Thermoelectrics – An Opportunity for the Automotive Industry?

Daniel Jänsch(✉), Jens Lauterbach, Markus Pohle, and Peter Steinberg

IAV GmbH, Berlin, Germany
Daniel.Jaensch@iav.de

Abstract. The paper looks at the key issues in terms of what thermoelectrics (TE) can and must do for the automotive industry through to 2020^{+}.

A brief introduction to the topic of waste heat recuperation and thermoelectric generators (TEG) is followed in the first section of the paper by an illustration of the potential offered by a fictive TEG ideally rated for use in the exhaust system of a passenger car with conventional powertrain, with an estimate of possible benefits and costs. This begins by asking which minimum contribution a new technology has to provide for it to be included by the automotive industry in the package of measures needed to achieve future CO_2 targets. A proposal is presented as the basis for the subsequent observations. The paper then looks at the necessary material/module efficiency and the required mean ZT value as well as availability.

This is followed by a brief description of the objective, consortium, job split, contents and scope together with a summary of selected results obtained with the consortium project TEG2020 funded by the BMBF (German Federal Ministry of Education and Research).

The very general theoretical observations in the first section are then compared in the second section with selected results obtained in test bench and vehicle measurements using the laboratory generator developed in the project. The focus here is not on the generator itself but on the impact of the conventional generator, the additional mass of the TEG and its exhaust gas backpressure, auxiliary power consumption and the necessary recooling.

The project results show that it is possible to realize the fictive TEG featured in the estimate of potential using the existing possibilities.

1 Introduction

Today and in the foreseeable future, most vehicles will be driven by fossil fuels. Reserves of fossil fuels are finite. Their extraction and utilization place a considerable burden on health, the environment and climate. Even so, it is still generally accepted that only a very small part of the energy contained in the fuel is used to actually propel the vehicle (Fig. 1). More than half of the fuel energy is still lost to the environment unused as waste heat, with considerable costs and consequences [1]. However, waste heat recuperation could help to achieve future CO_2 limits. The aim must therefore be to make use of this lost energy on the basis of economically viable technologies.

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This is where thermoelectric converters come in. They convert heat directly into electrical energy for the vehicle electrical system; by relieving the pressure on the mechanically driven generator, they make it very easy to save fuel and reduce CO_2 emissions. Their unique properties are based on their solid-state-physical principle of operation. They therefore need neither chemical nor mechanical processes. However, a poor cost/benefit ratio and the critical availability of TE materials and modules have so far prevented the widespread industrial use of this technology. But many research teams throughout the world are being driven by the attractive prospects in combination with the huge technical and economic potential of the technology in order to solve the remaining challenges. For years now, there has been a growing number of scientific publications to this effect in renowned journals and papers presented at international energy, material and thermoelectrics conferences. More and more companies are announcing promising second-generation TE materials and modules in interesting quantities, or are even capable of supplying the same already today. We can therefore expect to see adequate volumes of TE materials and modules being made available in the next few years that also meet the special requirements of the automotive industry in terms of efficiency, quality, quantity and price. This would then also fulfill a significant prerequisite for the automotive industry to get involved in TEG development. Another particular challenge, especially for automotive use of this technology, consists in the need for high efficiency paired with the low energy supply in the urban cycle as well as resistance to high temperatures and alternating loads, in order to achieve CO_2 reductions in the test cycle in a relevant magnitude.

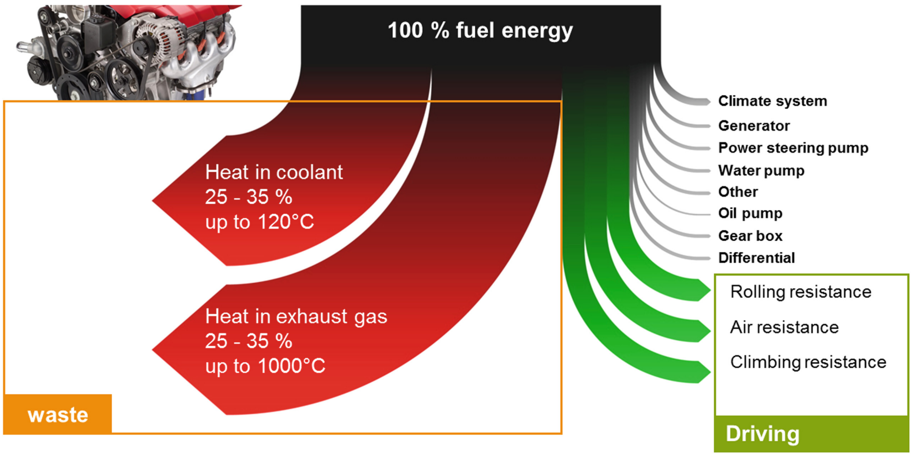

Fig. 1. Energy utilization of a passenger car engine

2 Benefits, Costs, Potential, Requirements and Availability

Before users will take a technology seriously, a reliable estimate is required of its potential contribution to achieving the set goals. New technologies in particular must provide early evidence of what they can offer when first introduced and which costs would be involved or acceptable. The central question for concepts looking at waste heat recuperation is: Which fuel savings or CO_2 reductions will be possible at which price?

2.1 Minimum Savings

Fuel savings of just one percent can already make a concept interesting, depending on its maturity and potential, and the costs involved in development and integration. In light of the economic aspects involved (e.g. costs for saving 1 % fuel or reducing 1 g CO_2, necessary mileage for reaching the payback point), TEGs will have to provide at least two to three percent in the **WLTC** (Worldwide Harmonized Light-Duty Vehicles Test Cycle) before they can be included in the industry's package of measures to cope with future CO_2 targets. For the vehicles described in the following potential estimate, this would mean a reduction of a good three, five and eight grams of CO_2 per kilometer in the **WLTC** in the standard/customer configuration, i.e. with corresponding load on generator and A/C compressor. Supercharged gasoline engines need to relieve the generator by about 50 W in the **WLTC** per gram of CO_2 reduction (see also Fig. 8). Accordingly, TEGS will have to supply approx. 150, 250 and 400 W into the vehicle electrical system on average throughout the **WLTC** in order to achieve the CO_2 targets.

2.2 Estimate

To get an idea of the potential offered by the technology and thus of its possible benefit, this paper estimates the possible CO_2 reduction that can be achieved with a TEG in the best case in the homologation and customer cycle. A simple method but one that it is accurate enough for the purpose involved here consists in roughly estimating the fuel consumption and thermal energy in the exhaust gas in relevant operating states for representative reference vehicles, in this case with conventional standard gasoline engine drives. The thermal energy available in the exhaust gas is used to derive the electrical energy or power that can be supplied to the vehicle electrical system on average by an ideally rated fictive reference TEG. It is then possible to obtain the potential fuel savings or CO_2 reductions in the cycle. The estimate takes account of all power consumption and consumption-enhancing effects of the TEG. It is also presumed that the power supplied is absorbed completely thanks to corresponding energy management and is used in a suitable way to relieve the combustion engine. Consideration is given to the following variants to obtain a field of potential that describes reality as generally as possible:

- Three reference vehicles with two auxiliary drive configurations
- Various fictive reference TEGs in a close-coupled position and away from the engine
- 80 driving profiles, including five real "customer journeys" with different driver types.

2.3 Reference Vehicles

The reference vehicles are defined by their rolling resistance levels and drive systems based on corresponding data. They represent the following segments: C/D (mid-range class) with 5.0 l/100 km, E/F (upper/luxury class) with 7.5 l/100 km and M/J (multi-van, SUV, utilities) with 10 l/100 km mean consumption in the **NEDC** (New European Driving Cycle), without generator and A/C compressor load (homologation configuration). Consumption in the normal configuration is about 20 % higher than the homologation configuration. It should reflect real average operation on the roads [2].

2.4 Fuel Savings

The graph shows possible fuel savings for a fictive TEG installed away from the engine in the cycle, on the highway and on a customer journey as well as cruising at constant speed (on the right) for the three vehicle segments. A TEG with ideal rating for the specific operation is scarcely capable of achieving targets values in excess of 2 % (yellow area, dotted lines) in the current **NEDC** homologation cycle. In the future **WLTC** homologation cycle and with a normal configuration, fuel savings of a good 2 % to 3 % are possible (green area, continuous lines), depending on the vehicle segment. Savings of more than 3 % and up to 5 % can be achieved in the customer and highway cycle respectively (Fig. 2).

