The Turbo-Fuel-Cell 1.0 – family concept
Compact Micro Gas Turbine (MGT) – Solid Oxide Fuel Cell (SOFC) energy converters in the 100-500 kW electrical power range for the future.

H. P. Berg1*, A. Himmelberg1, M. Lehmann1, R. Dückershoff2 and M. Neumann3
1 Brandenburg University of Technology (BTU), Department of Combustion Engines and Flight Propulsion, Siemens-Halske-Ring 14, 03046 Cottbus, Germany,
2 University of Applied Sciences Mittelhessen (THM), Friedberg, Department of Mechanical Engineering, Mechatronics and Material Technology, Wilhelm-Leuschner-Str. 13, 61169 Friedberg, Germany
3 Professor Dr. Berg and Kiessling GmbH, Burger Chaussee 25, 03044 Cottbus, Germany

* Corresponding Author: peter.berg@b-tu.de

Abstract. The “Turbo-Fuel-Cell-Technology” has been described as a MGT-SOFC hybrid system consisting of a recuperated micro gas turbine (MGT) process with an embedded solid oxide fuel cell (SOFC) subsystem. SOFC stacks are connected to “SOFC stack grapes” and are equipped with the so called HEXAR-Module. This module is composed of a high-temperature heat exchanger (HEX), an afterburner (A) and a steam reformer (R). The MGT-concept is based on a generator driven directly by the turbomachine and a recuperator, which returns the exhaust heat to the pressurized compressor outlet air. This provides the necessary base for a highly effective, pure MGT process and the “MGT-SOFC-high-efficiency process”. This paper describes the concept and the thermodynamic background of a highly effective and compact design of the “Turbo-Fuel-Cell 1.0-Family” in the electrical performance class from 100 to 500 kW. The technological state of the system is shown and a rating of the system with comparative parameters is discussed. It becomes visible that all necessary basic technologies should be available and that the technology (for stationary applications) can have the “entry into services (E.I.S.)” in the next 10 years. The MGT-SOFC performance map under different operation conditions is discussed. This article also provides an overview of the research on MGT-SOFC Systems and the scenario of an energy supply network and a mobile energy conversion of the future introduction.

1. Introduction
In the redesign of our future habitats, research is looking for novel solutions for mobility and energy supply. These must have high fuel flexibility in order to be able to be used in a wide variety of ways and to enable an infrastructural change (for example, the transition from conventional fuels to fuels for energy storage from renewable sources).

In the present article, the “Turbo-Fuel-Cell 1.0 (TFC1.0)-Family” concept is suggested and discussed physically. The basis for compactness results from a multilayer pressure vessel (DE patent application number: 10 2017 107 003.6 / MLC = multi-layer container) with integrated hybrid micro-gas turbine SOFC process. The “TFC1.0-Family” System is designed for the 100 to 500 kW electrical energy range.
with a very high overall efficiency $\eta_{\text{MGT-SOFC}}$. Furthermore, the system can also be scaled to smaller capacities.

**Figure 1.** View of the first stationary TFC1.0-Concept (from 2014) based on the MGT-100 technology developed by BTU-CS. Motivation for the MAXEFF-research programme sponsored by the European Union (European Regional Development Fund)

In the years 2010-2014, research and development projects at the BTU-CS (Brandenburg University of Technology Cottbus-Senftenberg) were carried out in cooperation with industry partners for an air-bearing micro gas turbine (figure 1, A and B) with a high efficiency potential. The result was a 100 kW CHP with high fuel flexibility (figure 1, C). This basic machine was chosen for the concept of a first highly compact micro gas turbine SOFC system (figure 1, D and E, MTG-FC 500 from the year 2014). As the “TFC1.0 Concept One”, it was the source of the “TFC1.0-Family (100 to 500 kW)” based on MLC technology. In addition, smaller performance classes were analysed, which also use the MLC basic principle and turbomachinery with air bearings.

Own studies also show a lower application range down to 20 kW (automotive application / TFC-M1), while studies of Siemens-Westinghouse on pilot plants clearly demonstrate the application areas over 150 kW [2, 3]. The first “TFC1.0-270” system (example in this publication) will be based on an air-bearing micro gas turbine (MGT), a technology from B+K (Prof. Dr. Berg and Kiessling GmbH, Germany) which is currently in the industrialization process.

