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The design of stationary and mobile solid oxide fuel cell–gas turbine systems

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Abstract

A general thermodynamic model has shown that combined fuel cell cycles may reach an electric-efficiency of more than 80%. This value is one of the targets of the Department of Energy (DOE) solid oxide fuel cell–gas turbine (SOFC–GT) program. The combination of a SOFC and GT connects the air flow of the heat engine and the cell cooling. The principle strategy in order to reach high electrical-efficiencies is to avoid a high excess air for the cell cooling and heat losses. Simple combined SOFC–GT cycles show an efficiency between 60 and 72%. The combination of the SOFC and the GT can be done by using an external cooling or by dividing the stack into multiple sub-stacks with a GT behind each sub-stack as the necessary heat sink. The heat exchangers (HEXs) of a system with an external cooling have the benefit of a pressurization on both sides and therefore, have a high heat exchange coefficient. The pressurization on both sides delivers a low stress to the HEX material. The combination of both principles leads to a reheat (RH)-SOFC–GT cycle that can be improved by a steam turbine (ST) cycle. The first results of a study of such a RH-SOFC–GT–ST cycle indicate that a cycle design with an efficiency of more than 80% is possible and confirm the predictions by the theoretical thermodynamic model mentioned above. The extremely short heat-up time of a thin tubular SOFC and the market entrance of the micro-turbines give the option of using these SOFC–GT designs for mobile applications. The possible use of hydrocarbons such as diesel oil is an important benefit of the SOFC. The micro-turbine and the SOFC stack will be matched depending on the start-up requirements of the mobile system. The minimization of the volume needed is a key issue. The efficiency of small GTs is lower than the efficiency of large GTs due to the influence of the leakage within the stages of GTs increasing with a decreasing size of the GT. Thus, the SOFC module pressure must be lower than in larger stationary SOFC–GT systems. This leads to an electrical-efficiency of 45% of a cycle used as a basis for a design study. The result of the design study is that the space available in a mid-class car allows the placement of such a system, including space reserves. A further improvement of the system might allow an electrical-efficiency of about 55%.

Keywords: Fuel cells; Gas turbines; Steam turbines

1. The thermodynamic principles of the solid oxide fuel cell–gas turbine (SOFC–GT) design

The potential efficiency of any combined fuel cell–heat engine system has been estimated to be about 80% by a generalized thermodynamic model already in 1993 [1]. The US Department of Energy (DOE) has mentioned this figure for combinations of SOFC and GTs in its announcement for research in 1999 [2]. The principles of the design of SOFC–GT systems can be learned from the generalized thermodynamic model: the generalized fuel cell–heat engine cycle is given in [1], Fig. 1.

The fuel cell is a "power producing burner" defined by the ratio of power delivered and the heat in the area of thermal engineering and the resulting engineering tasks are listed in Fig. 1. The thermal integration of the fuel processing is necessary to avoid entropy losses by an extra combustion that can lead to efficiency losses in the order of 10% as already shown in [3,4]. The generalized cycle shows that the heat recovery process for the air heating and the fuel heating is independent of the heat engine cycle. We could realize such a cycle by using, e.g. a Stirling engine as the heat engine. But we get a matching between the GT cycle and the air heating, if we use a common GT as the heat engine, because the air flow of the fuel cell becomes a part of the GT process as well. The design process of such a GT cycle is directly determined by the restrictions of the thermal stresses of the SOFC. The maximum allowable temperature difference $\Delta\vartheta_{max}$ between the inlet and the outlet temperature of the cathode, e.g. 150 K delivers a very high air flow for the SOFC cooling only by air. If we allow this, the waste gas loss will drastically increase and the system- or

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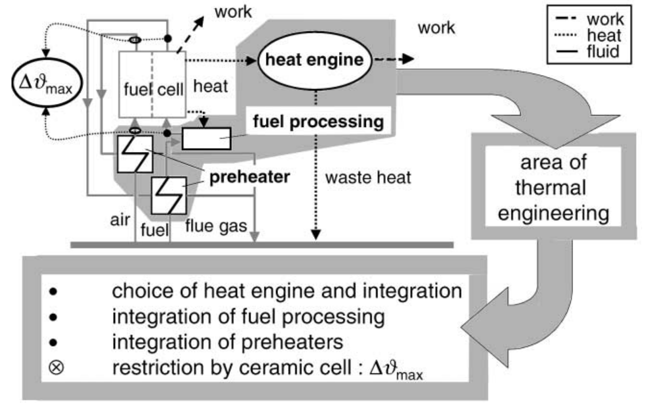

Fig. 1. The generalized fuel cell–heat engine cycle and the tasks of the thermal engineering.

electrical-efficiency can become lower than the cell-efficiency itself.