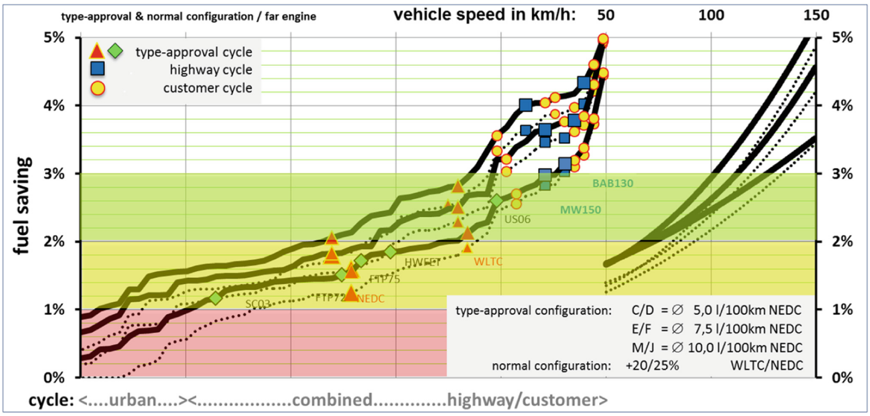

Fig. 2. Possible fuel savings for urban, combined and highway cycles and for customer driving and constant-speed cruising (on the right) in three vehicle segments

2.5 TEG Power

The corresponding electrical TEG power is shown here in Fig. 3. Accordingly, no effective power is possible for the reference vehicles in the urban/off-highway cycle for **NEDC** homologation configuration, and less than 150 W is possible in the **NEDC**. However, on average, power of between 200 W and > 1000 W is possible in the customer and highway cycle. Average TEG power of at least 150/250/400 W defined as being target-relevant is possible for the future **WLTC** homologation cycle for reference vehicles with normal configuration.

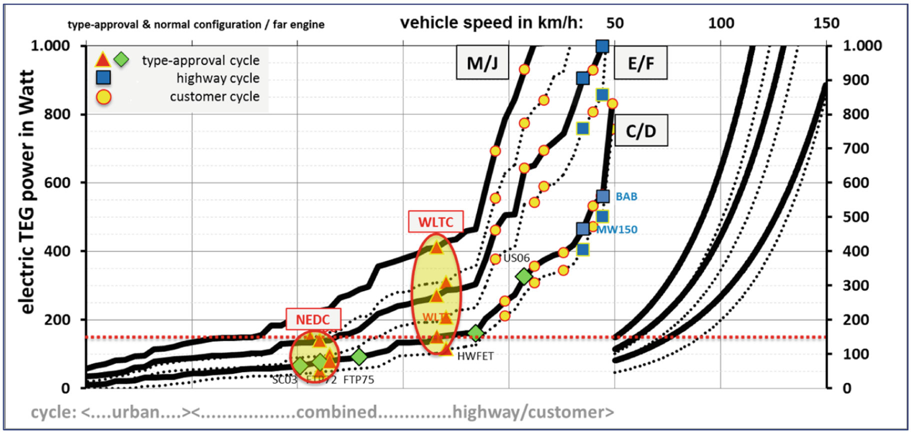

Fig. 3. Possible TEG power for urban, combined and highway cycles and for customer driving and cruising at constant speed (on the right) in three vehicle segments

3 CO_2 Reduction

Figure 4 shows the possible CO_2 reduction for all driving cycles und review and for cruising at between 50 and 150 km/h:

- For the urban cycle, only the upper segment shows relevant CO_2 reduction
- For the homologation configuration in the **NEDC**, CO_2 emissions are reduced by 1.5 respectively 2.8 and 4.2 grams per kilometer
- The reduction for highway and customer cycle and cruising at constant speed exceeds 12 g CO_2/km
- For the normal configuration in the **WLTC**, CO_2 emissions are reduced by 3.2 respectively 5.6 and 8.5 grams per kilometer
- For the urban cycle, the reduction is 2 to 5 g CO_2/km for the upper segments
- The reduction for highway and customer cycle and cruising at constant speeds amounts to up to 16 g CO_2/km

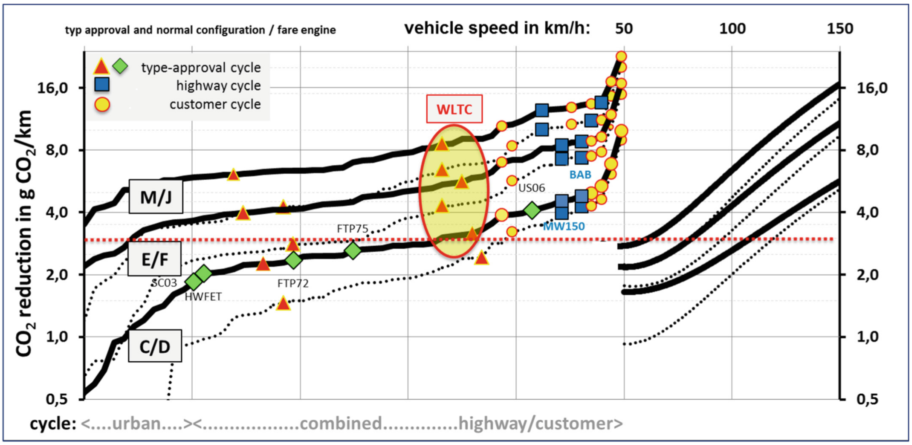

Fig. 4. CO_2 reduction of a TEG after EAT in cycle mode and cruising at constant speed for reference vehicles in homologation and normal configuration

Moving the TEG from the thermally less favorable position downstream of the EAT (**E**xhaust gas **A**fter-**T**reatment system) to a close-coupled position clearly increases the TEG power on account of the higher exhaust gas temperatures. The increase amounts to approx. 50 % for the single-flow system analyzed here. Although just a rough indication, this value clearly shows that close-coupled concepts are definitely worth checking and also pursuing, even if these are far more complex.

3.1 Material and Module Efficiency

That leaves the question as to what a TEG has to be like in order to achieve the intended target power. To start with, TEG power is greatly influenced by the heat supply, i.e. exhaust gas mass flow and temperature. This depends primarily on the vehicle and its drive and mode of operation. Anything that improves the heat supply or ensures that this is not used up before reaching the TEG is helpful, including in particular making adjustments to the position of the TEG (close-coupled position or away from the engine). Insulating the exhaust gas system up to the TEG also makes sense, where possible and permissible. Only two aspects of the TEG itself will be considered here.

For a constant heat supply, prime responsibility for the power lies with the efficiency of the heat exchanger systems and the modules. An estimate has been given of the module/material efficiency necessary for the target power. Figure 5 shows the average material/module efficiency required for the vehicle segments for three different heat exchanger systems with 50/66/75 % heat utilization in a position away from the engine (black) and a close-coupled position (red). The target power can be achieved with a good 8 %, or even less than 5 % with excellent heat exchangers in a close-coupled position.

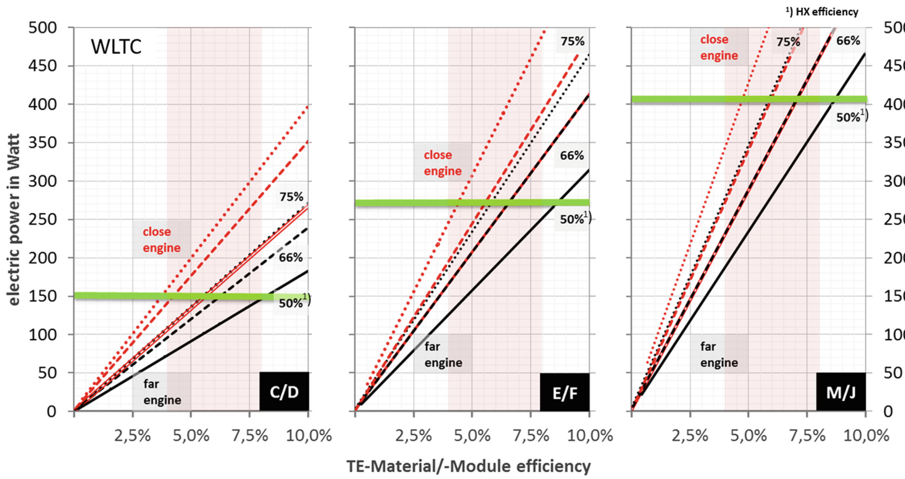

Fig. 5. Necessary material/module efficiency

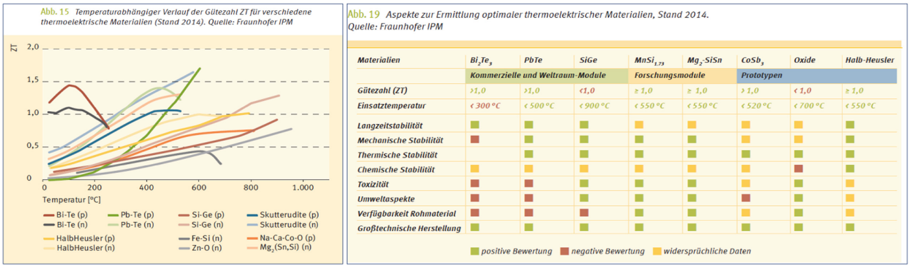

Fig. 6. ZT curve and development status of promising TE materials [3]