This machine concept (figure 2) has the necessary technology (air bearing, recuperator, turbomachine and generator). Furthermore, there are already industrialized SOFC stacks on the market.

**Figure 2.** Overview about the combination of MGT and SOFC and an illustration of the change in the rotational axis of the MGT

For the “TFC1.0-270 (250-300 kW)” this MGT basic technology (figure 2: left side /without combustion chamber, yellow cross) is to be used. The components generator (1), turbo set (2) and
recuperator (3) are arranged vertically (figure 2: “change in the rotational axis”) in combination with the MLC (5). Conventional SOFC stacks (4) are to be integrated as stack grape in the MLC.

The “Turbo-Fuel-Cell 1.0” will be realized with an embedded SOFC system (instead of the combustion chamber). As SOFC technology, the planar technology is used. This has the advantage of a relatively high power density [4], which contributes to the compactness of the system. However, the sealing in the fuel cell stub must be ensured by a careful selection of materials and by means of sensible preloading. Another advantage is the high degree of industrialization of the planar SOFC technology. The resulting high availability at a comparatively low price level represents advantageous boundary conditions for the realization of the “TFC1.0-Family Series”.

Therefore, planar SOFC technologies are currently under investigation in a BTU-CS research program (EU-funded, acronym “MAXEFF”). In this case, an examination of the pressure charge (in the MGT pressure range) is carried out, in particular taking into account the structural integration and design concept. In addition to the planar SOFC technology, tubular SOFC technologies have been used in connection with a hybridized gas turbine process [2, 5, 6].

The monolith concept and the Sulzer-Hexis technology (combined tube stack module) are also to be mentioned. The monolith concept (MSOFC) promises the highest power density (8 kW/kg, without charging) and could therefore be of great interest to the mobile sector [6; 4]. However, the monolith concept with the above-mentioned high conduction densities does not yet exist in industrialization.

2. Examples of some future applications
For the Turbo-Fuel-Cell (TFC) technology, there will be a large number of applications in the stationary and mobile sectors. In both cases a TFC1.0-270 can be the right system for the entry into market (E.I.S.) in 2027.

2.1. Use as immobile application
As a decentralized energy supplier, a TFC system can be used in the highly effective conversion of chemically stored energy into electricity (gas to power) in the future network with renewable energies (figure.1 (D) and figure 2 (5) a sketch of a stationary application).

A practical advantage is the relatively fast availability for the “Smart Grids”, since one does not have to wait for a new energy carrier (e.g. hydrogen) including infrastructure, but can also use fuels of the same market. TFC-converters could be used further in the modification of the infrastructure (e.g. hydrogen economy). This hybrid system can provide electrical energy faster than a single MGT or SOFC system. Müller [7] has made an investigation on a Capstone C60 MGT with SOFC and found a response of 100 kW/s.

2.2. Use as mobile application
As an energy converter for the mobile sector, an application in the rail, automotive and marine sector can be conceived as shown in figure 3 and 4. The TFC for rail applications (figure 3) is very similar to the stationary situation (figure 1 and 2). At present, rail vehicles with diesel-electric drive systems are mainly used on non-electrified track connection. A TFC system can eliminate the NOx and particulate problems with low CO2 emissions. A TFC system represents a zero emission system. In image of figure 3 this application area is exemplarily visualized.
Figure 3. Example of a train application

Ten TFC1.0-270 packs can provide 2.7 to 3 MW emission-free electrical power. The fuel could initially be diesel or natural gas with the option of a subsequent conversion to other chemical energy carriers, e.g. "Power to gas" - fuel / hydrogen H₂.