Thus, any successful cooling strategy of the SOFC of a SOFC–GT system must avoid a high excess of air at the outlet of the total system. Fig. 2 gives an overview over the possible strategies. One strategy is to divide the SOFC module into sub-modules and to extract the heat of the SOFC module by cooling down the waste air of the first sub-module to the inlet temperature of the cathode of the following sub-module by a GT and producing additional power. This process of an intermediate expansion (INEX) can be carried on until the last GT delivers the waste gas for the air heater and the fuel heaters. The other strategy is to cool the SOFC module by an external cooler (EXCO) fed with the flue gas that has been cooled down by the air and the fuel heating.

The SOFC module is the heat source of the GT cycle and the air is heated by the flue gas as shown in the generalized model. This cycle is the result of the trial to use the cold air for the cell cooling by using the full temperature difference between compressor and cell outlet [5]. But the direct heat transfer to the cold air by the SOFC would lead to damage of the SOFC. The integrated gas heater–cell cooler can be heated by radiation and this clearly reduces the danger of cell damage by unacceptable temperature differences. The integrated gas heater allows an optimization of the temperature level of the cooling flows around the cell together with an integrated air heater and this avoids unacceptable thermal stresses of the cell ceramic and disturbances of the electrochemical process.

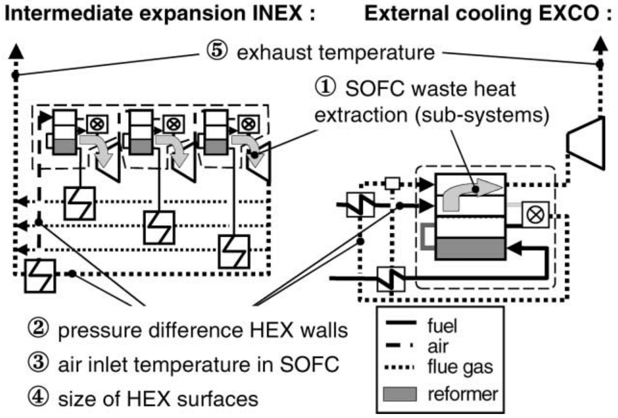

Fig. 2. Cooling strategies of SOFC modules by GT cycles.

	INEX :	EXCO :
① SOFC waste heat extraction (sub-systems)	2 - *n* pressure levels (systems)	1 pressure level (system)
② pressure difference HEX walls	maximal pressure differerence	only pressure loss
③ limit for air inlet temperature in SOFC	gas turbine outlet temperature	SOFC temperature
④ size of HEX surfaces	min. 1/2.5 of ambient system	min. 1/7 of ambient system
⑤ exhaust temperature	~ 200 °C	500 - 600 °C

Fig. 3. Comparison of the INEX and the EXCO design.

The main differences between INEX and EXCO are listed in Fig. 2 and compared in Fig. 3 [6,7]. The waste heat extraction ① is achieved in one pressure level in the EXCO design. The waste heat extraction is achieved in up to *n* pressure levels in the INEX design, depending on the allowable temperature difference of the cathode. The number of pressure levels is equal to the number of pressurized sub-systems.

The pressure difference between the two sides of the HEX walls mainly of the air heater ② is the maximal pressure at the INEX design and only the pressure loss of the module at the EXCO design. The demands of an EXCO design on the material quality for the HEXs is thus, relatively small. The maximum air heater outlet temperature ③ is limited by the SOFC (module outlet) temperature at the EXCO design and by the lower GT outlet temperature at the INEX design. The size of the HEX ④ of an INEX design is about 2.5 times smaller than under ambient conditions caused by the pressurization at one side, but the EXCO design has up to about seven times smaller HEX surfaces than under ambient conditions caused by the pressurization on both sides [6]. The electrical-efficiency of an INEX design with two turbines is about 70% [8] similar to the EXCO design. But the exhaust temperature ⑤ of the INEX design is about 200 °C and of the EXCO design is from about 500 to 600 °C depending on the individual parameters. The EXCO design has thus, the potential for a combination with a steam turbine (ST) cycle that could be, e.g. a Cheng cycle. This would lead to an electrical-efficiency of about 75% [5].