Table 1. ZT_{avg}, ZT_{peak} und material efficiency η for TE-Material of Fig. 6

	Bi-Te(p)			Pb-Te(p)			Skutterudite(p)			HalbHeusler(p)			Na-Ca-Co-O(p)		
T_{cold} / T_{hot} [°C] / [°C]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]	ZTavg [-]	ZTpeak [-]	η [%]
25 / 250	1,23	1,46	10,3%	0,09	1,65	1,2%	0,44	1,06	4,9%	0,29	0,86	3,4%	0,16	0,71	2,0%
50 / 250	1,21	1,46	8,9%	0,10	1,65	1,1%	0,47	1,06	4,4%	0,30	0,86	3,1%	0,17	0,71	1,8%
50 / 500				0,41	1,65	6,8%	0,72	1,06	10,5%	0,45	0,86	7,3%	0,31	0,71	5,4%
100 / 500				0,45	1,65	6,3%	0,77	1,06	9,4%	0,48	0,86	6,6%	0,33	0,71	4,9%
100 / 600				0,65	1,65	9,5%	0,82	1,06	11,2%	0,54	0,86	8,3%	0,40	0,71	6,5%
150 / 600				0,71	1,65	8,9%	0,86	1,06	10,2%	0,57	0,86	7,5%	0,43	0,71	6,0%
	Bi-Te(p)			Pb-Te(n)			Skutterudite(n)			HalbHeusler(n)			Mg2(Sn,Si)(n)		
25 / 250	1,01	1,09	9,1%	0,51	1,41	5,5%	0,64	1,67	6,5%	0,34	0,98	3,9%	0,53	1,31	5,7%
50 / 250	1,00	1,09	7,8%	0,54	1,41	5,0%	0,67	1,67	5,8%	0,35	0,98	3,5%	0,56	1,31	5,1%
50 / 500				0,92	1,41	12,4%	0,96	1,67	12,8%	0,56	0,98	8,7%	0,84	1,31	11,6%
100 / 500				0,99	1,41	11,2%	1,01	1,67	11,4%	0,60	0,98	7,9%	0,89	1,31	10,4%
100 / 600				1,00	1,41	12,9%	1,12	1,67	13,9%	0,67	0,98	9,7%	0,97	1,31	12,6%
150 / 600				1,06	1,41	11,7%	1,18	1,67	12,5%	0,71	0,98	8,9%	1,02	1,31	11,4%
	Bi-Te(p)			**Pb-Te(p)(n)**			**Skutterudite(p)(n)**			**HalbHeusler(p)(n)**			**Na-Ca-Co-O /Mg2(Sn,Si) (p)(n)**		
25 / 250	1,12	1,27	9,7%	0,30	1,29	3,6%	0,54	1,31	5,7%	0,31	0,92	3,7%	0,35	1,01	4,0%
50 / 250	1,11	1,27	8,4%	0,32	1,29	3,2%	0,57	1,31	5,1%	0,33	0,92	3,3%	0,36	1,01	3,6%
50 / 500				0,66	1,29	9,9%	0,84	1,31	11,7%	0,51	0,92	8,0%	0,57	1,01	8,8%
100 / 500				0,72	1,29	9,0%	0,89	1,31	10,4%	0,54	0,92	7,2%	0,61	1,01	8,0%
100 / 600				0,83	1,29	11,3%	0,97	1,31	12,6%	0,61	0,92	9,0%	0,69	1,01	9,9%
150 / 600				0,89	1,29	10,4%	1,02	1,31	11,4%	0,64	0,92	8,2%	0,73	1,01	9,0%

It is also possible to roughly ascertain the average necessary ZT values for the **WLTC**: ZT_{max} values $\leq$ 1.2 or ZT_{avg} values $\leq$ 1.0 would be sufficient. TE material is usually described by means of its ZT_{peak}. However, without knowing the temperature-dependent ZT curve (Fig. 6), this value gives very little indication of the practical suitability of the TE material as shown in Table 1.

3.2 Availability

Thermoelectrics are increasingly becoming suitable for large-scale use [3]. At the moment, researchers are investigating promising materials and synthesis methods which already achieve figures of merit of ZT_{peak} = 1.5 to 2.5 in the laboratory. Materials with ZT_{peak} values of up to 1.5 are already suitable for use. TE materials with ZT_{peak} values of around 1.0 are commercially available. Together with the three classic examples Bi_2Te_3, PbTe and SiGe, the preferred materials include silicide, skutterudite or half-Heusler materials. There is currently no knowing which material will win the race. In the end, the choice of material will depend on the requirements (costs, efficiency, weight etc.) of the specific application. Such materials and corresponding modules have been available as prototypes for some time now, although scarcely on the free market. Today it is possible to produce silicides by the kilo, half-Heusler and PbTe materials on a multi-kilo scale and some skutterudites and Bi_2Te_3 by the ton. Current developments focus particularly on material and production costs.

[4] looks in detail at the "availability and maturity of thermoelectric materials for use" (as of 2014). The Austrian company Treibacher Industrie AG is featured as an example, offering powdered skutterudite material with *ZT* values > 1 on a multi-kilo scale for some time now. Half-Heusler modules should be available in small-scale production as from 2017. As part of the thermoHeusler[2] consortium project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) [5], Vacuumschmelze GmbH & Co. KG is looking at further development of a powder metallurgy process for manufacturing half-Heusler compounds, while Isabellenhütte is investigating further development of a smelting metallurgy process to the same end. The project aims to "develop material and module production suitable for volume production, together with a near-production manufacturing and installation concept for the TEG that boost cost efficiency to such an extent as to permit standard use of this technology in the medium term" [6, 7]. The Fraunhofer Institute for Physical Measurement Techniques (IPM) in Freiburg "has now developed and commissioned the world's only pilot production line for thermoelectric high-temperature modules" [8]. The semi-automatic production line produces large quantities of thermoelectric modules for up to 600 °C operating temperature at far lower costs than hitherto possible.

Finally it is also worth mentioning that module efficiency levels of 4 to 8 % depending on TE material have been reported in numerous publications for a long time now, e.g. [6, 9, 10].

3.3 Costs

The costs of innovative technologies are initially borne by the vehicle manufacturers, who then pass on the additional costs to their customers. Even if customers do not see the costs of measures reducing fuel consumption and emissions, because they are incorporated in the overall vehicle costs, each one must be economically viable in itself.

For customers buying new cars, lower operating costs and low fuel consumption are the most important purchasing criteria. More than half of new vehicles are used in the business customer segment (in Germany). Here as well as with commercial vehicles, economic rationale is almost exclusively decisive for the adoption of technical innovations. Technologies only prevail in the market if the higher acquisition costs are balanced out by lower operating costs.

The question as to what a TEG may cost needs to be answered by customers and manufacturers.

Various publications have indicated that manufacturers must invest up to € 50 for every gram of CO_2 saved per vehicle [11]. Accordingly, a TEG should not cost more than € 158 (C/D), € 280 (EF) or € 427 (M/J) referred to the **WLTC** in order to be included in the package of measures of the OEMs. Given that the respective mean net electrical power capacities are nearly identical in terms of amount, the costs referred to electrical power are almost exactly equal to the initial target of € 1 per watt indicated in many publications. However, it is also clear that the costs per gram of CO_2 and TEG efficiency can increase further going beyond 2020, so that even higher system costs will be acceptable in future. And the threat of penalties also means that new technologies in future will certainly offer better value for money.

Comments often say that the € 95/g excess emissions penalty would actually then be applicable. However, that would only be true once the automotive industry will have exhausted all measures that are "cheaper" than € 95/g and the fleet objectives are still not reached.

3.4 Payback Point

As far as the customer is concerned, the extra costs for a TEG would reach payback point "at the fuel pump" after about 77,000 km of mileage, depending on driving style, based on a price of € 1.50 per liter of gasoline fuel in the **WLTC**. In terms of appropriate payback periods, this is a challenge for customers with comparatively low mileage. However, the payback period will be far shorter in real customer cycles with **WLTC**-based costs, and may even be halved, depending on vehicle use.

3.5 Summary

To summarize the benefits of a suitably rated TEG in a passenger car, it can be said that depending on the vehicle and driving style, relative fuel savings and CO_2 reductions of two to three percent are possible on average in the combined cycle and up to five percent in the customer and highway cycle. The technology offers scarcely any improvement in the purely urban cycle on account of the low heat supply and the great influence of cold starts. Higher relative savings are possible with higher energy supplies and higher exhaust gas temperatures (close-coupled positions!) or more efficient TEGs. It can be presumed that such TEGs can fulfill the initial conditions for many vehicle manufacturers, particularly for large and heavy vehicles. In our opinion, such generators could certainly be ready for volume production using materials and modules that are currently in development by 2020. For the most part, the prerequisites have been established in recent years. Prototypes of corresponding TE materials and modules are available. At the moment, global developments focus on industrialization, availability, costs, quality and durability.

4 Funding Project TEG2020

Making this outstanding technology accessible to the mass market was the motivation behind the consortium project TEG2020 (03X3552A) funded by the German Federal Ministry of Education and Research **(BMBF)** in the framework of the WING program - Material Innovations for Industry and Society.

The aim of this research project was to develop highly efficient, economical concepts and systems for thermoelectric generators (TEG) suitable for volume production that have been validated in theory and by experiments for recuperating heat lost from transport, propulsion, work and energy systems. An innovative, flexible modular concept should offer possibilities for adapting the TEG to different applications, target systems and output classes.

In the interests of high system efficiency, new installation and connection technologies have been pursued together with innovative approaches to integration and energy management which can be applied to a broad range of thermoelectric (TE) materials.

A flexible demonstrator system was produced by developing a suitable installation and connection technology, working with established bismuth and lead-telluride material systems. At the same time, attention also focused on half-Heusler materials as a suitable substitute for lead telluride on the high-temperature side. The key issue was to obtain a positive substance bond between the TE material and the heat exchange media, both on the cold and on the hot side. To this end, unimpeded contact should be warranted between the heat exchanger and the TE material to the greatest possible extent. Special measures took account of thermomechanical effects. The concept was also extended for friction-locked installation to allow for the use of TE modules currently on the market.

