

# EXHAUST GAS Converted into LIGHT





Two polymer electrolyte membrane fuel cell stacks on the test stand at DLR in Stuttgart. Identical fuel cell stacks are incorporated (installed) into the HyLite prototype of the Institute of Vehicle Concepts.

## Innovations in the Energy Management of Future Vehicle Generations

By Dr. Peter Treffinger, Jörg Ungethüm and Julia Förster

The energy balance of a car looks fairly sad: not even a third of the fuel's energy is really being used. The rest simply goes up in smoke – part of it quite literally. Vehicles are clearly in serious need of improved energy management. At the end of the day, it is not only a question of costs but also of the climate and valuable resources. DLR engineers at the Institute of Vehicle Concepts in Stuttgart are therefore scrutinizing the energy balance of vehicles and are developing ideas that make better use of waste heat, for example, electricity.

The goal is to reduce CO<sub>2</sub> emissions and the primary principle is therefore to use fuel in the most effective way possible. The higher the degree of fuel utilization, the lower the CO<sub>2</sub> emissions of the vehicle and the greater is the range of fossil and renewable fuels. In order to drastically increase the degree of fuel utilization, the engineers must fully know and understand every path, transformation and type of energy flow within the vehicle. Once this has been achieved, the second step is to embrace even

those ideas that may at first glance appear strange and to evaluate whether or not they may help gain a few percent more energy efficiency. If we take this another step further, we find that as soon as such a small idea is considered at series vehicle production level, it may in fact hold a great deal of overall potential.

The research is thus very promising – and it begins with the engine because it is the first energy converter in the process. Today, it is almost exclusively

internal combustion reciprocating piston engines that produce mechanical torque. The first area of potential for optimization thus already lies with the vehicle manufacturers and engine developers who are seeking the highest possible degree of efficiency from this primary energy converter. The present buzzwords are “new combustion methods,” “downsizing” and “adapted turbocharger technologies.”

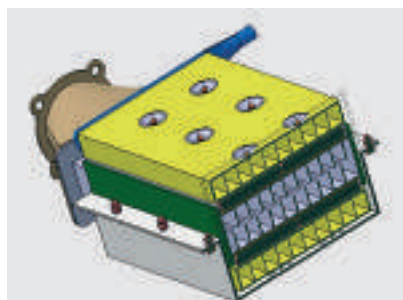
All these methods focus on a single goal: achieving maximal output with small engines designed for minimum friction loss and low pollutant emissions in order to increase the degree of efficiency in the combustion process.

DLR is tackling this issue with the “free-piston linear generator” (FPLG) project. This combines the advantages of a combustion engine with those of a linear electric generator. The electricity generating part of the engine has lost its crank shaft. This setup allows for a variable adjustment of the stroke and compression. In this manner, the fuel can be combusted highly efficiently with low emissions both with a full and partial load. Additionally, several different fuels can be used. The FPLG has the potential of lowering costs through the use of a modular method of construction that can easily combine several modules to increase the performance.

The next options for improvement already concern the car as a system. The car is a highly dynamic system, very different to a power plant that is switched on once and then works virtually continually. A car only seldom runs under a full load and is supposed to warm up quickly when

it is started. Already these two aspects illustrate that energy management involves a highly complex interplay between numerous requirements and functions.

What can be done if a car typically seldom travels at top speed on highways or with a heavy load on steep mountainous roads but rather much more frequently under highly dynamic partial loads? – Research is currently seeking to enable the engine to operate at a high degree of efficiency and to recuperate braking energy. This can be achieved through the hybridization of the drive train which allows the vehicle to be driven with either an electric or combustion engine as well as through adapted torque converters, such as CVT transmissions (Continuous Variable Transmission), which means gearless transmissions. And what about the warming-up period of the vehicle? Everything needs to be done quickly – defrosting the windscreens, heating up the interior for the passengers



Layout of a thermoelectric generator: The hot exhaust gas flows through the channels (light blue) and transfer heat to the cooling water, which also flows through channels (yellow). The heat then flows through the thermoelectric material which is located between the channels (green). Part of the heat is converted into electrical energy.

and warming up the engine to reach optimal consumption and emission values. In order to optimize these and other components of the vehicle’s energy system, such as thermal, electrical and mechanical components, one must understand them and their energy flows as well as their interaction. This is most easily achieved with a simulation.

