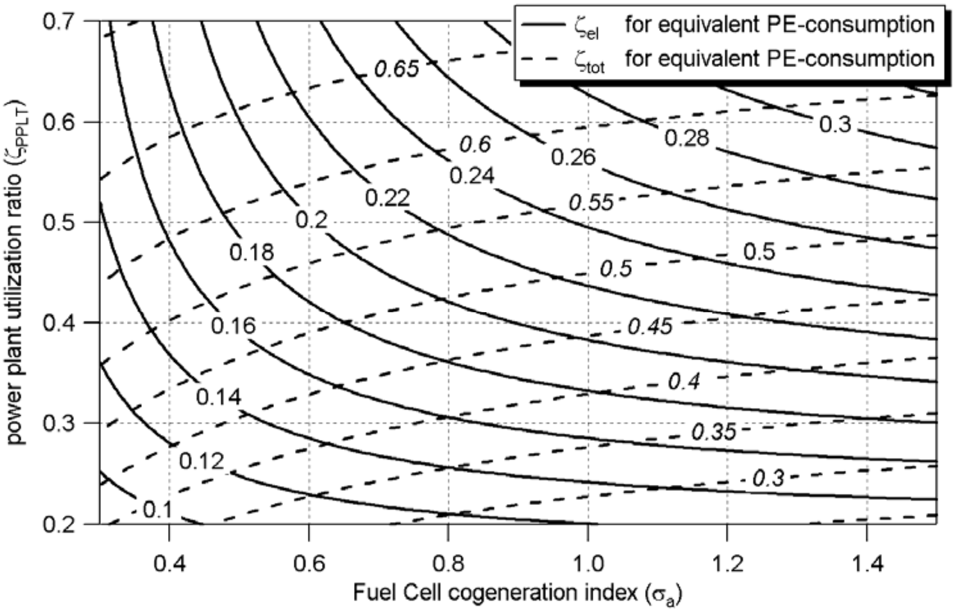

Figure 3: Minimum utilization ratios of residential Fuel Cells for an equivalent PE-consumption compared to conventional electricity and heat generation

For residential Fuel Cell system at the present development stage with a cogeneration index between 0,40 (SOFC: HXS1000 of Sulzer HEXIS) and 0,67 (PEFC: EURO2 of Vaillant / Plug Power) the following numbers of the minimum utilization ratios can be derived from Figure 3:

– compared to the German power plant mix in the year 2004 (ζ_{PPLT} = 0,381):
$\zeta_{el,eq}$ = 0,14 .. 0,18 and $\zeta_{tot,eq}$ = 0,50 .. 0,44,

– compared to a gas & steam turbine combined cycle power plant (ζ_{PPLT} = 0,55):
$\zeta_{el,eq}$ = 0,17 .. 0,22 and $\zeta_{tot,eq}$ = 0,60 .. 0,55.

Although those numbers seem to be easily achievable, they currently denote a quite challenging goal for the developers of residential Fuel Cell systems. Only if these estimated requirements in the conversion efficiency are roughly fulfilled, a justification for the use of residential Fuel Cell systems is given. A considerable energy-economic advantage of Fuel Cells in decentralized CHP generation will only be achieved at even higher numbers of the primary energy utilization.

3.2 Electricity and heat demand structures of individual consumers

The maximum values of the electricity and heat demand of individual consumers by far exceed the average numbers to be expected from standardized load curves or annually accumulated energy amounts. Exemplary measurements in several German single family households have shown, that a maximum electrical power demand between 5 and 8 kW_{el} and a maximum heating requirement between 16 and 20 kW_{th} (due to hot water preparation) can be generally assumed.
The dimensioning of a residential Fuel Cell system on the basis of the expected maximum demand values would result in a much too oversized unit, with limited chances for showing operational profitability, and violating the capacity limit of power input to the low-voltage distribution grid. In consequence of this, during the operation of a well sized residential Fuel Cell the power distribution grid acts as a peak load source in times of higher electricity demand - and an auxiliary burner covers the higher thermal loads. Due to those circumstances, the main components of the conventional electricity and heat supply system are still required and only a partial substitution of the base load by CHP generation with residential Fuel Cells will appear.