The individual components and the complete demonstrator system were operated and analyzed virtually by simulation and in real terms on a laboratory and engine test bench as well as in the project vehicle.

These demanding project targets can only be achieved with a consortium that offers interdisciplinary skills covering all necessary work steps from material development via connection technologies and module production through to system production and integration. The project includes seven partners from science and industry (see Sect. 3.3) who had already been intensively involved with the issue of waste heat recuperation before the project began. The partner were responsible for their particular section of the development scope according to their core expertise and technological know-how.

This paper presents some of the project's simulation and test results. Rather than concentrating on the TEG itself, attention instead focused not just on the opportunities, benefits and potential but primarily on the known drawbacks of the technology, such as costs, weight, exhaust gas backpressure, auxiliary power consumption and recooling. Experience gained during the project shows that it is possible to reduce the potential weaknesses to an acceptable level with an optimum strategy, layout and design of the TEG, thus clearing the way forward onto the automotive volume market.

The test vehicle for investigating the impact factors of a TEG on fuel consumption consisted of a VW Golf GTI with 2.0 l displacement and an output of 147 kW. All curves and values presented below are mean values obtained from several tests in each case. The following changes to the standard vehicle were examined during the project:

- Increasing vehicle mass by +100 kg
- Narrowing the flow cross-section of the exhaust gas system to about 20 %
- Additional load of +900 W on the conventional generator
- Integration of a self-sufficient cooling system
- Operation without (standard) and with TEG

5 Conventional Generator

In contrast to commercial vehicles, passenger cars use a considerable share of their drive power output as supply for the vehicle electrical system. Constantly growing electrification of the vehicles will increase this share even further, despite greater efficiency of future mechanical generators and electrical vehicle components. TEGs supply electricity from heat. They boost efficiency directly via the electrical path without additional conversion subject to losses (Fig. 7). Only the voltage needs to be adjusted. Further conversion into mechanical energy is conceivable, but is put into second place by the conversion losses. This is appropriate if the electrical energy supplied by the TEG can no longer be absorbed because of insufficient demand from the vehicle electrical system and when the accumulator is full. The prime aim for using TEGs is to relieve the pressure on the mechanical generator powered by the combustion engine. Furthermore, additional beneficial effects can be obtained by TEGs working in combination with other vehicle systems.

Power generation in the vehicle is actually rather inefficient because of the need for double conversion; the efficiency achieved depends greatly on the operating point of the combustion engine and the claw-pole generator. On average, it is between 22 % and 35 %, depending on engine speed and load, and can be far lower under unfavorable operating conditions [12]. Power generation can easily account for more than 10 % of engine output. In [13, 14], the additional fuel consumption from the added generator load is put at 1 l/100 km for 1 kW generator load. Figure 8 gives a numerical estimation for the additional fuel consumption in l/100 km and the relevant CO_2 emissions in g/km; this is then visualized on the basis of the additional fuel consumption according to [15, 16] as a function of average vehicle speed and generator load.

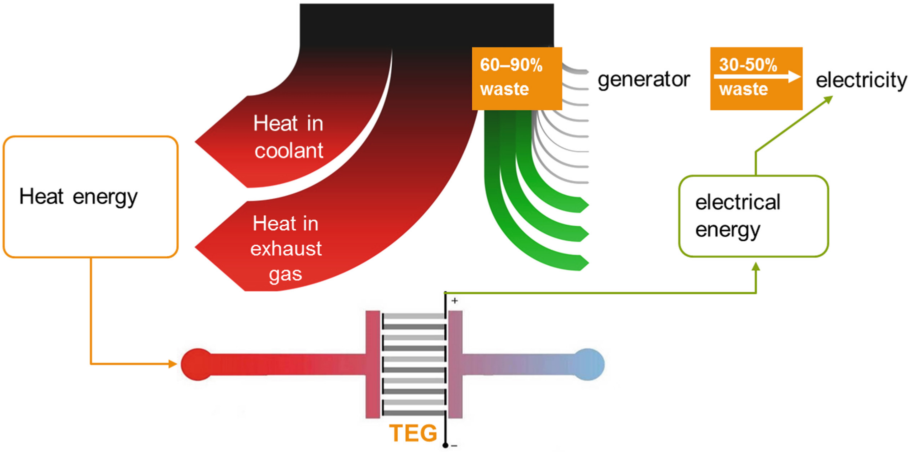

Fig. 7. TEGs in the vehicle electrical system

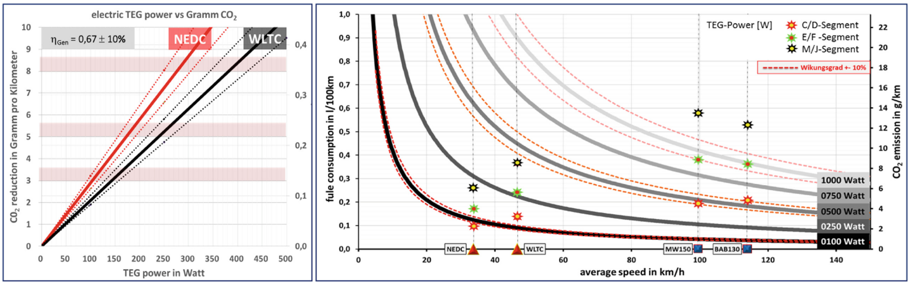

Fig. 8. Additional fuel consumption/CO_2 emissions as a function of average vehicle speed and generator load

The four comparison cycles are marked according to their average vehicle speeds. Many publications (see e.g. [17]) state as a general principle that power demand from the vehicle electrical system is essentially independent from the cycle so that the consumption effect should be evaluated in liters per second. For supercharged gasoline engines, this is approximately 0.4 l/h for one kW electrical power. The route-related consumption or CO_2 reduction effect therefore decreases with increasing average vehicle speed of the driving cycle, as shown in Fig. 8.

To gain a real impression of basic and normal load together with the maximum load of the vehicle electrical system, preliminary tests were carried out with the standard vehicle at two different operating points shown to Table 2.

No electrical consumers were switched on in the vehicle during the base load tests. During the journey, the generator only had to provide the electrical power needed to operate the engine. Typical electrical consumers were switched on for normal operation, while all the test vehicle's electrical consumers were switched on for the maximum possible load on the vehicle electrical system.

Table 2. Generator power at two operating points using various consumers in the test vehicle

	Basic load [W]	Normal load [W]	Maximum load [W]
Idling	162	359	999
125 km/h in 6th gear	198	401	1137

Table 3 shows the additional consumption for adding +900 W to the base load. As explained above, the higher generator load has a far greater impact on fuel consumption in the **WLTC** than in the **MW150** (Artemis Motorway 150) and fits in well with the estimate given in Fig. 8.

Table 3. Additional fuel consumption for (max.) load on the vehicle electrical system in two different cycles (**WLTC** and **MW150**)

	Additional load [W]	Additional consumption [l/100 km]
WLTP (∅v ~ 047 km/h)	900	0.90
MW150 (∅v ~ 100 km/h)	900	0.47

As already mentioned above, the prime aim of a TEG is to relieve the mechanical generator in order to save fuel and reduce CO_2 emissions. Considerable potential is seen particularly at low vehicle speeds and high power demand. This depends on the TEG being offered adequate thermal energy with sufficiently efficient subsequent conversion into electrical energy. However, this is not the case in the two EU homologation cycles **NEDC** and **WLTC**, as clearly illustrated in Fig. 8. The mean electrical power is relatively low here. To a limited extent, this can be counteracted by optimum layout of the TEG for the respective cycle and with a corresponding energy management system which decouples power generation and consumption in terms of time. In this way, TEGs can make an important contribution to achieving the target with kinetic and thermal recuperation covering all the vehicle's electrical energy demands for all conceivable modes of operation, using the combustion engine to supply electrical power only as a reliable redundancy solution. Such solutions are possible with hybrid drives.

6 Thermoelectric Generator

During the project, a modular TEG concept was devised among others and investigate in the test vehicle. A diagram of the concept is shown in Fig. 9.

The TEG consisted of altogether ten modules, in two rows of five facing each other. Two separately actuated servomotors controlled the flaps constantly as a function of defined component temperatures and exhaust gas pressure loss.

