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Holistic Development of Thermoelectric Generators for Automotive Applications

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One of the major challenges of the future automotive development is to achieve the required reductions of the CO_2 emissions. Therefore, it is necessary to investigate all potential technologies for efficiency improvement. In a combustion engine, about 2/3 of the chemical energy of the fuel is dissipated as waste heat. Due to its high temperature level, the waste heat in the exhaust gas is very promising for the technology of thermoelectric generators (TEG). In this work the methodology for a holistic TEG optimization for automotive vehicle applications will be presented. Thereby, all system interactions between the vehicle and the TEG are modelled and the CO_2 reduction can be optimized within the vehicle system. Moreover the costs are calculated for each TEG design, and the method realizes an optimization of the cost–benefit ratio in a direct way. The optimization method is applied with a highly integrated TEG design, which has been developed to be compact and lightweight. Through the combination of improvements in TEG design and system optimization, a gravimetric power density of 267 W/kg and a volumetric power density of 478 W/dm^3 could be achieved. These power densities are about 900% and 700%, respectively, higher than the state of the art. The optimization method was applied exemplarily to a conventional vehicle (Volkswagen Golf VII) and a hybrid vehicle (Opel Ampera/Chevrolet Volt). As a result, reductions in consumption and CO_2 emissions of up to 2.2% for the conventional and 3.4% for the hybrid vehicle could be achieved within the worldwide harmonized light duty driving test cycle. The cost–benefit optimum is 81.3 €/(g/km) for the conventional vehicle and 54.8 €/(g/km) for the hybrid vehicle in charge sustaining mode.

Key words: Thermoelectric generator, automotive application, waste heat recovery, conventional and hybrid vehicles, holistic overall system development, cost–benefit ratio

Abbreviations

CFD	Computational fluid dynamics
CO	Coolant
CO_2	Carbon dioxide
COHX	Coolant heat exchanger
DLR	Deutsches Zentrum für Luft- und Raumfahrt/German Aerospace Center
DSG	Dual-clutch gearbox
HG	Hot gas
HGHX	Hot gas heat exchanger
ICE	Internal combustion engine
PHEV	Plug-in hybrid electrical vehicles
TEG	Thermoelectric generator
TEM	Thermoelectric module
TSI	Turbocharged stratified injection
WLTC	Worldwide harmonized light duty driving test cycle
WLTP	Worldwide harmonized light duty vehicles test procedure
Wp	Peak power

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Variables

ψ_{TEG}	Gravimetric power density (W/kg)
ϕ_{TEG}	Volumetric power density (W/dm^3)
$P_{\mathrm{TEM,rp}}$	Electrical peak power/electrical rated power (W)

INTRODUCTION

In automotive development one of the major challenges is to achieve the required reductions in the CO_2 emissions. Various scenario analyses predict that even in studies with electric vehicle friendly boundary conditions, the proportion of vehicles with combustion engines is dominant in future vehicle sales. For example, the prediction for 2030 according to[1,2] is a share in vehicle sales of over 80% with internal combustion engines (ICE). Hybrid vehicles account for a share of these vehicles. According to,[2] which provides a summary of the literature, global vehicle sales in 2030 are expected to be about 150% of the sales in 2015. This leads to the prediction, that in absolute terms, more vehicles with combustion engines will be sold in 2030.[2]

Considering the overall CO_2 balance of purely electric vehicles with a large battery range, in many areas vehicles powered by an ICE have a better CO_2 balance.[3–6] The continued use of combustion engines, to whatever extent, requires investigation of all potential technologies for efficiency improvement. Regardless of whether a conventional or hybrid vehicle concept is used, approximately 2/3 of the fuels chemical energy dissipates as waste heat. In particular, the part of the exhaust gas offers the highest potential for waste heat recovery due to its high temperature level. The technology of thermoelectric generators (TEG) is very promising for waste heat recovery and under investigation for several years, eg., at the DLR—Institute of Vehicle Concepts in Stuttgart since 2005.[7–11] The electrical energy converted by a TEG can provide a part of the vehicle's onboard power supply and thus leads to a decrease in the load on the electrical generator and thus to a reduction in consumption and CO_2 emissions.

The technologic challenges for automotive application of TEG systems relate to the gravimetric and volumetric power density, as well as the improvement of the cost–benefit ratio. These two challenges are being addressed in the ongoing investigations. In this paper an overview of the methodical approach will be given and the current results will be presented.

METHODOLOGY FOR A HOLISTIC TEG OPTIMIZATION

The aim of the methodology is to significantly improve the cost–benefit ratio of thermoelectric generators (TEG) in vehicles. In the state of the art a successive development is used and thus the technological issues were developed separately from the costs.[10,12] The approaches resulted in large TEG systems with high costs. This is regarded as one of the reasons why the cost–benefit ratio at the state of the art has not been sufficient. Another reason was that the overall system interactions with the vehicle were only partially modelled and analyzed. An optimization under overall system aspects in the vehicle for dynamic driving conditions was therefore not realized. A direct optimization of the cost–benefit ratio for automotive TEG was also not possible with the state of the art and therefore developed in this work. An overview of this holistic method for the optimization of TEG systems is shown in Fig. 1.