2. The layout of a RH-SOFC–GT–ST cycle

The first ideas of the EXCO design included a RH cycle [5] but with an additional HEX within the SOFC module.

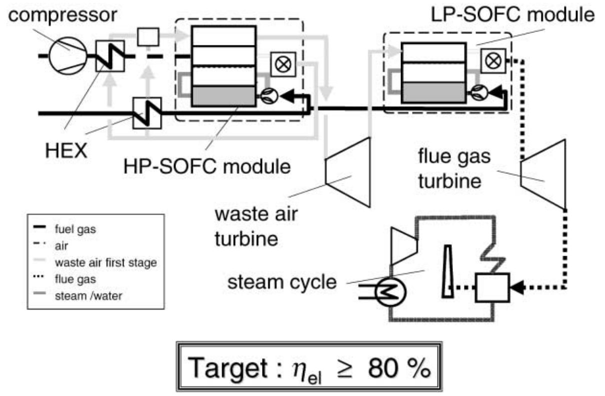

Fig. 4. The layout of the RH-SOFC–GT–ST cycle.

This design didn’t seem very easy to realize. But a comparison of the INEX and the EXCO design shows that the benefit of the EXCO design to reduce the excess air in one process step at one pressure level with small HEXs can be combined with the benefit of the INEX design to allow a simple cascading of GT cycles as needed for a RH-GT cycle. This led to the following proposal of the RH-SOFC–GT cycle with a bottomed ST cycle—the RH-SOFC–GT–ST cycle—as shown in Fig. 4.

The EXCO design is the first stage of the RH-SOFC–GT–ST cycle. The first GT, after the high pressure (HP) section (HP-SOFC module) as the first stage, is named “waste air turbine” to show that the waste air is used as the combustion air of the second stage. The second stage, the low pressure (LP) section, doesn’t need any external gas cooler because the relatively small LP-SOFC module is cooled by a relatively high waste air flow coming from the HP-SOFC module. The waste gas boiler of the ST cycle is supplied with the flue gas of the last GT—the “flue GT”—to use the waste heat of the cell in a most efficient way.

This cycle has been calculated by a PC-based SOFC–GT model with methane as the fuel. Some results are presented in [9]. The examination of the RH-SOFC–GT–ST cycle will be continued. Fig. 5 shows the electrical-efficiency of the system (produced power related on LHV) of the RH-SOFC–GT cycle and of the RH-SOFC–GT–ST cycle as well to give a first impression of the performance of this design.

The efficiency of the RH-SOFC–GT cycle depends more on the HP-SOFC module pressure than the efficiency of the RH-SOFC–GT–ST cycle. The results of the RH-SOFC–GT cycle are similar to the results of a RH-GT cycle cooling the SOFC module as published in [5] in a combination with a Cheng cycle. But the new design shows a more stable performance if the system pressure is changed. It seems to be a benefit to separate the RH-SOFC–GT cycle and the ST cycle. The effect of the addition of the ST cycle is that the optimal HP-SOFC module pressure is reduced and the differences between the efficiencies at different HP-SOFC module pressures at one certain temperature level are reduced as well. However, the influence of the SOFC module temperature is relatively small. Thus, near 80% seems to be a limit, as predicted.

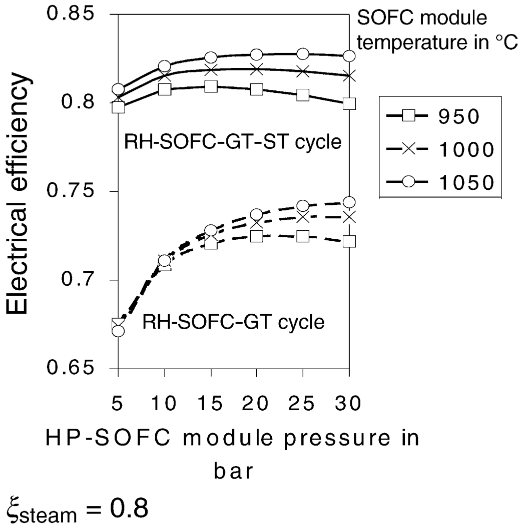

Fig. 5. The electrical-efficiency of the RH-SOFC–GT cycle and of the RH-SOFC–GT–ST cycle.