Figure 10 shows the TEG fitted in the test vehicle. Commercially available modules were used in each case (oxides and chalcogenides). Each module was fitted with temperature sensors on both the cold and the hot side to monitor the component temperatures and to use the real module temperatures as input variables for parallel

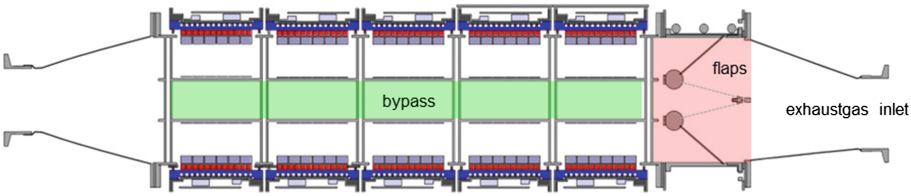

Fig. 9. Schematic set-up of the TEG

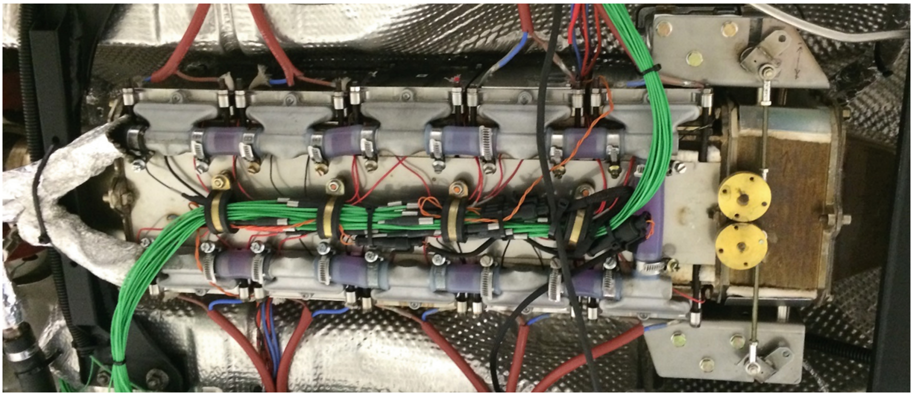

Fig. 10. TEG fitted on the underfloor of the test vehicle

hardware-in-the-loop simulations. A self-sufficient cooling system was responsible for recooling.

Figure 11 shows selected measurement variables for assessing TEG system behavior compared to the standard vehicle for the **WLTC**. It is apparent that the temperature difference over the TEG is higher than in the standard state already shortly after starting the engine (max. 400 K). Even so, pressure loss over the TEG is almost the same as the standard state. The bypass flaps only have to open in the last segment of the **WLTC**. However, this is in order not to exceed the maximum surface temperature of the modules, rather than as a result of elevated backpressure. Among others, two effects are responsible for this positive behavior in terms of pressure losses. Firstly, the flow rate is altogether on a low level, and secondly, the decrease in temperature over the TEG reduces the pressure losses in the downstream parts of the exhaust gas system, cf. [18]. This effect compensates for part of the anticipated higher pressure losses.

In the same fashion as Figs. 11 and 12 shows the measurement variables for the **MW150**. The vehicle speed profile is clearly increased compared to the **WLTC** so that the components heat up more quickly, while the temperature difference over the TEG section is also clearly above the standard state (max. 480 K).

The additional flow resistance caused by the TEG also has a clear effect on pressure losses at times, compared to the standard state. Compensating pressure losses by reducing the temperature is only possible here to a limited extent. The bypass flaps also

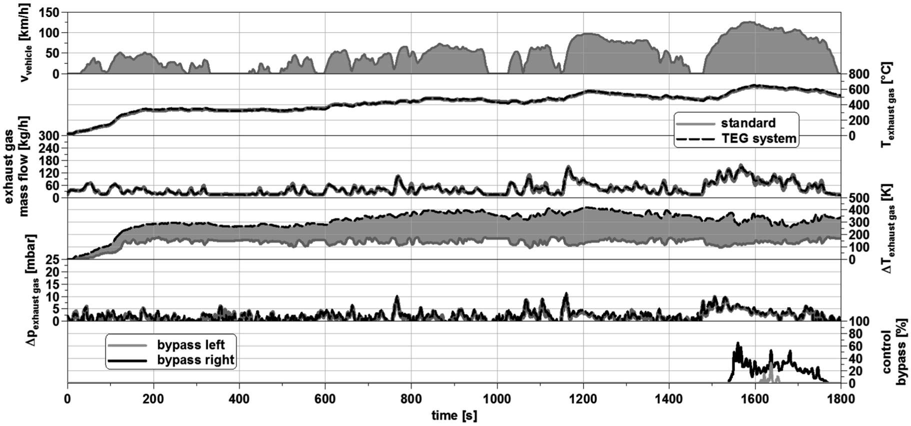

Fig. 11. Selected TEG measurement variables in the **WLTC** compared to the production vehicle

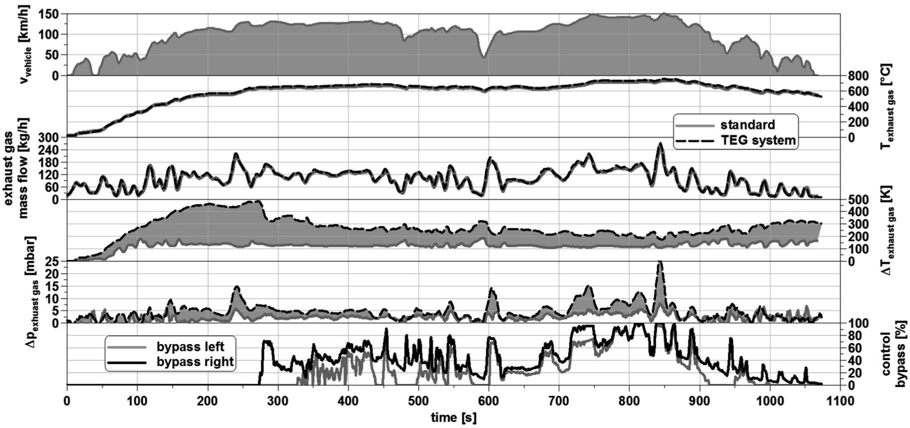

Fig. 12. Selected TEG measurement variables in the **MW150** compared to the production vehicle

have to open relatively early to protect the modules from excessive temperature. The opening of the bypass channel is clearly indicated by the marked decrease in exhaust gas temperature difference.

However, the total accumulation effect caused by the TEG exceeds 10 mbar only briefly in strong acceleration phases and does not exceed this level at all for most of the **MW150**. As indicated in Sect. 2.5 below, an increase in exhaust gas backpressure in this magnitude is not seen to influence fuel consumption.

Figure 13 shows the HiL simulation results obtained during the vehicle trials for virtual TE modules with PbTe (ZT ~ 1). It presents the curves for electrical TEG power computed from the process data after deducting DC/DC conversion losses.

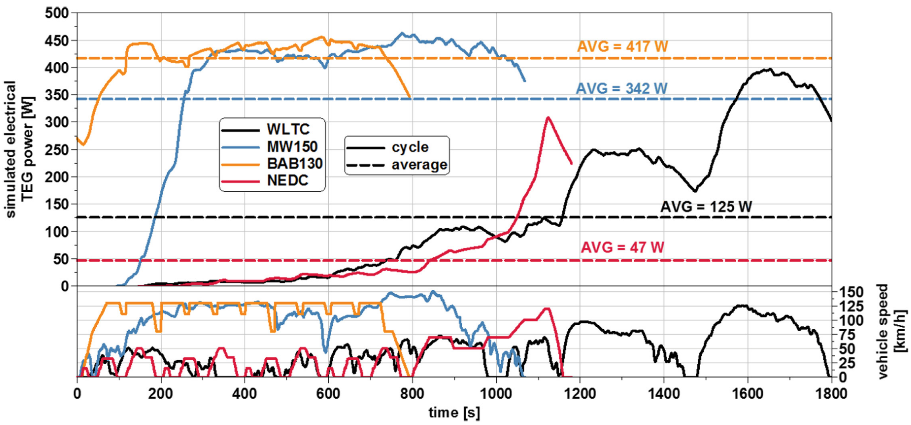

Fig. 13. Simulated electrical TEG power in various cycles

In the **NEDC,** the maximum simulated TEG power increases to about 300 W in the interurban segment, with mean power of approx. 47 W. The limited exhaust energy available in the four urban phases of the **NEDC** results in only slow increases in component temperatures. The first two phases of the **WLTC** (low and middle) show similar behavior to the **NEDC**. In the last two phases of the **WLTC** (high and extra high), there is a clear increase in the TEG power computed for PbTe, which is ascribed to the higher energy available in the exhaust gas. The maximum value for electrical power increases to about 400 W in the phase with the highest vehicle speed, with a mean of about 125 W. In contrast to the **NEDC**, in the **WLTC** the temperature control opens the bypass at the end of the cycle.

Driving cycles with higher average vehicle speeds, e.g. the **MW150** or the **BAB130** (ADAC Highway Cycle), offer greater heat, generating an adequate temperature difference at the TEG module. The maximum power output in the **MW150** thus exceeds 460 W with a mean value of approx. 342 W. Actuating the bypass flaps limits the component temperature of the modules at position 4 and 5 (Bi_2Te_3!), resulting in lower power output. Without activating the temperature control, there would be more than 500 W of power here.

The **BAB130** was always carried out as a warm start so that the simulated TEG power exceeded 250 W already at the start. Electrical power during the cycle ranged from 400 to 450 W, limited by controlling the maximum component temperature of the last TEG modules. The lack of a cold start in the **BAB130** results in a higher mean power output of 417 W.