Figure 4. Example of an automotive application with a TFC1.0-24M (24 kW)

A further future use is the automotive sector (figure 4, e.g. range extender for the E-mobility) and also in the field of aviation technology (APU systems, figure 5). Here, the monolith concept (MSOFC) technology may be of interest instead of the state of the art SOFC technology. A power weight ratio above 8 kW/kg can be achieved by turbocharging and the use of MLC technology. In combination with buffer batteries, a powerful actuation without a range problem can be represented. With the use of e.g. carbon-fibre-reinforced polymers or other fibres, the MLC technology allows a very compact and light design for the pressure containing outer skin. The image in figure 4 on the upper left shows the driving test bed of BTU-CS for automotive applications.
Figure 5. Example of a TFC-APU aerospace application (left) with a highly compact turbo generator (3) and main details of the “MTiG” (right).

Figure 5 shows an example of an aircraft concept (MTOW 9,300 kg, $M_a\text{Cruise} = 0.75$, $h\text{Cruise} = 11$ km) with a hybrid main drive [8, 9]. With an advanced fan technology (CRF = Counter Rotating Fan), two hybrid turbo compound engines are realizing the take-off power of 1,360 kW. The parallel-hybrid shaft-power system represents a combination between the turbo compound and an electric drive. The power coupling between the rotary piston engine (core engine) and the air-bearing power head (MTiG = micro turbine with integrated generator) are electrically coupled. The MTiG represents a derivative from the existing TFC powerhead. Furthermore, the drive system uses an MTiG based APU, which uses an advanced recuperator (oval tube bundle heat exchanger [7]. This APU could be replaced by a TFC system. In this case, the MTiG, the oval tube recuperator and the MSOFC would be used in conjunction with the aforementioned main engine. The result would have been an aviation-technical “TFC-AERO-System”. With it, the desired overall high power weights of the entire drive system of about 2-3 kW/kg can be realized in the future.

Figure 6. Sketch of the MGT-SOFC process (left) an the fundamental equations (right)

3. Thermal cycle of the MGT-SOFC process and the TFC-design concept
The cycle of the TFC (MGT-SOFC-process) is sketched schematically in figure 6. The basic principle is sufficiently known from the literature and has already been described in numerous publications, e.g. [6, 8, 9]. For this reason, a brief description in connection with the MLC (multi-layer container) is given below and the design of the TFC system is presented.
3.1. Basics of the MGT-SOFC process
According to [1] the efficiency chain of the MGT-SOFC process is shown in figure 6. In this case, the efficiency $\eta_{\text{MGT}}^{\text{real}}$ of the MGT base (depreciated with the heat and pressure losses of the MGT-SOFC system) is approximated. $\eta_{\text{SOFC}}^{\text{rev}}$ represents the efficiency of the ideal fuel cell.

$$\eta_{\text{SOFC}}^{\text{rev}} = \frac{n \cdot F \cdot U_{\text{rev}}}{\Delta R H}$$

$n =$ charge number, $F =$ Faraday constant, $U_{\text{rev}} =$ reversible voltage, $e =$ elementary charge, $N_A =$ Avogadro constant.

The Gibbs enthalpy $\Delta R G$ is the enthalpy of formation $\Delta R H$ minus the reaction entropy $\Delta R S$ multiplied with the operating temperature $T_{\text{SOFC}}$ (idealized assumption = isotherm) of the fuel cell. $\eta_{\text{SOFC}}^{\text{rev}}$ is further reduced by the electrochemical efficiency $\eta_U$, the current efficiency $\eta_I$ and the fuel conversion Efficiency $\eta_C$. The electrical work

$$\Delta W_{\text{electrical, SOFC}} = \Delta R H_{\text{High Syn Gas}} \cdot \eta_{\text{SOFC}}^{\text{rev}} \cdot \eta_U \cdot \eta_I \cdot \eta_C$$

is delivered by the SOFC (figure.7). The “High Syn Gas” is supplied to the SOFC from the reformer. It is generated by a steam reforming process (in the example CH$_4$ + H$_2$O steam) using the heat energy $\Delta Q_{\text{Reformer}}$. In addition to the waste heat from the SOFC ($\Delta R Q + \Delta I Q$), further heat $\Delta F Q$ is produced by the oxidation of the “Low Syn Gas” in the afterburner.