The SOFC modules deliver more than two-thirds of the power produced in the case of the RH-SOFC–GT–ST system and about more than three-quarters of that in the RH-SOFC–GT system. This shows that the optimization of the steam cycle is an important part of the system design to reach an efficiency target of more than 80%. But if we need a ST cycle we need a minimum capacity of the total system >10 MW. Only the demand of a very high efficiency, >73%, leads to an additional ST system including water treatment and boiler operation etc. Thus, it can be expected that the market entrance with small SOFC–GT units will happen without an additional ST cycle and the RH-SOFC–GT–ST cycle may become commercially interesting later. But the RH-SOFC–GT cycle can be built for smaller capacities, depending on the available GTs, with an efficiency over 70% and the benefits of delivering a waste gas with a very high temperature for different process applications in CHP units for industrial applications and operating at a relatively low SOFC module temperature.

3. Layout and design of mobile SOFC–GT

The development of the above mentioned cycles was only done for stationary applications. The car customers demand of a short start-up time could not be performed by SOFC stacks with a temperature gradient of about 200 K/h. However, the relatively simple use of hydrocarbons such as diesel oil in a SOFC would be a very interesting benefit for a mobile SOFC because it could solve all the open questions regarding the fuel infrastructure [10]. In the past, the size of available GTs was far away from capacity that might be interesting for a power supply in cars. Fig. 6 gives an overview over the basic developments and innovations of

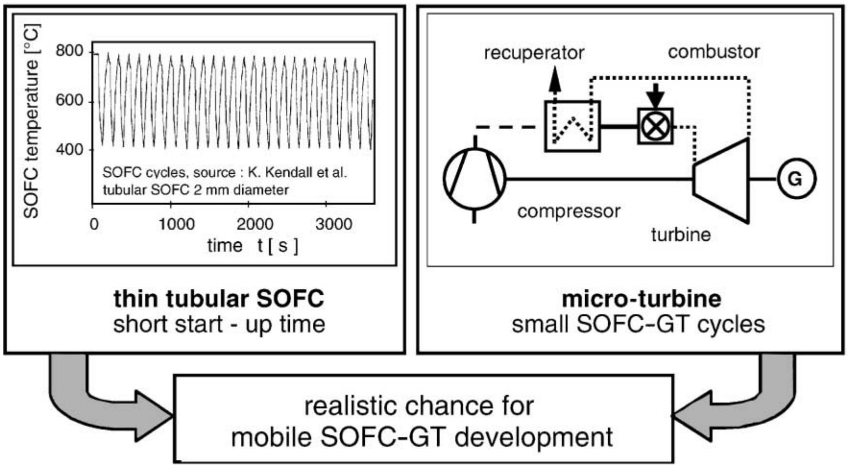

Fig. 6. The basic innovations for mobile SOFC–GT systems.

the recent years that could change this picture. The temperature gradients that can be realized by a thin tubular SOFC, as shown by Kendall et al. [11], give the impression that thin tubes could solve the start-up problem of SOFC in mobile applications. The second benefit of thin tubes in general is the high power density >1 kW/l that can be expected. The development and the market introduction of the micro-turbines show the availability of small-sized turbines down to 25 kW capacity [12]. These developments initiated the study about the feasibility of mobile SOFC–GT systems. However, mobile SOFC was already reported [13]. This indicated that a further consideration seems to be useful [14]. The realization of such systems depends on successful integration.

The system integration in a mid-class car with a capacity of 75 kW was discussed in recent seminars on fuel cells at the University of Applied Sciences in Hamburg and some proposals were worked out [15]. The basis of these discussions was the SOFC–GT cycle with an external cooling as shown in Fig. 7.

A cycle model was used to calculate the basic design data. The main purpose of the work was to find out what restrictions could occur by integrating such a system in a motor car. Thus, a principle design study was necessary. The differences between a stationary and a mobile SOFC–GT lead to the following restrictions for a mobile system design. The required space of the system is a key issue. Thus, higher pressure losses must be accepted to decrease the volume required for the SOFC module including the HEXs. The amount of leakage between the stages of GTs increases with decreasing size of the GT. Thus, the compressor and the turbine of a micro-turbine have a smaller isentropic-efficiency than GTs in power plants and the pressure ratio is smaller than in large GTs. The system must be started-up within a similar time as for a usual car. There are two principle possibilities to assure the power supply of the car during the heating-up time of the SOFC module. Either the capacity of the batteries can be extended to deliver the required power during the start-up time or the capacity of the micro-turbine can be increased to deliver the needed power during the heat-up phase of the SOFC. If the batteries are extended the dead load of the car increases and this will reduce the total efficiency of the automotive system. The electrical-efficiency of the SOFC–GT system decreases with