The method has been developed with regard to a multi-objective optimization. Thereby, the following two primary objectives were targeted:

- Maximal CO_2 reduction of the overall system within the driving cycle WLTC (g/km)
- Minimal TEG system costs (€)

The worldwide harmonized light duty driving test cycle (WLTC) was selected as dynamic boundary condition. The selection of this cycle aims to enable the comparison of the results with other work. Also this driving cycle is mandatory for the homologation and therefore represents the decisive boundary condition, since the fleet emissions of automobile manufacturers are determined in this cycle.

All relevant parameters for the calculation of the CO_2 reduction in the WLTC are included in the primary objectives. In addition, eight secondary objectives were defined in the method to obtain a balanced design, which achieves a good performance both within the driving cycle and outside. In particular these secondary objectives focus the optimization of the electrical peak performance, long-term stability, exhaust back pressure and weight of the TEG system. Although some of these quantities are included in the primary objectives, they are also individually of importance for the TEG development. For example, with the secondary objectives, it can be achieved, that with similar results in the primary objectives, a design is selected which has a lower weight and thus a lower influence on the driving dynamics of the vehicle.

For the optimization a global target was set by combining both primary objectives to a cost–benefit ratio. The target of less than 95 €/(g/km) was defined, since in the European Union, the penalties for exceeding the fleet consumption amounts to this value. If an efficiency technology is more cost-effective, its use is also economically viable according to market criteria.

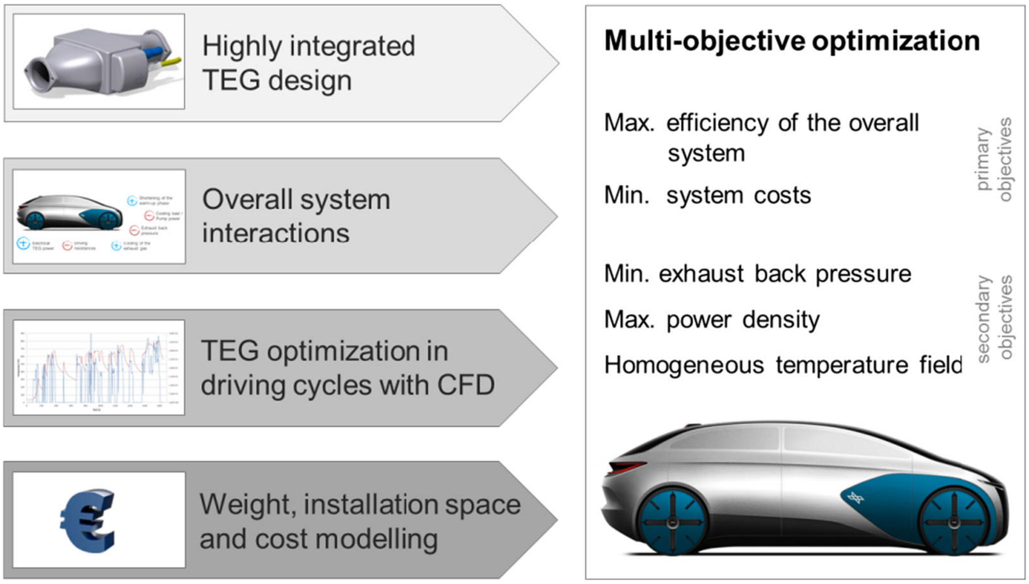

Fig. 1. Overview of the holistic method for TEG optimization with its sub-areas (left) which together enable a multi-objective optimization (right).

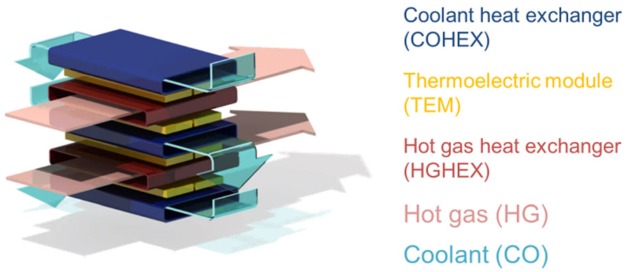

Fig. 2. Cross-flow heat exchanger concept.

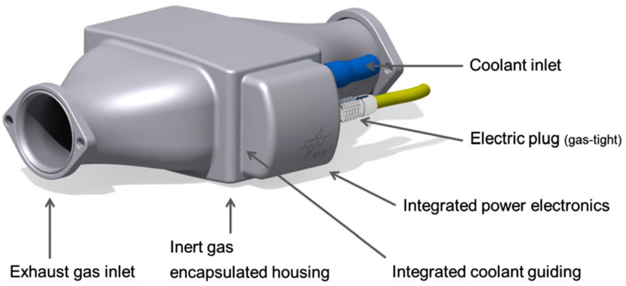

Fig. 3. Highly integrated TEG design—overall concept.