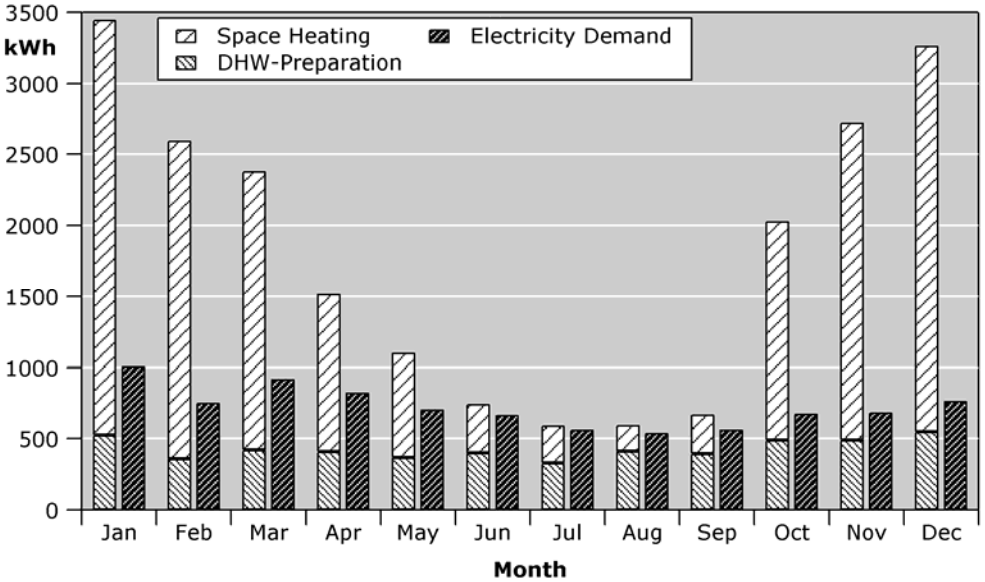

Figure 4: Exemplary measurement data of the monthly heat and electricity demand of a German single family househould (4 persons)

Looking at the monthly heat and electricity demand of an individual consumer (example in Figure 4), another dimensioning problem is obvious. Assumed that the Fuel Cell is designed to cover the household's electricity demand on a monthly or annual basis, a cogeneration index (electrical to thermal power ratio) close to the value of 1 or even above is required during the summer period in order to avoid heat dissipation to the ambient surroundings.
If the value of the cogeneration index is much lower, i.e. the thermal power output of the Fuel Cell process exceeds the amount of electricity generation, the unit's working point has to be reduced or usable heat has to be disposed, resulting in a decreasing total efficiency. In practice, most of the residential Fuel Cells operated in the field today are completely switched off outside of the heating period.
In conclusion of that it can be stated that residential Fuel Cells will unlikely substitute a noticeable share of central power generation capacity and that for a full coverage of the heat demand an auxiliary burner is required, which is in principle comparable to the conventional heating equipment that is installed at the customer site today.

3.3 Manufacturing cost of Fuel Cell systems

At present, the system cost of stationary Fuel Cells exceed the specific investment cost of conventional power generation technologies by a factor between 2,5 and 20 [7]. The transition from the current research and development stage to the expected market entry of stationary Fuel Cells leads to both the chance and the imperative requirement of substantial manufacturing cost reductions.
The effect of increasing production numbers, technological innovations and economic boundary conditions is commonly analyzed and forecasted using the theory of learning or experience curves. Starting from the current manufacturing cost of stationary Fuel Cells and with appropriate assumptions for the investment cost goals and the accumulated installed capacity until reaching the retail market readiness, the necessary progress ratios can be estimated. With respect to residential and block-type Fuel Cell systems the progress ratios to be achieved are in the range between 20% and 28% [8], i.e. when doubling the number of produced systems the manufacturing cost have to be reduced by a percentage in the denoted order of magnitude. Compared to the previous established development lines within the energy technologies those progress rates have to be seen as very ambitious cost reduction goals. In the manufacturing of conventional power plants within a period of several decades, only much smaller progress rates have been achieved. Progress ratios close to 20% were proved merely in the area of photovoltaics.