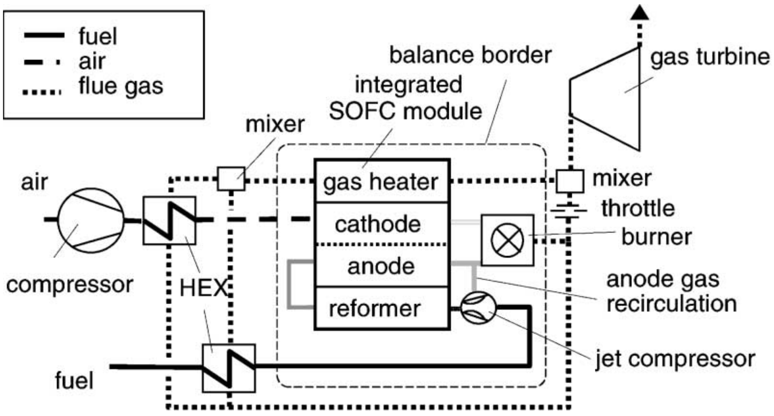

Fig. 7. The SOFC–GT system with an external cooling for mobile application.

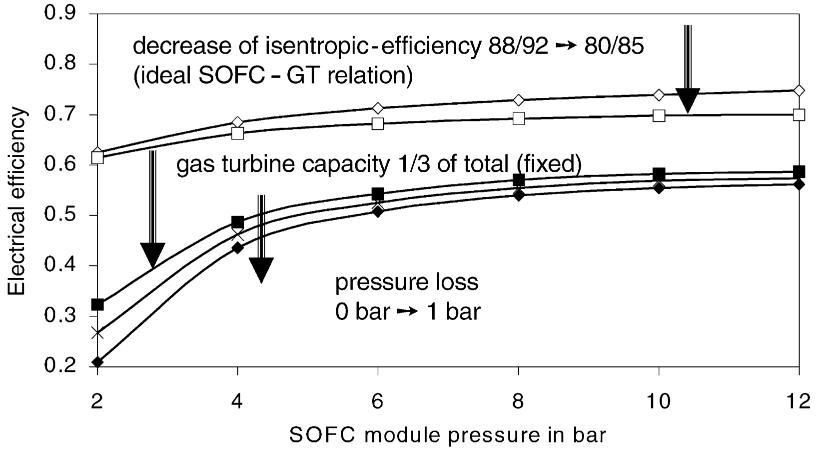

Fig. 8. The influences on the efficiency of mobile SOFC–GT systems at 900 °C SOFC module temperature.

a decreasing SOFC capacity share too, because an increasing part of the used fuel is burnt in the micro-turbine and not in the SOFC. Both influences need to be more thoroughly analyzed and optimized. The minimum available micro-turbine of today has a capacity of 25 kW. The size of the micro-turbine was fixed to 25 kW for the above mentioned design study. This is one-third of the total system capacity.

The calculations of the mobile SOFC system showed the connections between the electrical-efficiency and the restrictions of mobile systems mentioned above. Fig. 8 shows the results. The decrease of the isentropic-efficiency of the compressor and the turbine is illustrated by an efficiency curve for an isentropic-efficiency of 88% of the compressor and an isentropic-efficiency of 92% of the turbine as is known for big power plant GTs and the reduced values as 80 and 85% of a micro-turbine. The relation of the sizes of the SOFC and the GT is the ideal relation for a maximum efficiency at any pressure level. The influence of the isentropic-efficiency increases with the SOFC module pressure. The fixed combination of the capacities, one-third GT and two-third SOFC, as chosen for the study always delivers a lower efficiency than the ideal relation. But the influence on the efficiency decreases with an increasing SOFC module pressure. The reason for the lower efficiency is that the capacity of the GT is too high for the ideal combination with the SOFC and an increased part of the fuel has to be burnt in the burner compared with the ideal combination. This can be expressed by a reduced fuel cell-efficiency in the model. Finally the demand of reducing the volume leads to an increase of the pressure loss of the HEXs to increase the heat transfer coefficient. It is important to choose a micro-turbine with a SOFC module pressure of 4 bar or higher to reduce the negative influences of the pressure loss and to consider the fixed capacity relation of micro-turbine and SOFC module at a later stage.