In the MGT, the heat energy

$$\begin{align*}
\Delta R Q + \Delta I Q \quad &\rightarrow \quad \Delta F Q - \Delta Q_{\text{Reformer}} \\
\text{Heat from the SOFC} \quad &\rightarrow \quad \text{Heat from the Afterburner}
\end{align*}$$

is converted with the efficiency $\eta_{\text{MGT}}^{\text{real}}$ into electrical energy by the thermal circuit with the generator ($\eta_{\text{MGT}}^{\text{real}}$ includes in the definition of this publication all losses up to the generator). The electrical work

$$\Delta W_{\text{electrical, Generator, MGT}} = \eta_{\text{MGT}}^{\text{real}} \left( \Delta R Q + \Delta I Q + \Delta F Q - \Delta Q_{\text{Reformer}} \right)$$

is delivered by the MGT-Generator.

The Energy delivered by the whole TFC (MGT-SOFC)-System must be further reduced by the losses of the electrical converters, controllers and regulating units with the system efficiency $\eta_{\text{Sys}}$. The electrical work

$$\Delta W_{\text{Turbo Fuel Cell}} = \eta_{\text{Sys}} \cdot (\Delta W_{\text{electrical, SOFC}} + \Delta W_{\text{electrical, Generator, MGT}})$$

is delivered by the overall TFC (MGT-SOFC)-System.
The TFC1.0-270 will operate in its first application with natural gas. Therefore in this article the results are discussed with the fuel CH\textsubscript{4} with the formation enthalpy \(\Delta^R H\textsubscript{CH4}\). The combination of the SOFC with the MGT results in a revaluation of the efficiency, because the anergy of the SOFC is available as exergy for the thermal MGT-cycle. The overall efficiency of the TFC can therefore be described in the first approximation by \(\eta\textsubscript{MGT-SOFC\_real}\). With the electrical work of the MGT-SOFC System:

\[
\Delta W\text{\_Turbo Fuel Cell\_CH4} \approx \Delta^R H\text{\_CH4} \cdot \eta\text{\_MGT-SOFC\_real} = \Delta^R H\text{\_CH4} \cdot \eta\text{\_MGT\_real} \cdot \eta\text{\_SOFC\_real} \cdot (1 - \eta\text{\_MGT\_real}) \cdot \eta\text{\_sys} \quad \text{(5)}
\]

For the simplest explanation, the MGT-SOFC can be described by the process cycle shown in figure 6. E.g. the TFC1.0-270 is based on the MGT basic machine concept shown in figure 2 with air bearing without combustion chamber. Simplified the combustion chamber is replaced by the MLC-HEXAR-SOFC system which is described below.

### 3.2. The Multi-Layer Container (MLC) with an integrated SOFC-Stack-Grape

**Figure 7. Sketch of the energy situation in a SOFC-Cell**

**Figure 8. Sketch of the MLC = Multi-Layer Container**

(patent application number: 10 2017 107 003.6) with integrated SOFC-Stack-Grape (left) and description of the functionality on a simplified TFC(MGT-SOFC)-cycle (right)
The FC module is typically composed of SOFC stacks (SOFC = Solid Oxide Fuel Cell). In the TFC, they are located in a stack cluster (Stack-Grape, figure 9), which is surrounded by the MLC. However, another high-temperature fuel cell technology may also be used. The FC module (SOFC post-combustion reactor-reformer heat exchanger) replaces "the so-called" combustion chamber of a recuperated MGT and is installed in a pressure vessel (pressure dependent on the pressure ratio of the compressor of the MGT / figure 8, pressure vessel (-1-)).

The air is sucked in and compressed by the compressor (-8-) (slightly higher than the operating pressure of the high-temperature fuel cell due to component pressure losses). The compressed air flows through the multi-skinned pressure vessel (-1-) through the recuperator (-6-) with the channels 4a, 4b. Before the entry into the SOFC stack grape, another heat exchange takes place (in the range of the SOFC operating temperature). The heat exchange takes place on the duct wall 3b and in the pipe system. This is necessary because, in most operating points, the exhaust gas heat behind the turbine (-7-) is not sufficient to preheat the air in the recuperator (6) (to the operating temperature of the high-temperature fuel cells). This air flows to the cathodes (-2a-) of the high-temperature fuel cells. On the anode side, the “High Syn Gas” occurs (-2b-). The process of “High Syn Gas” generation is carried out in the reformer, which receives its heat from the post-combustion of the anode (“Low Syn Gas”) and cathode exhaust gas mixture.