To summarize, it can be said that it was possible to verify the function of the examined laboratory TEG and the implemented system concept. The TEG completed a large number of operating hours in many different cycles and operating points, also including high thermal loads. The measurement and simulation results have shown that the electrical power to be gained with the TEG mainly depends on the TEG heating up quickly and on the energy available in the exhaust gas. The thermal mass must be kept as low as possible to quickly achieve an adequate temperature gradient over the TE modules, particularly in the homologation cycles. To a certain extent, the reduction in temperature over the TEG can compensate for the just slightly higher flow resistance. This depends on the operating point of the engine and the position of the bypass flaps. Using suitable high-temperature modules would result in much later bypass control, if at all. In this case, the bypass flap would only have to open briefly, e.g. to deal with excessive backpressures or cooling loads. This would allow for simple design of the bypass flap and its control, e.g. just as a single flap open/close solution.

The HiL simulation results obtained during the vehicle tests for virtual TE modules with PbTe (ZT $\sim$ 1) also confirm the good potential estimate for vehicles in the C/D segment, which is where the test vehicle belongs. The achieved 125 W is only 17 % below the target of 150 W for a C/D vehicle in the **WLTC**, thus confirming its feasibility, especially in view of the fact that the laboratory TEG used in the project is not optimized for the **WLTC**, particularly in terms of thermal mass. The mean power output achieved in the **MW150** is only 342 W instead of 465 W, due to the massive intervention of the bypass control to protect the module, which is necessary.

7 Weight

The prime drawback of TEGs is that they make it very difficult to avoid an increase in weight. Consistent lightweight design is the only chance for minimizing the additional weight, with the TEG integrated in existing parts of the exhaust gas system or even substituting for them. A rough overview shows that system weights of between 5 and 25 kilograms must be expected for cars, depending on the configuration concept, design and power output.

Both theory and practice show that every additional weight in the vehicle increases fuel consumption. The mass of the vehicle impacts on three of the four rolling resistances, see Fig. 14.

$$\boldsymbol{F_{TTL} = F_R + F_{GRIN} + F_{ACC} + F_{Air}}$$

$$F_R = m \cdot g \cdot f \cdot \cos\alpha \qquad F_{ACC} = m \cdot e \cdot a$$

$$F_{GRIN} = m \cdot g \cdot \sin\alpha \qquad F_{Air} = \frac{\rho}{2} \cdot c_w \cdot A \cdot v^2$$

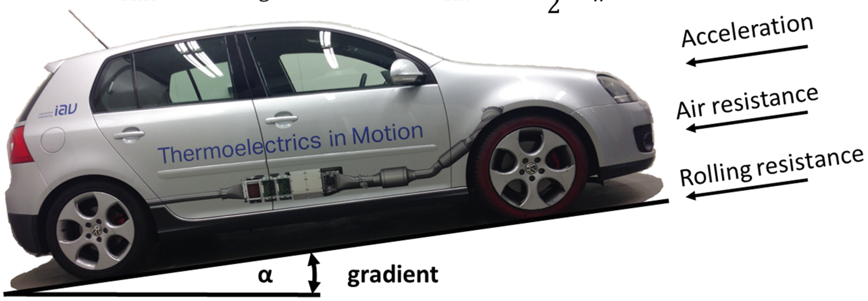

Fig. 14. The influence of mass on rolling resistances of the project vehicle [20]

Mass-related acceleration resistance is one of the biggest problems, given its dominant influence on consumption. Literature gives various indications and general rules for additional fuel consumption caused by added vehicle weight. According to [19] for example, 100 kg of additional vehicle weight increases fuel consumption by 0.4 l/100 km. According to [15], published values indicate between 0.3 and 0.7 l/100 km for 100 kg. In many cases, these values are just estimated. There is no physical derivation, nor is anything said about the mode of operation or driving profile. Strict attention must be paid to the boundary conditions for such “indicative values” in view of the significant impact of mass on fuel consumption.

According to [21, 22], the computed additional consumption for 100 kg of added weight in the **NEDC**, for example, is only about 0.137 l/100 km. In [15], a value of 0.15 l/100 km is obtained for a vehicle with supercharged gasoline engine and 1300 kg in the **NEDC**, and 0.23 l/100 km for a modified, more dynamic **NEDC**. This underlines the great impact of driving dynamics in terms of the frequency, duration and amount of vehicle speed changes.

The dynamics factor of a driving cycle as explained in **[**23**]** provides a very helpful description of the dynamics of driving maneuvers, showing that consumption due to added vehicle weight increases with driving dynamics. Figure 15 illustrates this relationship for constant alternator efficiency. It shows the additional consumption for a reference vehicle together with the increase in CO_2 emissions caused by 10 resp. 25 kg added vehicle weight (future TEGs will probably be within this weight range) based on the dynamics factor of a dozen scientific and homologation-relevant cycles as well as five customer cycles. The four cycles always used for comparison and assessment in the TEG2020 project are marked. According to Fig. 15 for example, a TEG with 10 kg added weight causes additional consumption of 0.018 l/100 km with emissions of approx. 0.42 g CO_2 per kilometer in the **WLTC**, corresponding to a weight factor of 0.042 g CO_2/km per kilogram.

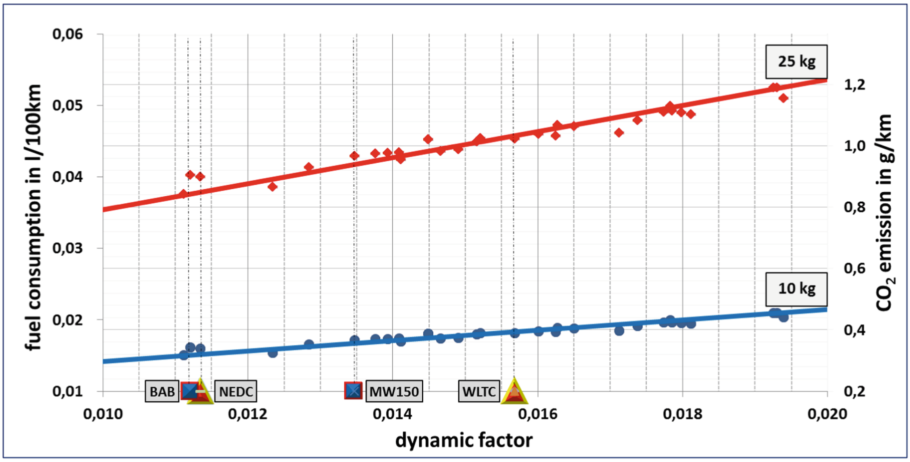

Fig. 15. Fuel consumption and CO_2 emissions in relation to the dynamics factor according to Prof. Helling [23] in the viewed cycles for 10 and 25 kg additional weight

From 2020 onwards, the permissible CO_2 emissions of a manufacturer's fleet of new vehicles must be calculated using the formula [24]

$$CO_2|_{specified} = 95 + 0.0333 \cdot (m - m_0) \quad (1)$$

whereby m is the vehicle mass and m_0 the average mass of new passenger cars in the last three years. Here the weighting factor is chosen so that 1 kg of additional weight increases the limit value by 0.0333 g CO_2/km (up to 2020: by 0.0457 g CO_2/km). According to [16], the weight factor Δm used to define the CO_2 correction amount in g CO_2/km obtained from the mass change of a vehicle after installing a system in the context of ecological innovation is calculated with the formula used there

$$\Delta CO_2|_{correctionamount} = 0.0277 \cdot \Delta m \quad (2)$$

to obtain a value of just 0.0277 g CO_2/km per 1 kg additional weight for vehicles with gasoline engine.

Measurements on the roller dynamometer in the WLTC resulted in additional fuel consumption of 0.28 l/100 km for 100 kg added weight. The real values are above the computed values, which is ascribed mainly to the real-life additional consumption of the respective engine in l/kWh.

In any case, the success of a measure depends significantly on the lightest possible design and a sophisticated integration concept, minimizing extra weight as far as possible. In the **WLTC**, every kilogram of additional weight has to be compensated by a good 2 W generator relief.

8 Exhaust Gas Backpressure

The relief for the conventional generator that can be achieved with the TEG depends on how effectively the hot side of the TEG is connected to the heat source. The exhaust system has to be fitted with a heat exchanger that is rated to withdraw a sufficiently large heat flow from the exhaust gas to convey it over the TE modules. The heat exchanger must be designed for transferring a large quantity of heat, as well as minimizing pressure losses in the exhaust gas system. A heat exchanger with a large effective surface improves heat transfer to the TEG but also increases the backpressure level. On the other hand, a small heat exchanger surface reduces repercussions on the charge cycle processes in the combustion engine, but has only a small heat flow to be withdrawn from the exhaust gas. This trade-off is solved by an effective exhaust gas heat exchanger that withdraws the necessary amount of heat from the exhaust gas while minimizing the increase in exhaust gas backpressure.