The benefit of a SOFC–GT system is the direct availability of electrical power. Fig. 9 shows a principle system lay out. All classic components such as gear box, clutch, etc. could be replaced by electric and electronic components if we use electrical wheel motors. Now the total power train consists of a SOFC–GT system connected with the electrical system consisting of battery, power electronic and wheel motors. This system design has the benefit, that the batteries can be recharged, e.g. by reducing the speed. The SOFC–GT system can be operated at constant conditions. It is very important to optimize the start-up procedure to reduce the necessary capacity of the micro-turbine at a lowest possible battery capacity, to increase the system-efficiency as shown in Fig. 8.

These results were the basis that led to the conceptual design shown in Fig. 10. The pressurized SOFC module including the air and the fuel heaters is under the hood of the car. The micro-turbine is flanged directly at the SOFC module. The batteries, the power electronics and the fuel tank are positioned in the center and at the rear of the car. One interesting result of the design study is that placement of the components still left space available. Thus, the failure tolerance of the system design is relatively high because there is still a space reserve available that could be used for corrections if further development should show that some assumptions had been too optimistic.

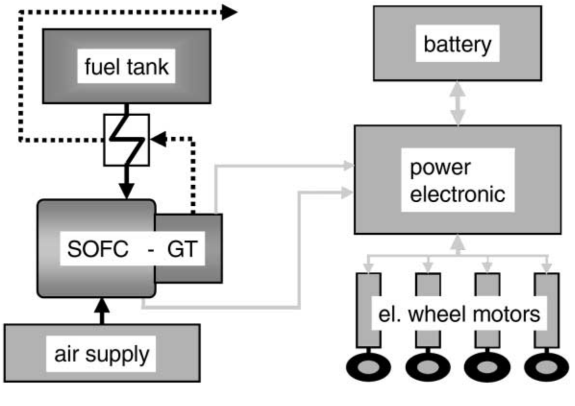

Fig. 9. The integration of the SOFC–GT system in the power train.

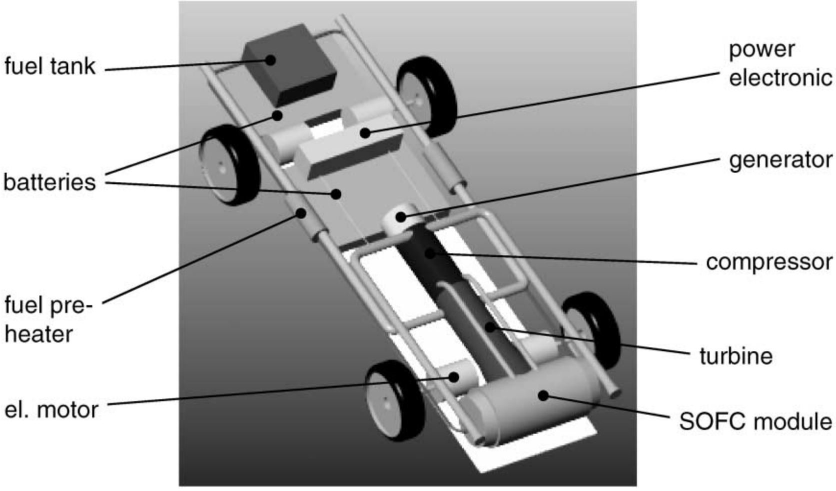

Fig. 10. Design study of a mobile SOFC–GT power train platform.

4. Conclusions

The results of the study of a RH-SOFC–GT–ST cycle indicate that a cycle design with an efficiency of more than 80% is possible and confirm earlier predictions by a theoretical thermodynamic model. The calculations show that an additional optimized ST cycle is necessary to boost the RH-SOFC–GT technology. The RH-SOFC–GT–ST technology can be used later for units with a capacity > about 10 MW for a more centralized generation. But the RH-SOFC–GT system alone allows an efficiency of more than 70% and delivers a waste gas with a very high temperature for different industrial CHP applications at a relatively low SOFC module temperature which may be interesting for a market entrance as well. The restrictions within mobile systems regarding the volume, the capacity and the start-up operation lead to much lower efficiencies. The technical potential of the efficiency may be in the order of 55%. The results of the studies encourage a further and deeper evaluation of the potential of the SOFC–GT technology in different applications.

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