For the purposes of modeling the “Vehicle” system, over the last few years DLR has created software libraries based on the newly developed object-oriented simulation language MODELICA, which can depict various vehicle energy systems. This means that this library contains data about the presently examined vehicle details such as chassis, tires and other components. These are then “assembled” into a comprehensive vehicle model, which can simulate, e.g., how quickly the exhaust of the vehicle heats up. A potential observation could be that the exhaust heats up so quickly that its warmth could be used to heat up the still-cold transmission more quickly.

What is still a dream of the future is the utilization of such models in the vehicle’s control unit to guarantee optimal operation at all times through constant analysis of the state of the system. This requires real-time simulation since the simulated system must also work exactly as the real-world system with regard to the timeline. DLR is currently researching into such models. Synergies with the field of space research can be exploited here since the energy management issues related to aircraft are similar to those of vehicles.

Back to the present and to a simulation of a reference vehicle with a

<sup>1</sup>[www.modelica.org](http://www.modelica.org)

diesel engine to represent the compact car segment. In the simulation, the reference vehicle drives the so-called NEDC, which is the New European Driving Cycle – a standardized velocity profile which forms the basis for emission and consumption measurements. The result is not very impressive. Of the total energy quantity of the fuel, only 30 percent is utilized to overcome the drive resistances or to power auxiliary units in the vehicle. The greatest proportion of the fuel's energy is already transformed into waste heat in the engine. The amount of energy required to heat up the units from their cold state alone is already 27 percent of the fuel energy, which is even more than is rejected by the cooler. Approximately 23 percent of the fuel's energy is emitted via the exhaust gas. For vehicles with a gas engine, the outcome is even worse. Their share of the energy utilized is even lower and the proportion of energy that is emitted via exhaust gas is even higher.

The obvious question is therefore: How can the amounts of energy that are emitted to the environment as heat be utilized? This is where really innovative ideas are called for. Nevertheless, even the most creative ideas cannot bypass certain basic requirements: The lost energy must be stored and converted into a form that is usable within the vehicle and it must be transported to the area in the vehicle where it can be used.

Using heat is obviously easiest if it is directly used as thermal energy. It would be imaginable, for example, to create a passenger compartment heating system which draws its energy from a heat accumulator at the start of the journey. Once the engine is at operating temperature, it re-charges

## New Energy Management for Future Vehicles

By Dr. Johannes Liebl,  
Head of Energy Management at BMW



The automotive industry has achieved substantial reductions in vehicle consumption and carbon dioxide (CO<sub>2</sub>) emissions. Classical developments, especially with Otto and diesel engines, have considerably contributed to this.

Climate change, a globally increasing energy demand, the finiteness of fossil energy resources and increases in individual transport are forcing us to further reduce CO<sub>2</sub> emissions.

Reducing a vehicle's CO<sub>2</sub> emissions alone does not promise the required customer acceptance and or market success. Customers' wishes are extremely diverse. Some need big cars, others are satisfied with small city cars, some mainly want to get from A to B and stay dry, others additionally demand safety, comfort and luxury. The BMW Group has chosen an integrative and function-oriented holistic vehicle approach in order to bridge this conflict between customers' wishes and environmental demands.

All physical levers must be taken into account and evaluated in their cause-effect context. What is new about this approach is only creating energy flows in the vehicle (mechanical, electric, hydraulic, pneumatic and thermal flows) when they are actually needed. If this is not possible, we need try to recapture this lost energy. In order to understand these complex relationships and be able to derive the correct decisions,

simulations of the energy flows in a vehicle play a vital role.

Over the last few years, DLR has developed software libraries based on the newly created simulation language MODELICA, which serve to model the highly interacting system of a car. These allow a depiction of various vehicle energy systems. Such software will be used in future for optimization and control purposes in vehicle control units in order to optimize these systems in operation. DLR is focusing its research on developing such real-time capable models. For the BMW Group, these applications are a development tool for EfficientDynamics™.