In “TFC1.0-Family” systems, the water for the steam reforming process (with the concept of a superimposed water-steam cycle) is passed through the outer shell of the multi-skinned pressure vessel (-4c-) in order to "trap residual heat loss" and to keep the temperature very low (e.g. allows the use of plastics). In this case, the water is brought to a pressure above the operating pressure, preheated and evaporated in a steam generator (in the region of the recuperator, see figure 10) with the aid of the exhaust gas heat, then superheated in the stack-grape and fed to the methane stream for the steam reforming process. At the same time, the steam serves as an inert gas in the sheathed tube system of the high and low syngas. The “High Syngas” reformed in (-9-) is brought to operating temperature and flows to the anode.

In the SOFC, the oxygen ions at the anode (-2b-) react with the carbon monoxide and the hydrogen of the fuel gas (syngas from the reforming) to water and carbon dioxide (figure 7). The oxygen is fed to the SOFC stack on the cathode side (-2a-) by the heated air. There, each oxygen molecule $O_2$ is divided into $2O^2-$-ions with the aid of four electrons $4e^-$. These diffuse through the YSZ-electrolyte to the anode to oxidize the “High Syn Gas”. Between the anode and the cathode, an electron potential difference
result. The resulting direct current is converted in an inverter (not shown here) to the desired demand. There is no complete conversion in the SOFC stack. In order to use the remaining portion of the combustible components in the anode exhaust gas, this is fed to a post-oxidation (post-combustion). The residual oxygen in the cathode exhaust gas serves as an oxidation partner. The resulting hot exhaust gases flows from the Afterburner-Reformer module (AR see figure 10) to the turbine. Here the expansion takes place. The turbine (7) drives the generator (11) and the compressor (8) via a common shaft. The turbine exhaust gas delivers heat energy to the inner vessel wall and in the recuperator (6) to the compressed air. The remaining heat energy is used in heat exchangers for preheating the steam, the fuel gas and can be used for heating purposes.

The MLC (1) forms through its concentric channels the main supply lines of the circular process. It also provides a compact containment for the process. In the case of steam reforming with a superimposed water-steam circuit, the concentric channel located outside serves for water pre-heating (4c) by means of residual heat losses.

The MLC design allows a very compact design of an MGT-SOFC small-scale power station by means of channels (4) layered around a central axis (including the heat-insulating layers, 3). In the MLC design, the channels are arranged in such a way that waste heat is always transported back through the fluid flow direction.

The pressure vessel is formed in the TFC1.0 family by the outer layer which is at a lower advantageous temperature level (approximate ambient temperature). With TFC1.0, the exhaust gas removal takes place centrally and helps in recuperation of heat. The inner pressure receiving passage is therefore metallic. It also serves as a diffuser between the turbine outlet and the recuperator due to its conical shape.

**Figure 10.** Sketch of the main components inside the MLC and circuit diagram

The MLC concept is based on annular layers (insulation, channel wall, channel, channel wall, insulation, channel wall, channel, channel wall, etc.). Only the cool channel wall near the surroundings
must absorb the pressure in the outer area. Thus, the pressure vessel can be made more thin-walled and made of a more cost-effective material. This also affects the heat capacity favourably. Due to the radial integration of the process-related guide channels, these can be designed very thin-walled since no large pressure differences act. Furthermore, these may also have smaller leakages in the case of the process air guidance, since only relatively small mass flow components (advantageously: in the direction of the hotter inner ring / in the "SOFC" direction) flow due to the low pressure difference. Due to the drastic reduction of the heat capacity of the system, the time behaviour (heating process, load change, etc.) is favourably influenced.