HIGHLY INTEGRATED TEG DESIGN

The already described challenge to increase the power density has to be solved to achieve a high CO_2 reduction in the overall system. At the state of the art, the weight of the TEG system has the largest negative effect on the vehicle.[10] A high weight leads to high driving resistances and thus reduces the efficiency improvement achieved by the TEG. A reduction of this negative effect requires a high gravimetric power density. Since the required installation space is also an important issue in vehicle development, the volumetric power density of the TEG must also be high. As target values for this work a fivefold increase of the state of the art[13] to more than 145 W/kg and 335 W/dm^3 was defined.

Cross-Flow Heat Exchanger Concept

In order to realize a very compact design, the concept of a cross-flow heat exchanger was chosen. As shown in Fig. 2, several stacks are arranged on top of each other. If necessary, the hot gas (HG) can be split into several hot gas heat exchangers (HGHEX). Also depending on the configuration, the coolant (CO) can be fed either serially or parallel through the coolant heat exchangers (COHEX) of the TEG.

Overall Concept

In order to protect the thermoelectric modules from the oxidizing atmosphere, they are encapsulated in an entire housing (Fig. 3). In an effort to reduce the weight and volume of the encapsulated TEG system, various functional integrations were implemented in the housing.

The thermoelectric modules were force-fit mounted with a contact pressure. To achieve a uniform contact pressure distribution, the thermomechanics of the entire TEG architecture were considered. Another goal of the thermomechanical development was to achieve the required reduction of weight. The application of the contact pressure basically requires a rigid and stable housing. Only by a sophisticated design, could a good contact pressure could be achieved simultaneously with a lightweight design. As described in more detail below, the power density could be increased

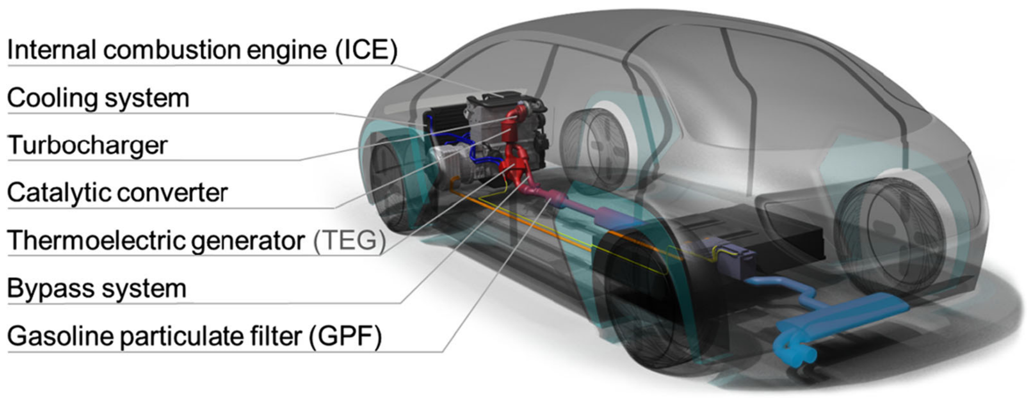

Fig. 4. Vehicle integration concept close to the engine through a high volumetric power density.

considerably due to the manifold investigations on the TEG architecture.

VEHICLE OVERALL SYSTEM

Vehicle Integration Concept

The volumetric power density of the TEG system determines which mounting position can be selected in the vehicle. With the high volumetric power density of the TEG system, an integration concept close to the combustion engine could be used in this work. As already shown in[10], the temperature along the exhaust system drops by about 100 K/m. Therefore, an installation position close to the engine is thermodynamically more efficient for the TEG. In the developed integration concept, as shown in Fig. 4, the TEG is located behind the catalytic converter. The exhaust gas temperatures after the catalytic converter are slightly higher than before due to the exothermic reaction.

In addition to the installation position, the vehicle integration concept includes the integration of the TEG system into the fluid flows of the vehicle with the aim to improve the overall system interactions.

Vehicle Overall System Interactions

In order to optimize the TEG system under holistic aspects, all relevant overall system interactions have to be included in the simulation. Thereby, the simulation of these interactions must cover dynamic driving conditions.

The interactions shown in Fig. 5 were investigated, modelled in the simulation and individually validated. Beside the input of the electrical energy from the TEG, a special focus was given to the appropriate modeling for the shortening of the warm-up phase. The TEG transfers heat from the exhaust system to the vehicle's cooling system. Part of the heat is converted into electrical energy by the TEG. The remaining heat can be used by a sophisticated integration concept to accelerate the time needed to bring the vehicle to operating temperature. An additional positive effect of the TEG is that the heating-up of the passenger compartment is accelerated, and; thereby, the comfort is increased. The shortening of the warm-up phase has a positive influence on the emissions both on-cycle and off-cycle. Within the worldwide harmonized light vehicles test procedure (WLTP) with the associated driving cycle WLTC, the vehicle starts tempered to the ambient temperature and thus goes through a warm-up phase. In this work, an ambient temperature of 20°C was used. In the homologation procedure of the European Union an additional test with 14°C is done. At a lower ambient temperature, the TEG increases the efficiency of the vehicle in the warm-up phase more than determined in this work with 20°C.