A TEG with its necessary heat transfer structure constitutes an additional flow resistance in the exhaust gas system. Pushing the exhaust gas out of the cylinder against a higher level of pressure has a negative impact on the charge cycle; the higher residual gas level in the combustion chamber leads to increased fuel consumption if the same effective power output is to be produced [25–27] indicate that if there is only a slight increase in the exhaust gas backpressure, it is not possible to say anything reliable

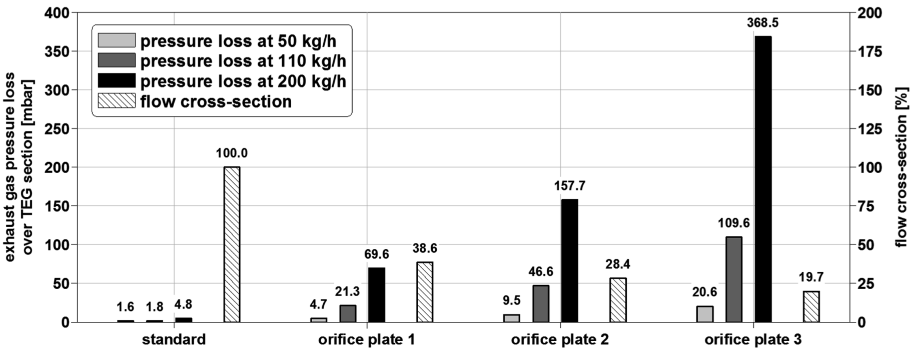

Fig. 16. Percentage change of flow cross section and exhaust gas pressure losses over the TEG segment with the throttles in constant operating points

about the relationship between increased pressure level and fuel consumption. It is only possible to make a rather general statement at engine operating points with high exhaust mass flows and backpressure increases above 250 mbar.

In order to assess the impact on fuel consumption of an additional throttling point, the original diameter of the exhaust pipe (56.3 mm) was reduced to 35, 30 and 25 mm (throttles 1 to 3). As a general rule, the higher the engine operating point and thus the mass flow and temperature of the exhaust gas, the greater also the pressure losses over a defined segment. Figure 16 shows this behavior in real measurements. The pressure losses are indicated both in the standard state and also for the three throttles in three different constant exhaust gas mass flows.

Figure 17 shows the measurement results for the three exhaust throttles in the **WLTC**. The **WLTC** with its mainly lower engine operating points and therefore lower exhaust gas mass flows has comparatively low pressure losses, mainly below 50 mbar.

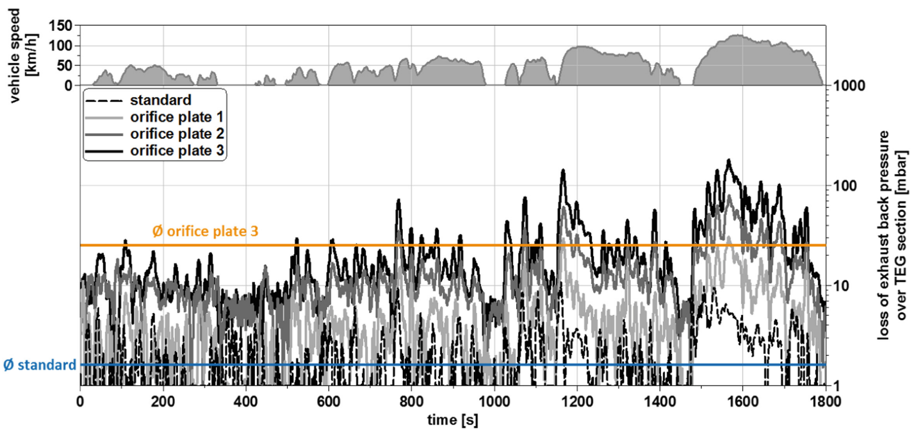

Fig. 17. Comparison of pressure losses over the TEG segment with the different throttles in the **WLTC**

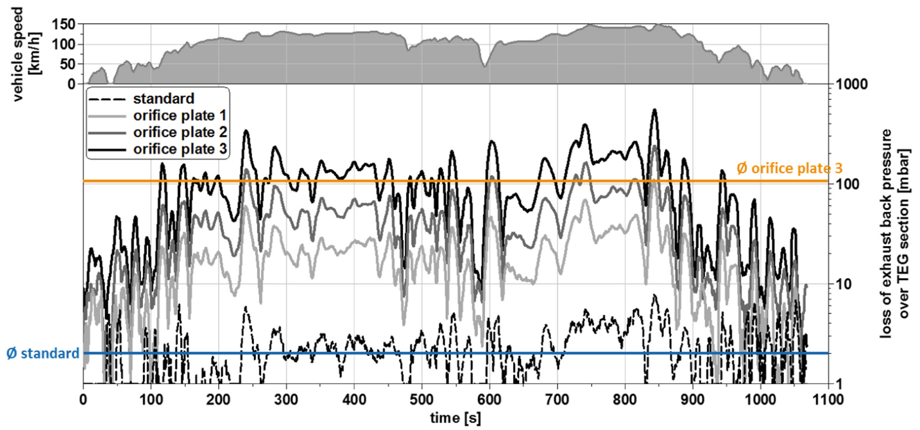

Fig. 18. Comparison of pressure losses over the TEG segment with the different throttles in the **MW150**

It is only in the strong acceleration phases and the last segment of the **WLTC** that the exhaust gas pressure loss over the TEG segment with throttle 3 comes close to or briefly exceeds a value of 100 mbar. The maximum value is about 180 mbar.

The higher speeds in the **MW150** also result in higher engine load points, reflected in higher mass flows and higher exhaust gas temperatures with far larger pressure losses. The measurement results with the three throttles are shown in Fig. 18. When throttle 3 is used, pressure losses exceed 100 mbar for an extensive part of the driving cycle and reach a maximum value of approx. 620 mbar.

Table 4 shows the relative additional consumption rates compared to the production vehicle and the mean pressure losses over the TEG segment in the **WLTC** and **MW150** when using throttle 3. The very slight consumption increase of 0.2 % in the **WLTC** clearly shows that even when the smallest throttle is used, there is no clear influence on fuel consumption. By contrast, in the **MW150** the additional consumption is clearly visible with 2.9 %.

Table 4. Relative additional consumption compared to the production vehicle and mean exhaust gas pressure loss over the TEG segment in the **WLTC** and **MW150** with exhaust throttle 3

	Additional consumption [%]	Mean pressure loss [mbar]
WLTC	0.2	24
MW150	2.9	102

To summarize, it can be said that only a drastic reduction in the cross section results in a significant increase in fuel consumption. However, the measurements obtained with the TEG used in the project indicated that it is possible to minimize the pressure increase with a suitably rated module which therefore also has only a very low impact on fuel consumption.

9 Auxiliary Power Consumption

In order to be able to make a reliable statement about the real benefit of a TEG and to produce an energy balance, due consideration has to be given not just to all effects on engine and vehicle but also to all additional consumers needed to operate the TEG, such as water pump, exhaust flap actuator and voltage converters. The additional power needed by these components depends greatly on the overall concept and the respective mode of operation, so that the following calculation is only intended to give a qualitative overview. The electrical consumers are estimated with reference to the TEG used in the TEG2020 project. Here the focus was on functional capability and safety with the greatest possible variability in the overall system, and not on optimizing the cooling system or each individual consumer. However, the holistic design of a TEG for a target system must presume various potential optimizations for minimizing "power consumption".

A look at the overall progression of the **WLTC** shows that with consistent, optimized layout of the system, the additional consumers such as servomotors or water pump only need to be used when absolutely necessary, thus minimizing their ON times. Minimum coolant circulation is sufficient during the cold start and in the urban and interurban cycle. A constant increase in pump power to 100 % is only necessary for higher loads. The same strategy also applies to the servomotors. They are only needed briefly to deal with a high heat supply and when the system exceeds the limits for module temperature, exhaust gas backpressure and cooling system load. Otherwise they remain inactive and de-energized. Their power consumption is irrelevant in terms of energy balance.

The efficiency of the power converters depends on the operating range of the TEG as a function of the transient heat supply from the consumption engine. A high conversion rate therefore depends on optimum rating of the system layout according to the anticipated range. (The efficiency of the DC/DC converters is taken into account in the results shown in Fig. 13!)

In Fig. 19, the real pump power (taking account of efficiency) from vehicle measurements is entered for the coolant temperature range 25 °C (left edge) to 60 °C (right edge). This shows the necessary pump power for the overall system and also proportionately for the TEG itself. The TEG is clearly seen to account only for a small share of the required pumping capacity. The remaining cooling circuit with hoses, recooler and various sensors has a far greater impact. The required power can certainly be halved in the range of 20 to 25 V by intelligently connecting the TEG coolant circuit to the engine coolant circuit, or at least by optimizing the separate coolant circuit. The required power is reduced by giving due consideration to the fact that the water pump is only on for about half the time.

Finally, it can be said that while the additional electrical consumers reduce the power obtained, this is to a far lesser extent than often presumed. With intelligent rating and usage of existing resources as well an ideally calibrated DC/DC converter, a potential estimate can work on the basis of auxiliary power consumption in the TEG between 10 % and maximum 15 % of the converted electrical power, referred to the mean electrical power in the WLTC.