4. Turbo technology of the TFC1.0-system

In the TFC process the MGT is important as a heat engine and for the air supply of the fuel cell. In addition, the system becomes more powerful due to the pressure boosting. In TFC-power units up to 500 kW the combination of small size single stage radial turbine and compressor pair are well suite option. At a speed range from 30,000-130,000 rpm, the size and weight of the rotor components are lying in the range of 60 N at 90,000 rpm. The temperature of the rotor components is roughly between the compressor outlet temperature and the turbine inlet temperature. Due to the fact that the ion exchange in SOFC process is directly related to the surface area, oil contamination in the process medium will result in (unburn) particle deposition on the Cathode surface in the stacks which leads to efficiency degradation [2]. Therefore, the MGT for a hybrid system has to be completely oil-free to ensure the long term efficiency. Together with the high-speed, high-temperature and oil-free process gas requirement, the foil bearing is one of the promising solutions for the power unit in MGT-SOFC system.

Figure 11. General configuration of bump type radial and thrust bearing and a leaf type bearing in a typical TFC1.0 power head

Foil bearings are hydrodynamic, self-acting gas bearings which generally consist of a top foil, compliant foil and bearing bushing. The foils are made from a sheet of nickel base super-alloy. The assembly of these components forms a hydrodynamic wedge contour to the rotating shaft. The hydrodynamic lubrication film pressure is formed between the opposing surfaces due to the high relative speeds [3].
The top foil is supported by a series of compliant structures which has a spring like function usually made of corrugated foil. The compliant foil acts as an elastic foundation that permits the top foil to locally deflect in response to changes in the hydrodynamic pressure and accommodates misalignment, shock load, thermal distortion, centrifugal growth of the shaft and engine housing. These effects limit the use of rigid air bearings and represent the most important advantage of compliant foil bearings. The small sliding motions between contact surfaces of top foil, compliant foil and bushing caused by shaft motion during the operation generates Coulomb damping. Additionally viscous damping mechanisms can be realized by air chambers between the gas foil bearing Components. These viscous and Coulomb damping effects increase the dynamic stability of the rotor bearing system. Further research in development of innovative coating technologies reduced friction and increased the thermal resistance above 300°C in operation with a number of start stop cycles up to 40,000 [3, 4, 5, 6].

5. Characteristics and performance maps of the Turbo-Fuel-Cell1.0 (example: TFC1.0-270)

SOFC fuel cells require an operating temperature $T_{SOFC}$ of 700°C to 900°C (TFC1.0-270, $T_{SOFC} = 740°C$ to 880°C) which is generally above the outlet temperature of the recuperator (TFC1.0-270, $T_{Design \_Point} = 580°C$) and below the turbine inlet temperature (TFC1.0-270, $T_{Turbine \_in \_Design \_Point} = 888°C$).

To close the cycle in the heat supply of the recuperated micro turbine process the heat input

$$\Delta Q_{Input} = \Delta Q_{Heat \_Ex} + \Delta Q_{SOFC-\_Turbine} = \Delta R Q + \Delta I Q + \Delta F Q - \Delta Q_{Reformer}$$

is required (see Chapter 3).

Only the heat quantity $\Delta Q_{Input}$ of the SOFC can be used for the thermal cycle of the MGT. It is determined using the SOFC efficiency chain ($\eta_{SOFC}^{rev} \times \eta_U \times \eta_I \times \eta_C$). The heat quantity is the not in electricity converted chemical energy and can be described by using the formation enthalpy $\Delta^R H$ of the fuel.

$$\Delta^R H \times (1 - \eta_{SOFC}^{rev} \times \eta_U \times \eta_I \times \eta_C) = \Delta Q_{Heat \_Ex} + \Delta Q_{SOFC-\_Turbine} = \Delta Q_{Input}$$

In this equation $\Delta Q_{Heat \_Ex}$ is the amount of heat required to increase the recuperator outlet temperature $T_e$ to the operating temperature of the fuel cell $T_{SOFC}$ and $\Delta Q_{SOFC-\_Turbine}$ is the amount of
heat required to increase the operating temperature of the fuel cell $T_{SOFC}$ to the turbine inlet temperature $T_{Turbine\_in}$. In the TFC1.0 the operating temperature of SOFC $T_{SOFC}$ does not match the exit temperature of the recuperator $T_e$, so that the needed amount of heat $\Delta Q_{Heat\_Ex}$ has to be exchanged by a high-temperature heat exchanger HEX which is part of inner layer of the MLC (see figure 10).