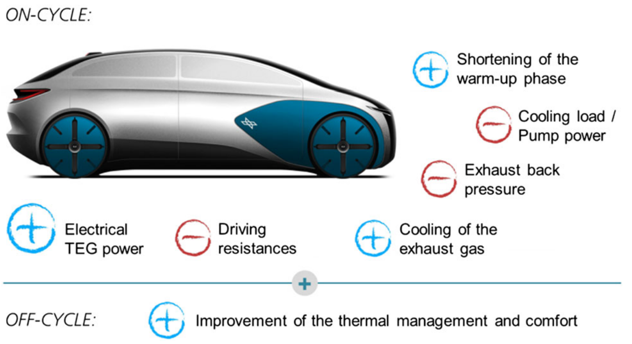

Fig. 5. Overall system interactions of the TEG system with the vehicle.

TEG OPTIMIZATION UNDER DYNAMIC CONDITIONS

Boundary Conditions

In order to achieve realistic results in the simulation and to consider all transient effects, such as the warm-up phase, the entire driving cycle WLTC[14] is used for the optimization. The cycle is 1800 s long, has an average speed of 46.5 km/h and a top speed of 131 km/h. The dynamic velocity profile in Fig. 6 shows that a very low load level is specified in the first third. A high speed is only

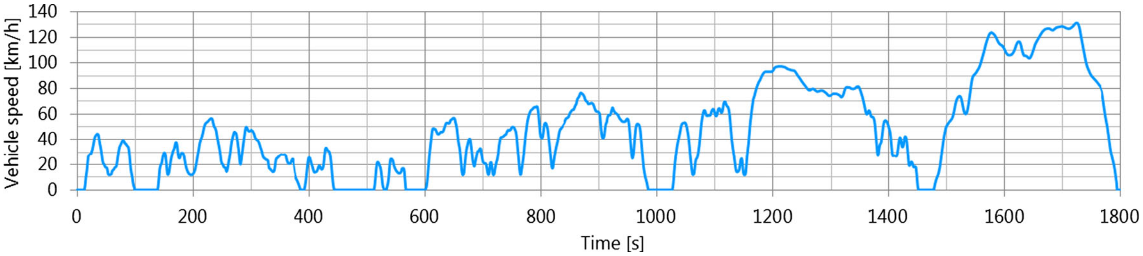

Fig. 6. Velocity profile of the WLTP driving cycle.

driven in the last 323 s of the cycle, in the so-called extra high part.

For the waste heat recovery, this driving cycle represents a much more challenging boundary condition than motorway driving with a constant high load, for example. For this reason, the WLTC is used for the optimization in order to get a TEG design that achieves a possibly high performance with low costs in the entire spectrum, also in the low load range.

Simulation Environment

The work on optimizing the TEG system has shown that special attention has to be given to the development of efficient heat exchangers. In order to be able to freely design the special heat exchangers and thus exploit the potentials, the entire simulation environment was developed based on a CFD simulation. In addition, it has been shown that the thermoelectric modules must be designed and optimized together with the heat exchangers in the system. To evaluate the effects of the TEG on the vehicle system, the overall system interactions were integrated into the simulation environment. To integrate the thermoelectric modules (TEM) in the simulation, measured module values were used. The state of the art has shown that the efficiency calculation of thermoelectric modules based purely on material data shows a lower accuracy. Therefore, thermoelectric modules were designed and built in an iterative way. The measurement data of the thermoelectric modules were integrated into the simulation and the efficiency achieved modelled. In cooperation between Yamaha and the DLR Institute of Vehicle Concepts the procedure was executed.[15] Thereby, Yamaha was able to build the TEM according to the specifications of the DLR. This enabled the DLR, with the work on a holistic design, to improve the entire system including the TEM in the optimization. The simulation values presented below are based on Half-Heusler TEM. The efficiency measured by the cooperation partner on their TEM test bench was 7% in the maximum power point at a hot side temperature of 550°C and a cold side temperature of 80°C. The TEM developed according to the design of this work is shown in Fig. 7.

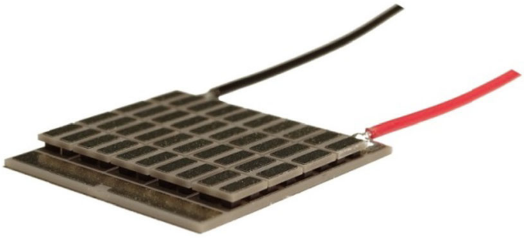

Fig. 7. Thermoelectric Modul developed according to the design of this work. (Reprinted from[15] under CC License BY 3.0).