Furthermore, heat management is constantly increasing in importance. Even today, approximately two thirds of the chemical energy used in a combustion engine is still transformed into waste heat. This heat is generally released to the environment and is consequently lost. A solution for using the waste heat is to transform it into electric energy.

The BMW Group is cooperating with DLR on a basic principle project regarding thermoelectric generators. Our cooperation ranges from research into the fundamentals of energy transformation through to verification on test benches and in the vehicle. This prepares a further step in the expansion of the EfficientDynamics™ program.

the heat accumulator. Another very interesting idea in principle is to use the heat to power a cooling machine for the air conditioning in the vehicle. This means to basically use the heat to create cold air. Using a power conversion process, the heat can also be transformed into mechanical energy.

A thermoelectric generator could directly generate electricity from heat. The fuel could lastly be upgraded in

terms of energy via a fuel reforming process that uses the heat of the exhaust gas to enhance the fuel's energy content.

And already we arrive at the actual main field of activities of vehicle energy optimizers. All around the world, researchers are especially working on the utilization of power processes and their conversion into electrical energy. DLR is primarily working on designing thermoelectric generators, a field in which DLR already has substantial experience from space engineering. In space engineering, thermoelectric generators provide space probes with energy on their discovery trips which take several years.

In thermoelectric generators, the areas of different temperature lead to the so-called thermal diffusion of the electrons (a.k.a. the Seebeck effect) and a voltage is generated which can supply an external circuit.

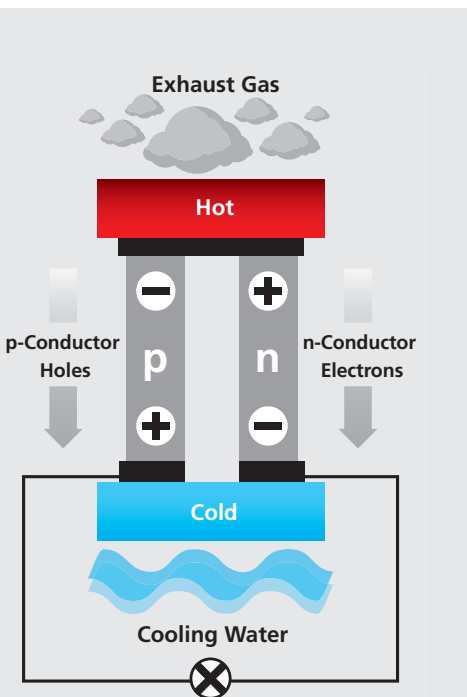
If one was to presumptuously formulate this idea, one could now prophesize that such a thermoelectric generator will one day replace the alternator. Expressed in more modest terms, it is conceivable that such generators can cover the continually increasing demand for electric energy in cars. Either way, there are quite a few tasks to be solved yet before this principle can be utilized in vehicles. Thermoelectric materials that provide high degrees of efficiency in the temperature range relevant for cars are needed. DLR is working on just such materials.

Furthermore, the properties of these materials must satisfy the requirements of a thermoelectric generator within a vehicle in terms of design. For example, the generator must not strongly retroact on the engine if it is integrated into the exhaust system. It must operate stably even when the temperatures vary strongly and it must fit into the exhaust system, the cooling system and the electrical system of a vehicle in terms of both geometry and function. DLR researchers and engineers are therefore working on solutions in cooperation with suppliers and the automotive industry.

The first self-designed prototypes of such thermoelectric generators are already being tested at the hot gas test bench at DLR. The best electric performance achieved so far is approx. 200 Watts, but concepts suitable for vehicles are already being realized that promise an electric performance of more than 300 W under a partial load.

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Principle of a thermoelectric generator: A positively doped and a negatively doped semiconductor leg are located between a heat source and a heat sink. A current is created through thermal diffusion of the electrons and holes (Seebeck effect), which can be tapped from the outer circuit.