In order to design the thermal arrangement between the MLC-HEX-function, the SOFC-Grape-channels and the afterburner-reformer (AR, see figure 10) the size $X$ was introduced in [1] as the ratio between the exchanged heat quantity $Q_{Heat\_Ex}$ and the required amount of heat $\Delta Q_{Input}$ to close the MGT-cycle.

$$X = \left(\frac{\Delta Q_{Heat\_Ex}}{\Delta Q_{Input}}\right)$$

In [1] it is shown that $X$ can be approximated.

$$X \cong \left(\frac{T_{SOFC} - T_e}{T_{Turbine\_in} - T_e}\right)_p = \left(\frac{T_{SOFC} - k_e T_{Turbine\_out}}{T_{Turbine\_in} - k_e T_{Turbine\_out}}\right)_p = \frac{\theta - k_e \pi \phi}{1 - k_e \pi \phi}$$

The quality of the recuperator is represented by the factor $k_e < 1$. $\pi_{Turbine}$ is the pressure ratio of the turbine and $\theta$ is the ratio of the SOFC operating temperature $T_{SOFC}$ and the turbine inlet temperature $T_{Turbine\_in}$

$$\theta = \frac{T_{SOFC}}{T_{Turbine\_in}}$$

For $\phi$ the polytrophic efficiency of the turbine $\eta_T$ and the adiabatic exponent $\gamma$ of the exhaust gas is used

$$\phi = \frac{1 - n}{n} = \frac{1 - \gamma}{\gamma} \eta_T$$

The targeted operating temperatures $T_{SOFC}$ of the SOFC-Stack-Grape is generally below the turbine inlet temperature $T_{Turbine\_in}$ and above the recuperator outlet temperature $T_e$. The $X$-values are therefore in the range:

$$0 \leq X \leq 1$$

The diagrams shown below are based on real-cycle calculations. CH$_4$ gas is used for fuel. The CH$_4$ is converted by a steam reforming process in a synthesis gas (H$_2$, CO / “High Syn Gas”) and fed to the SOFC as described in figure 10.

For MGT SOFC process is the design point of interest, which is technologically feasible. Herein a suitable turbomachinery basic technology (figure 1 and 2) has been developed during own development and research programs. Furthermore, the SOFC technology exists in an industrialized version. It can be seen in figure 13 (SOFC stacks combined with the MGT basic technology), that an operating range at the selected pressure ratio of $\pi = 4.5$, within the limits makes sense.
Figure 13. Performance maps of a calculated TFC1.0-System at \( \pi = 4.5 \) (e.g. TFC1.0
\[ P_{\text{Design Point}} = 270 \text{ kW} \]

Figure 14. Influence of the recirculation rate according to the turbine inlet temperature and the efficiency

It is seen that the overall efficiency \( \eta_{\text{MGT-SOFC}}^{\text{real}} \) increases with increasing turbine inlet temperature \( T_{\text{Turbine in}} \) while the SOFC operating temperature \( T_{\text{SOFC}} \) is constant. In this case, \( X \) decreases. It is also
physically interesting and logical that the efficiency will decreases after reaching the X = 0 line. In this case, the temperature of the SOFC is always equal to the recuperator outlet temperature (coupled).

For realising an operation on the right site of the green dotted line (border line $T_{turbine,in} = 900^\circ C$), a higher technological effort is needed (turbine cooling, material). So, it is better to design the TFC1.0-processes on the left side of the border line, because the use of an uncooled turbine is possible. Furthermore it fits to the development line of future technologies (planed for a “TFC 2.0-Family”). In this case, the proportion of recirculation is to be increased, as the turbine inlet temperature drops (figure 14).

This potential of recirculation has the strongest impact, as it directly affects the efficiency 
\[ \eta_{SOFC}^{real} = \eta_{SOFC}^{rev} \cdot \eta_U \cdot \eta_T \cdot \eta_F. \] 
An increase in the recirculation (fuel gas recirculation) leads to an increase of $\eta_F$. This increases the efficiency $\eta_{SOFC}^{real}$ of the SOFC. Unfortunately, this results in a lower heat generation. At too low and material costs (high temperature resistant steels, more insulation, more material use, etc.) are higher. The MLC concept makes it possible to build compact MGT-SOFC systems in the future. The described multi-skinned pressure vessel is an important key component for the realization of compact systems.