In the CFD simulation, the hot gas heat exchanger was modeled together with the thermoelectric module. Thereby, an automated parameter variation was realized for the geometry and mesh creation. Furthermore, the bypass control was integrated into the CFD simulation. This was necessary in order to ensure that an automated optimization would not lead to excessively high results, which would not be feasible, eg., due to exceeding the maximum temperatures. The integrated bypass control automatically adjusts the exhaust gas mass flow when the maximum hot-side temperature of the TEM is exceeded and also when a maximum exhaust gas back pressure is exceeded.

In order to perform a holistic optimization, a cost model was developed in this work that contains the cost items for the entire TEG system listed in Fig. 8.

APPLICATION OF THE HOLISTIC OPTIMIZATION METHOD, RESULTS AND DISCUSSION

Reference Vehicles

To demonstrate an application of the holistic design method two reference vehicles were selected. Both vehicles are from the compact class, a conventional and a hybrid vehicle. To represent a common conventional vehicle the Volkswagen Golf VII with a turbocharged engine and 1.2 L displacement was selected. As hybrid vehicle the Opel Ampera (Chevrolet Volt) with 1.4 L displacement is chosen. The Opel Ampera with its power train as a power-split hybrid represents the majority of current plug-in hybrid electrical vehicles (PHEV). The main characteristics of the reference vehicles are shown in Fig. 9.

To compare the hybrid vehicle with the conventional vehicle, the hybrid vehicle was operated in the charge sustaining mode. In this mode, the cycle

Costs - TEG system

- **Costs - TEM**
  - **Thermoelectric legs**
    - Raw materials
    - Production TE material
    - Separation and cleaning of the legs
  - **Ceramic substrat, bridges and other materials**
  - **Production of TEM (industrial)**
- **Costs - TEG**
  - **Raw materials and semi-finished parts**
    - HGHEX / COHEX / TEG
  - **Production of TEG Parts**
    - Heatexchangers
    - Housing and mounting parts
  - **Assembling of TEG**
  - **Joining of TEG**
  - **Electronics**
- **Costs - Exhaust gas bypass**
  - **Bypass valve**
  - **Bypass pipe**

Fig. 8. Item list of the cost model for the entire TEG system.

	Vehicle type	Battery capacity	ICE	Type of engine	Displacement	Max. Performance	Operating strategy	Transmission	Weight of vehicle	Year of launch	Fuel consumption (measured)	CO_2 emissions (calculated)
	[-]	[kWh]	[-]	[-]	[dm³]	[kW]	[-]	[-]	[kg]	[-]	[l/100km]	[g/km]
Volkswagen Golf VII	Conv.	-	Turbo (TSI)	4 cyl. in-line	1.197	77	Start-stop	Autom. (DSG)	1300	2012	5.63	131.2
Opel Ampera	Hybrid	16	Otto	4 cyl. in-line	1.398	63	Power-split		1700	2012	6.76*	157.5*

* within the charge sustaining mode

Fig. 9. Main characteristics of the reference vehicles.

Fig. 10. Reference vehicles at the roller dynamometer test bench.[16]

is started with an empty traction battery, and the required energy is supplied by the combustion engine. The measured fuel consumption for both vehicles is shown in Fig. 9. The value of the hybrid vehicle refers to the charge sustaining mode.

Measurement data from the roller dynamometer test bench for both vehicles were used as input for the simulation. Thereby, the temperatures and mass flows of the exhaust gas and coolant from the measured WLTC were used. Also, the data of the ICE regarding speed, torque and temperature is used from the measurement.

The reference vehicles are shown in Fig. 10 on the roller dynamometer test bench of the DLR Institute for Vehicle Concepts in Stuttgart. A detailed comparison of the potential for waste heat recovery in both drive trains is presented in Ref. 16. The result of the comparison show that in hybrid vehicles a higher share of the energy supplied by the fuel is lost in the exhaust gas. Also, the temperature level of this exhaust gas is even higher than in the conventional vehicles. In addition, the comparison points that waste heat and exergy in the exhaust gas are higher in hybrid vehicles, despite the fact that the ICE has a higher efficiency. The average of the exergy flow in the WLTC is about 78% higher in the hybrid vehicle within the charge sustaining mode, than in the conventional vehicle.

Results Achieved for the Two Reference Vehicles

In the methodical procedure according to Fig. 1, an automated optimization of the entire TEG system is performed. Thereby, all relevant parameters are varied through an optimization algorithm. Goal of the algorithm is to optimize the two primary objectives and the eight secondary objectives. Result is a ten-dimensional Pareto set. Due to the complexity, only the two primary objectives are plotted as a Pareto front in Fig. 11 in order to give an overview. The ordinate of Fig. 11 shows the CO_2 reduction effectively achieved in the overall system within the WLTC. The abscissa specifies the corresponding system costs for the entire TEG system. Each dot in the diagram represents one unique TEG design and its parameter set.