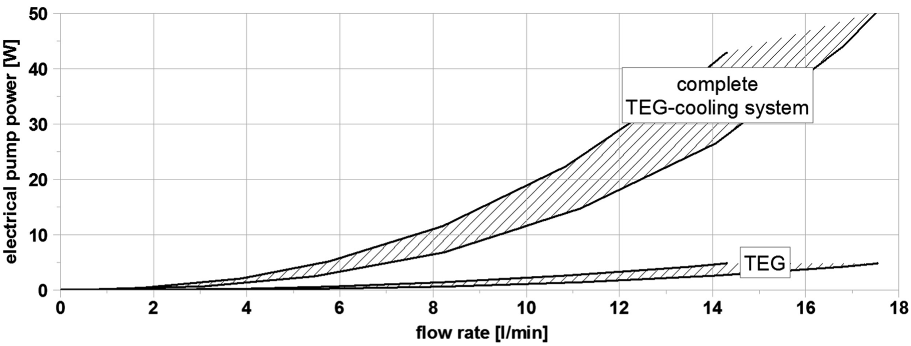

Fig. 19. Electrical pump power at 25 °C and 60 °C coolant temperature for the entire cooling circuit and proportionally for the TEG

10 Recooling

Besides the quality of the TE material's thermoelectric characteristics, it is also necessary to have a sufficiently large temperature gradient between the hot and the cold side in order to drive corresponding electrical power with the TE modules. The vehicle's exhaust gas acts as heat source. The heat sink in the vehicle consists, for example, of the separate, possibly available low-temperature cooling circuit or the engine cooling system, which absorbs the heat flow over the TEG and dissipates it via corresponding radiators back to the surroundings.

Depending on the TE material being used, the application and the possibilities in the vehicle, it is necessary to estimate to what extent reducing the coolant temperature will generate a further economic advantage in the overall system. Not every temperature reduction will always generate the desired effect. Usually it will be sufficient to "simply" connect the cold side of the TEG to the engine cooling system. Table 5 shows the gained power of the TEG as a function of coolant temperature for Bi_2Te_3 and PbTe, based on 90 °C coolant.

Table 5. Influence of coolant temperature on the power generated by the TEG

Coolant temperature	Power gain Bi_2Te_3	Power gain PbTe
10 °C	+88 %	+23 %
50 °C	+45 %	+11 %
90 °C	0 %	0 %

If the temperature level of the engine cooling system is adequate, the question arises whether this can absorb or recool the additional heat input from the TEG. According to [28], the maximum cooling capacity of modern cooling systems is rated for representative operating states. These include driving states with high heat input into the cooling system, such as long highway journeys at top speed or driving uphill with maximum payload and towed weight. Rating the cooling system to this high cooling demand means that it will be over-dimensioned for the predominant driving states, depending on the layout strategy pursued by the OEMs.

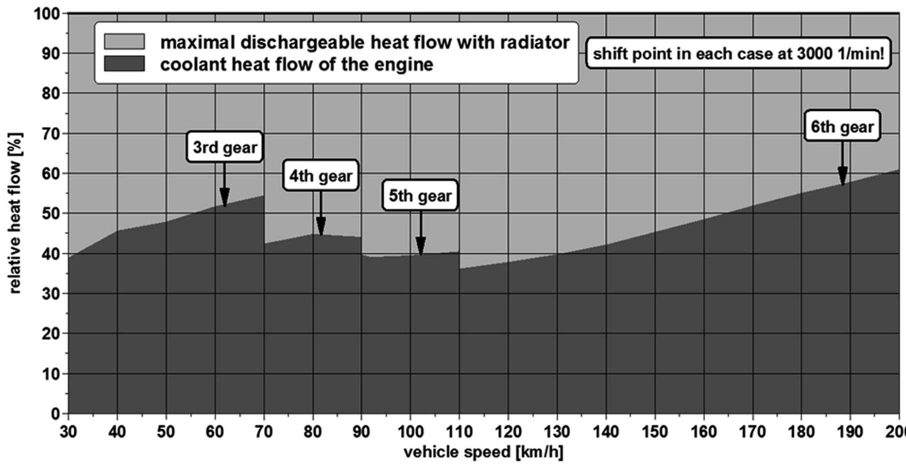

Fig. 20. Coolant heat flow of an engine relative to the maximum possible heat flow of the radiator (road part-load in 3rd to 6th gear on the flat at inlet temperature difference = 70 K)

Figure 20 shows the ratio of engine cooling demand to maximum possible cooling capacity of the vehicle radiator, illustrated with a mid-range vehicle. The values were defined for road part-load points when driving on the flat in 3rd to 6th gear and up to a speed of 200 km/h. It can be clearly seen that when driving on the flat up to 160 km/h, the cooling system of the example vehicle is only operating at up to approx. 50 % of its maximum capacity. With a corresponding layout strategy, the standard cooling system can therefore certainly cope with the additional heat input from the TEG. At operating points with high cooling demand, the TEG system has to be bypassed on the exhaust side to minimize the additional heat input and prevent overload on the cooling system. Taking the TEG system into account at an early point in the vehicle development is therefore an advantage.

Figure 21 shows the ratio of the heat flows in the project vehicle at various constant-speed driving points. On the one hand, it features the heat flow dissipated via the vehicle radiator to the surroundings. On the other hand, it also indicates the heat flow entering the separate cooling circuit from the TEG, with values at various vehicle speeds in 6th gear.

The higher cooling demand from the engine triggered by the road resistance that increases with speed can be clearly seen in the diagram. The higher engine operating point also increases the energy supply in the exhaust gas, so that there is a greater heat input from the TEG into the separate cooling system. As soon as the bypass control intervenes so that part of the exhaust gas mass flow bypasses the TEG, the coolant heat flow stagnates with practically no further increase. For the project vehicle with the examined TEG concept, the TEG results in additional cooling capacity demand of up to 25 % of the engine cooling demand, with the maximum value at low load points where the bypass is still completely closed. At higher load points, the TEG heat flow decreases continuously in relation to the overall cooling demand of the engine.

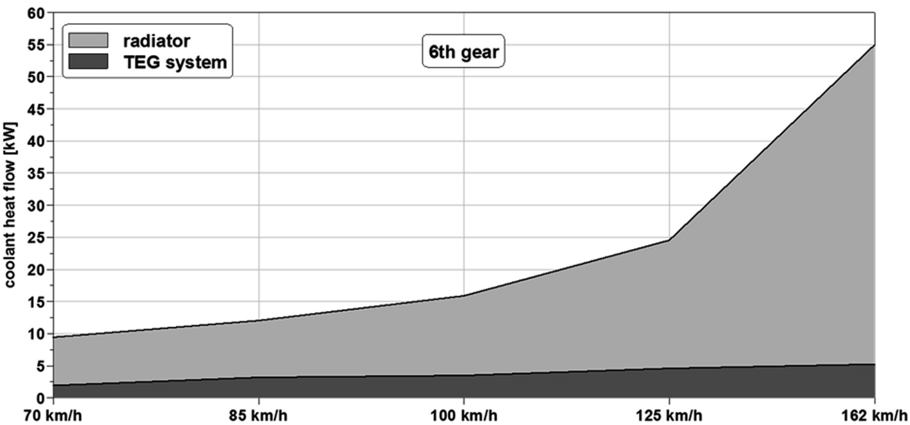

Fig. 21. Coolant heat flows over engine radiator and TEG system in the test vehicle

Comparing these values with the findings from Fig. 20 leads to the conclusion that the production cooling system is definitely capable of coping with the additional heat input from the TEG into the coolant in most driving states. This depends on optimum integration of the TEG in the cooling system, which can be achieved by including the TEG early on in the development process of a new vehicle.

11 Summary

A TEG that feeds mean net electrical power of 150/250/400 W (depending on the reference vehicle) into the vehicle electrical system, thus relieving the conventional generator, is capable of achieving 2 to 3 % fuel savings in the WLTC. With savings in this magnitude, the technology offers vehicle manufacturers a successful means of coping with their CO_2 deficits.

Although devised as a laboratory generator that has not been designed specifically for the **WLTC** and assessed only with provisional material (PbTe), the project TEG in the project vehicle (C/D) already produces 125 W. When rated accordingly for the **WLTC** with current or future TE materials, configuration and connection technologies respectively TE modules in suitably optimized concepts and designs, TEGs in vehicle quality will achieve the necessary conversion rates by 2020.

The challenges still posed by the technology are also manageable. **Costs** of less than € 50 for every gram of CO_2 saved per kilometer and vehicle, respectively less than € 1 per watt of net electrical TEG power should be sufficient to clear the way ahead for this technology into the automotive world. Without doubt, these cost targets are a huge challenge for many manufacturers of TE materials, modules and components. However, they are the entrance ticket to the mass market of the automotive industry and there are many different possibilities of achieving them.

Payback directly at the fuel pump is still unsatisfactory for the normal user, but certainly achievable for frequent drivers and commercial users. The **weight** has a critical impact because of its inevitability. On the other hand, this can be managed with consistent lightweight design and intelligent installation concepts. No drawbacks are anticipated from the **exhaust gas backpressure**, as long as the system uses an exhaust gas heat exchanger with a suitable, optimized design. A suitable heat exchanger design in a system with intelligent coolant and exhaust gas management also keeps **auxiliary power consumption** low. Voltage adaptation with a DC/DC converter is necessary on account of the TEG's characteristics, and reduces the net power. However, suitably designed converters will keep this in the single-figure percentage range. In a correctly devised and rated system, **cooling** is not a critical aspect. There are many options here which in some cases even offer secondary effects that compensate for the negative impact on the vehicle as a whole.

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− Berlin University of Technology, Institute of Energy Technology, Mechanical and Systems Engineering Faculty

− Berlin University of Technology, Institute of Energy and Automation Technology, Electronic Measurement and Diagnostic Technology Faculty

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