Furthermore, the use of aerodynamic air bearing is essential for the implementation of the described TFC-family. Oil-free process air is indispensable; otherwise the SOFC modules very quickly degenerate and become unusable. This technology is also already available, industrialised and will be continuously improved.

It is shown that the components for the technology are available to industrialize a MGT-SOFC process in about 8 to 10 years (TFC1.0-270) with the achievement of highest efficiencies ($\eta > 60\% - 65\%$). To achieve these high efficiencies it is not necessary to operate with high pressure ratios. The turbo technology can use moderate pressure ratios in the area of $\pi \approx 4.5$. Also the turbine can operate in a reasonable temperature range of $T_{turbine} = 800 - 900^\circ C$, so that no special blade cooling system is required. Furthermore, the increasing of the recirculation rate will reduce the turbine inlet temperature (from about 890°C to 810°C) and increase the efficiency (from 68% to nearly 80%). Additionally, the introduction of heat ratio “X” is an innovative tool for the design of a high temperature heat exchanger (HEX) inside the Multilayer Container (MLC). It has been shown that a practical range of $0.6 \leq X \leq 1$ can be considered.

Due to the great advantages of the flexible hybrid technology, the MLC design and the modular design of the basic technologies, a large number of applications, application areas and performance classes within the TFC product family are possible and feasible as described.
Acknowledgement and future cooperation
The realization of a compact MGT-SOFC system is a major challenge for research, development and engineering. It has an important future potential for the world of tomorrow.

We would like to thank the European Union and the Investment Bank of the State of Brandenburg (ILB) for the MAXEFF-project. Furthermore we like to thank our students, employees, cooperating colleagues and industrial partners.

At this point, we would also like to point out that we are looking forward to a future national and international cooperation with other institutions and industrial partners.

Together, the research, development and marketing of the described technology can be realized at an international level and provides an importance for future generations.

References
[1] Berg H P, Dückershoff R, Lehmann M and Prechavut N 2017 S. ETC2017-266
[2] Hassmann K 2001 Fuel Cells. 1. pp 78-84
[3] George R A 2000 Journal of Power Sources 86 pp 134-139
[4] Kurzweil P. 2013 Brennstoffzellentechnik - Grundlagen, Komponenten, Systeme, Anwendungen. 2
(Wiesbaden : Springer-Verlag)
[5] Zhou L, et al. 2008 Electrochimica Acta 53(16) pp 5195-5198
[6] Zhang X, et al. 2010 Journal of Power Sources 195(3) pp 685-702
[7] Mueller F, Gaynor R, Auld A E, Brouwer J, Jabbari F and Samuelsen G S 2008 Journal of Power Sources 176 pp 229-239
[8] Berg H P, Malenky U, Antoshkiv O and Mattke R 2015 Deutscher Luft- und Raumfahrtkongress. 2015.
[9] Berg H P, Himmelberg A, Malenky U, Meincke M and Soontronpasatch T 2016 Deutscher Luft- und Raumfahrtkongress
[10] Ahlinder S, Berg H P and Reile E 2005 Numerical Heat Transfer
[11] Berg H P and Krienke C 2015 Magdeburger Maschinenbau-Tage 12
[12] Calisea F, et al. 2006 Gas Turbine System 31(15) pp 3278-3299
[13] Prechavut N, Berg H P 2015 Deutscher Luft- und Raumfahrtkongress
[14] Dellacorte C 2011 Tribology Transactions. 4 pp 674-684
[15] Howard S, Dellacorte C, Valco M J, Prahl J M and Heshmat H 2001 Tribology transactions. 4 pp 657-663
[16] Heshmat H, Hryniewicz P, Walton li J F, Jahanmir S and Dellacorte C 2005 Tribology Int.. 11-12 pp 1059-1075
[17] Sammes N M, Du Y and Bove R 2005 Journal of Power Sources 145(2) pp 428-434