The result of the optimization shows for the conventional vehicle a maximal reachable efficiency improvement within the overall system of 2.9 g/km. This corresponds to a reduction in the CO_2 emissions of 2.2% for the conventional vehicle. Thereby, the overall system interactions shown in Fig. 5 were taken into account. The CO_2 emissions are equivalent to the fuel consumption. For this reason, the fuel reduction achieved in the overall system within the WLTC is also 2.2%.

For the hybrid vehicle within the charge sustaining mode an efficiency improvement of 5.4 g/km is achieved. This corresponds to an improvement of 3.4% in CO_2 emissions and fuel consumption. The reduction of the combined CO_2 emissions, where the charge sustaining and charge depleting mode of the hybrid vehicle is combined, is also 3.4%. This is because the reduction within the charge sustaining mode has a linear influence within the calculation equation in the WLTP.

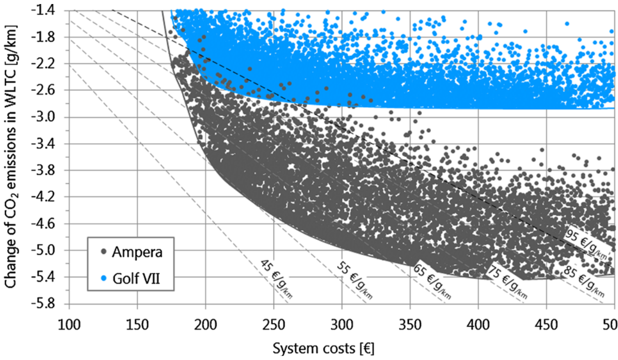

Fig. 11. Optimization result for the conventional and the hybrid vehicle—Pareto front of the two primary objectives.

Also the cost–benefit ratio, as a combination of the two objectives, is plotted in Fig. 11. The target value of 95 €/(g/km) is marked. It can be seen that through the optimization for both vehicles this target value could be achieved. For the conventional vehicle the TEG system has cost–benefit ratio of 81.3 €/(g/km). This signifies that the costs for using a TEG system are lower than the penalty in the European Union for exceeding the fleet CO_2 emissions.

For the hybrid vehicle within the charge sustaining mode a cost–benefit ratio of 54.8 €/(g/km) is achieved. The distinctly better improvement in the CO_2 emissions and in the cost–benefit ratio can be explained on the one hand by the higher exergetic potential in the exhaust gas as described above. On the other hand, the improvement in thermal management by the TEG is higher in the hybrid vehicle. Due to the lower ICE wall heat flows in the hybrid vehicle, as also described in Ref. 16, there are less heat flows into the cooling system. Therefore, the recovery of heat from the exhaust gas has a higher effect for shortening the warm-up phase.

Result Design Using the Hybrid Vehicle as an Example

The methodical procedure is to select the resulting design from the ten-dimensional Pareto set. Thereby, the two primary and eight secondary objectives are weighted with each other in order to achieve the desired balanced design. In Fig. 12 the resulting design for the hybrid vehicle is shown. This design is not directly located on the plotted Pareto front of the two primary objectives. This is due to the weighting of the secondary objectives. The selected resulting design is more balanced than one directly at the Pareto front.

The selected resulting design for the hybrid vehicle achieves a CO_2 reduction of 4.3 g/km for the reference vehicle within the WLTC. This corresponds to a CO_2 reduction of 2.7%. The system costs for the entire TEG system are estimated according to the developed model (Fig. 8) with 258 €.

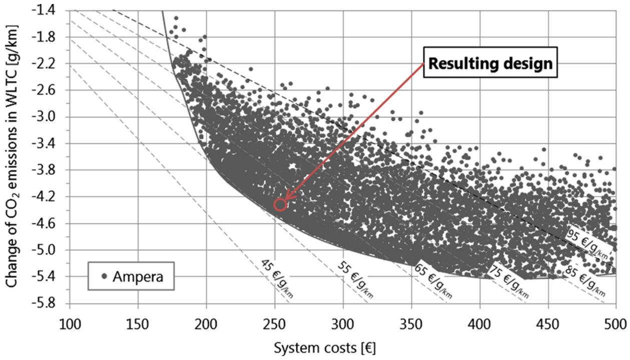

Fig. 12. Selection of a resulting design for the hybrid vehicle.

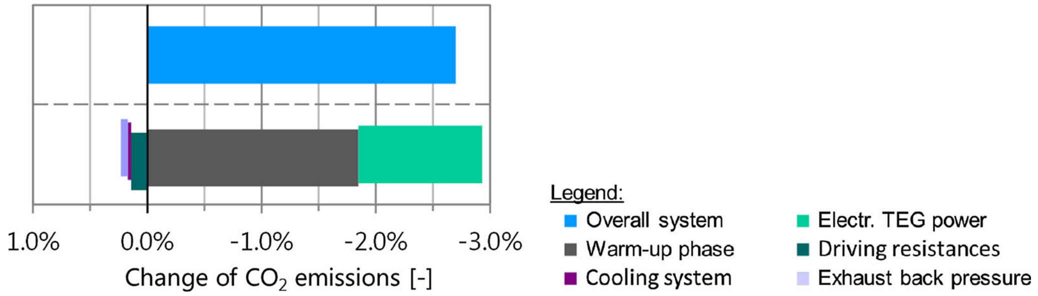

Fig. 13. Resulting design of the hybrid vehicle—overall system interactions as average within the WLTC.