3.4 Fuel Cells in Virtual Power Plants

Both the operation of stationary Fuel Cells as well as the networking of distributed units within so called virtual power plants are two independent technological concepts, discussed as possible future development trends in the field of the energy technologies. The combination of those two development lines in a common context frequently to be found at present is not based on an inevitable technological connection or a special suitability of Fuel Cells for the formation of virtual power plants. It is rather a result of the search for new operational and business concepts in order to prepare the market entry of Fuel Cells, assuming distinctive advantages compared to the classical sales structures in the heating equipment market.
A virtual power plant is a system of units and components which - at unique consideration - do not have the function and power output of an energy conversion process in the power plant scale. The networked operation of those units with a cen-

tralized or hierarchically structured control system is supposed to create a device that can fulfil the functionality of a power plant unit within a circumscribed accounting area. The functions to be accomplished as well as the supply tasks have to be defined by an operational or business concept that covers the economic boundary conditions for the use of the virtual power plant.
With the currently available Fuel Cell capacities an additional functionality by the networking of several single units may not be achieved, which limits the development of new business models in terms of a virtual power plant. Only by opening up larger power ranges some additional functions of a Fuel Cell network could be demonstrated, as for instance:

- optimization of the heat and electricity supply to a group of individual consumers,
- load balancing in low- and medium-voltage distribution grids,
- backup-power generation,
- reactive power compensation,
- voltage control in larger low-voltage grids.

4 Conclusions

Residential Fuel Cells have the potential to utilize the advantages of CHP-generation in a smaller power range. To achieve considerable primary energy savings a further development progress is necessary.
Residential Fuel Cells are an additional component in the existing energy supply system with limited possibilities to substitute central power plant capacity or conventional heating equipment.
At present, in the field of stationary Fuel Cell applications most of the research effort and industrial investment is focused on the development of smaller units in the power range below 10 kW_{el}. In order to utilize the characteristic advantages of the Fuel Cell technology for energy conversion processes in general, a shift to the emphasized development of Fuel Cell power plants and combined cycles is advised.

5 References

[1] Baker, A.; Jollie, D.: Fuel Cell Market Survey: Large Stationary Applications. Fuel Cell Today, 2004, URL: http://www.fuelcelltoday.com

[2] Adamson, K.-A.; Jollie, D.: Fuel Cell Market Survey: Small Stationary Applications. Fuel Cell Today, 2004, URL: http://www.fuelcelltoday.com

[3] Pfeifer, T.; Nehter, P.: Darstellung und Analyse der Techniklinie "Hoch- und Niedertemperatur-Brennstoffzellen". In: AGFW-Hauptstudie "Pluralistische Wärmeversorgung", Arbeitslinie 3: Technikentwicklung und -bewertung. AGFW, 2004

[4] Nehter, P.: Thermodynamische und Ökonomische Analyse von Kraftwerksprozessen mit Hochtemperatur-Brennstoffzelle SOFC. Dissertation, Technische Universität Dresden, 2004

[5] G.E. press release of August 22nd, 2005

[6] Pineda, I. L.: Design of a MW-class Solid Oxide Fuel Cell & gas turbine combined cycle power plant. Diploma thesis, Technische Universität Dresden, 2006

[7] Pehnt, M; Ramesohl, S.: Fuel Cells for Distributed Power: benefits, barriers and perspectives. WWF European Policy Office, Brussels, 2003

[8] Arnold, P.: Systemkosten von stationären Brennstoffzellenanlagen im Vergleich zu den historischen Kosten- und Technologieentwicklungen bei konventionellen Kraftwerkskonzepten. Project work, TU Dresden, Institute of Power Technologies, 2004