In the following the resulting design will be described in detail. Figure 13 shows the interactions between the vehicle overall system and the TEG system. The positive and negative effects to the vehicle correspond to Fig. 5. It can be seen that in the driving cycle WLTC an improvement of about 1.1% can be achieved by the electrical power of the TEG. This improvement could be achieved even though the cycle has a very low load over a wide range. The second major positive effect is the shortening of the warm-up phase. Here, the TEG has approximately a ten times higher heat flow than a conventional state-of-the-art exhaust gas heat recovery unit.

The model for calculating the improvement in the warm-up phase, validated by measurement data, results in a saving of about 1.8%. Since hybrid vehicles still have issues with thermal management, the TEG can help to recover the heat from the exhaust gas and has a positive effect on efficiency and comfort.

Although the power density could be increased considerably, the weight of the TEG system is the greatest negative effect. The weight of the entire TEG system is 7.8 kg. The system includes the TEG with its power electronics, the exhaust gas bypass with its bypass flap and the additional coolant for the TEG. The weight of the TEG itself as part of the system is 4.5 kg, for the TEG with the exhaust gas diffusors and without the power electronics. At this point it should be mentioned that the intensive optimization with regard to the cost–benefit ratio has led to a considerable reduction of the used thermoelectric material. In this resulting design only about 30 g of the thermoelectric Half-Heusler material is used per vehicle.

The effect of the exhaust back pressure on the CO_2 emissions is decisive. For this reason, the exhaust gas heat exchangers were intensively developed and a exhaust gas back pressure of less than 30 mbar within the WLTC could be achieved. As a result, the influence on the CO_2 emissions could be reduced (see Fig. 13).

To further detail the resulting design, the electrical power converted by the TEMs (P_{TEM}) is shown in Fig. 14. This power includes all TEMs within the TEG system without the losses of the power electronics (DC/DC converter). The average of the electrical power within the WLTC is 131.5 W. In addition, the shaft power of the ICE (P_{ICE}) is plotted in Fig. 14 and the reduction of the ICEs shaft power which can be achieved through the TEG ($\Delta P_{\mathrm{TEG,shaft\ power,ICE}}$).

The results are based on the measured input data of the reference vehicle in the WLTC. The measured time-dependent profiles for temperatures and mass flows of the exhaust gas and coolant were used. In a further step, the maximum performance of the TEG, designed for cost–benefit in the driving cycle WLTC, was analyzed. For this purpose, the load point of the vehicle was increased in the simulation until the maximum hot side temperature of the TEM with 600°C was reached. As coolant temperature 20°C was used only for the examination of the maximum performance. This corresponds to the temperature in the cooling system during a drive at low ambient temperatures. As a result from the analysis of the rated power, a maximum electrical peak power ($P_{\mathrm{TEM,rp}}$) of 1094.3 W could be achieved.

STATE-OF-THE-ART ASSESSMENT

Finally, a comparison between the results presented here and the state of the art shall be given. This comparison shall be demonstrated on the basis of the gravimetric and volumetric power density.

$$\psi_{\mathrm{TEG}}\left[{}^{\mathrm{W}}\!/_{\mathrm{kg}}\right] = \frac{P_{\mathrm{TEM,rp}}}{m_{\mathrm{TEG}}}, \tag{1}$$

$$\phi_{\mathrm{TEG}}\,[\mathrm{W/dm\hat{}3}] = \frac{P_{\mathrm{TEM,rp}}}{V_{\mathrm{TEG-Core}}}. \tag{2}$$

The power density is calculated according to Eqs. 1 and 2. Thereby, the rated power ($P_{\mathrm{TEM,rp}}$) is used. In order to be able to show a comparison with the state of the art, a uniform basis must be chosen. For this reason, the power electronics both in weight (m_{TEG}) and volume ($V_{\mathrm{TEG-Core}}$) are not considered at this point. The resulting design of the hybrid vehicle presented in this work has a gravimetric power density of 242 W/kg and a volumetric power density of 478 W/dm^3.

An assessment with the state of the art, using relevant projects of the recent years,[8,13,15,17,–19] is made in Fig. 15. The values for the state of the art[13]

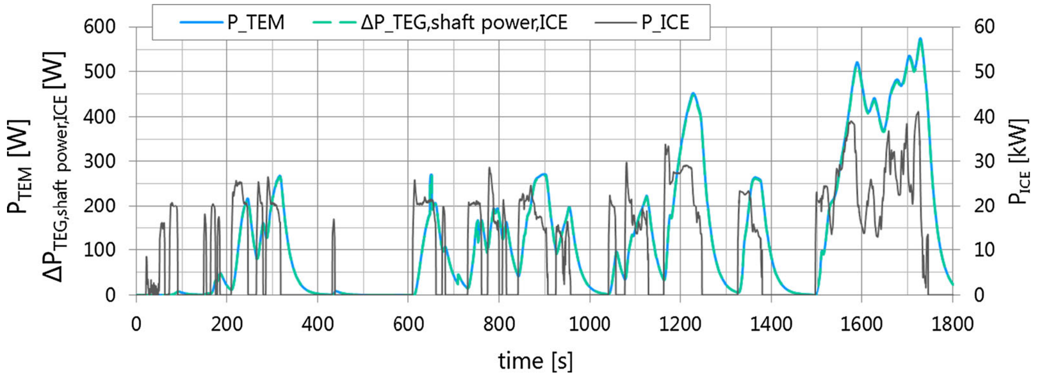

Fig. 14. Resulting design of the hybrid vehicle—converted electrical power by the TEG within the WLTC.

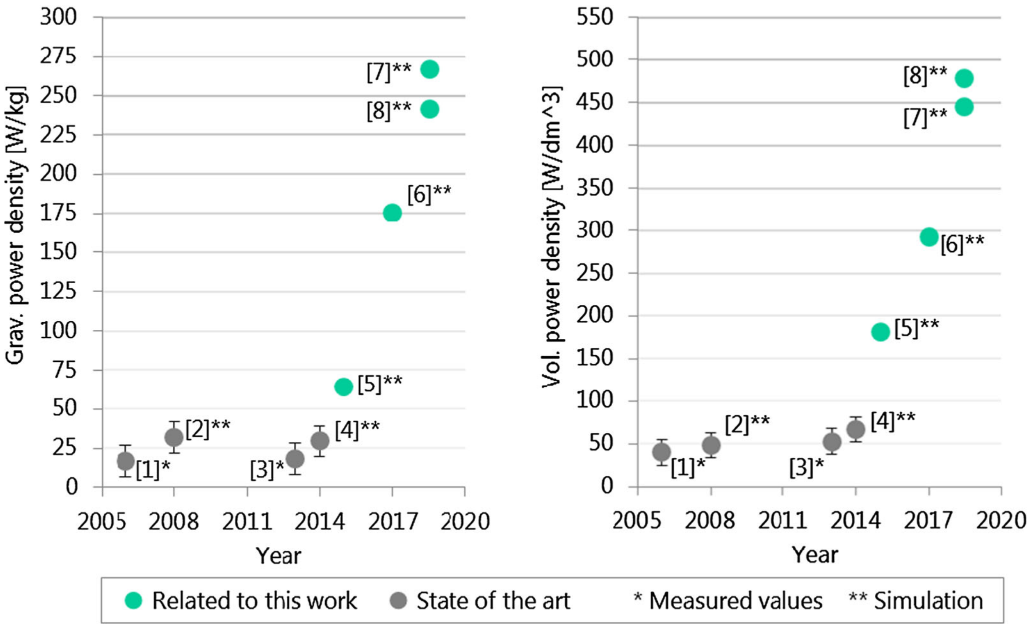

Fig. 15. Overview over the development of the gravimetric and volumetric power density for TEG in automotive applications over the years. (References: [1],[17,18] [2],[18] [3],[19] [4],[13] [5],[20] [6],[8] [7] Resulting design for the conv. vehicle in this work, [8] Resulting design for the hybrid vehicle in this work).

were set to 29 W/kg and 67 W/dm^3. These values could be exceeded by about 900% and 700%, respectively. The power densities achieved are up to now the highest published values for thermoelectric automotive generators known to the author to date.

CONCLUSIONS

Methodology for a holistic TEG optimization has been introduced, ranging from a highly integrated TEG design to vehicle overall system interactions to a multi-objective optimization. The simulation environment has been explained, which was developed based on a CFD simulation. This was done due to the importance attached to the heat exchangers. To optimize the thermoelectric modules in combination with the heat exchangers, they have been integrated into the simulation environment as well, together with a cost model for the entire TEG system. The aim of the presented method for a multi-objective optimization is to be able to optimize the cost–benefit ratio directly. An application of the optimization method has been presented for a conventional and a hybrid vehicle. The results of the holistic optimization have been discussed and a resultant design selected. On the example of the hybrid vehicle, this design has been further evaluated. The validation of the different models has also been addressed. Further validation on an entire functional TEG model will be described in Ref. 21.

Finally, a state-of-the-art assessment has been shown which demonstrates the achieved increases on the basis of the gravimetric and volumetric power density. Through the overall system optimization, the goal to realize a TEG system with a cost–benefit ratio of less than 95 €/(g/km) could be achieved. Thus, an economically attractive TEG system could have been presented, and the hope is that it will be utilized in the future to reduce the greenhouse gas emissions.

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