Thermoelectric generator systems for waste heat usage in diesel electric vehicles

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Abstract

It is widely known, that the main part of the life cycle costs of diesel electric locomotives are the consumption costs for diesel fuel. On top of that the rising awareness of politics and society for environment protection and rising prices for energy shift that topic into the focus [1]. One possibility to lower the fuel consumption is to recover the exhaust waste heat of the combustion engine. This can be achieved by converting the energy of the exhaust into mechanical energy (e.g. Steam Expander) or into electrical energy by a thermoelectric generator (TEG). Using a high power TEG in a diesel electric locomotive is advantageous because of the electrified powertrain. That means there is a considerably high demand of electric power in almost all driving states. The challenge is to develop a system with a sufficient efficiency in order to achieve a short return of investment period.

Up to now some TEG system prototypes have been developed for automotive applications. For example a combination of a TEG with the EGR, where cooling of the exhaust gas is necessary, proved to be promising. But because of the low temperature gradient in the EGR the output power is very limited [2]. In future automotive systems the TEG could be integrated directly into the exhaust tract which leads to high temperature gradients and promises a higher power output [3]. The challenge is to develop an efficient TEG material and a system which withstands the mechanical stress caused by the thermal cycles.

For diesel electric locomotives a relatively good efficiency can be achieved by using a heat transfer oil circuit as intermediary heat carrier instead of integrating the TEG directly into the exhaust tract. This offers the advantage of using the better heat transfer between exhaust and oil compared to the heat transfer directly from exhaust to the TEG. Therefore a high power can be transmitted. Furthermore it is possible to collect the waste heat of secondary heat sources like the brake resistor. Another advantage is the achievement of an almost constant temperature gradient which increases efficiency and minimizes thermal stress within the TEG system.

To evaluate the efficiency of the TEG system it is reasonable to simulate its performance and to calculate the reduction in fuel consumption depending on the operation mode of the locomotive (e.g. passenger or freight transport). For this task a model for the whole system has to be developed. This leads to a multi domain simulation including the powertrain (electrical and mechanical), the intermediary circuit (fluid and heat) and the TEG itself. For the simulation of the TEG a sufficient model needs to be established which takes all thermo electric effects into account, namely the Seebeck effect and the heat transmission between the different parts of the TEG (e.g. solder joints, isolators and conductors) as well as the semiconductor material [4].

1. Introduction

In the last decades sustainability and environmental protection became major requirements for almost all transportation tasks. Besides that, rising energy costs led to a higher demand of high efficient vehicles and to new possibilities to reduce the energy consumption, such as hybrid vehicles with different types of energy storage systems like batteries, flywheels or oil pressure tanks [6, 7].
Most components on conventional vehicles are technically mature and no major steps in increasing the efficiency of these systems can be expected any more. Therefore it is necessary to investigate these new and innovative possibilities to achieve a considerably reduction in energy consumption.
One potential solution is the usage of the exhaust waste heat of combustion engines. This is possible by using the waste heat as heat source for the operating medium of a piston expander (Figure 1), which is mechanically attached to the crankshaft and/or an electric generator [5] or by using the waste heat as heat source for a thermoelectric generator (Figure 2) which converts the waste heat directly into electric energy.

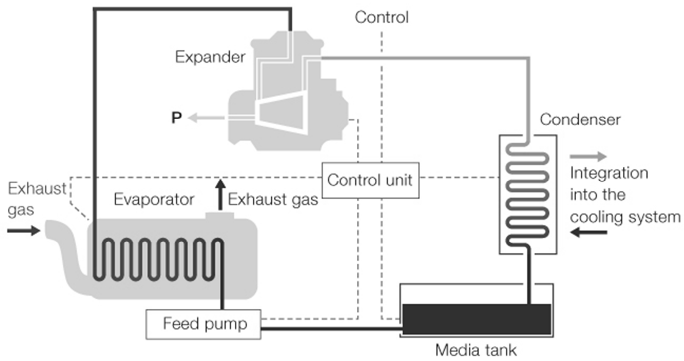

Figure 1: *Mechanical waste heat usage with the Voith SteamTrac System [5]*

The first solution is suitable for most combustion engine driven applications and has a high degree of efficiency at high temperatures, but has the disadvantage of moving parts, high volume and weight [8]. This paper focuses on the second solution which is suitable for combustion engine driven systems with electric consumers. The research done is part of the German BMBF-funded HiTEG-project.

Although the technology of combustion engines is quiet mature, the degree of efficiency is well below 50%. A great amount of the energy, around 30%, is lost as exhaust waste, and up to 30% is dissipated in the cooling circuits [9]. This is why thermal recuperation has a great potential for raising the efficiency of combustion engines.

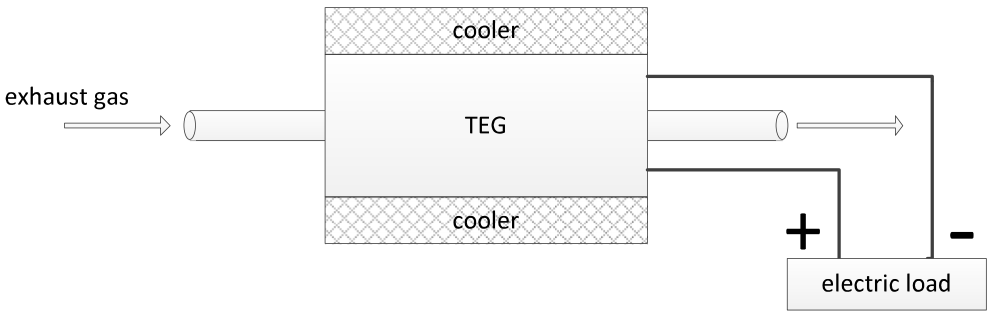

Figure 2: *Electrical waste heat usage with thermoelectric generator*

2. Thermoelectric Generators

Thermoelectric generators (TEG) consist of p- and n-conducting materials, which are electrically connected in series and thermal connected in parallel. A temperature difference applied to the TEG leads to a charge transfer in the material which is recognizable as electric voltage (Figure 3).

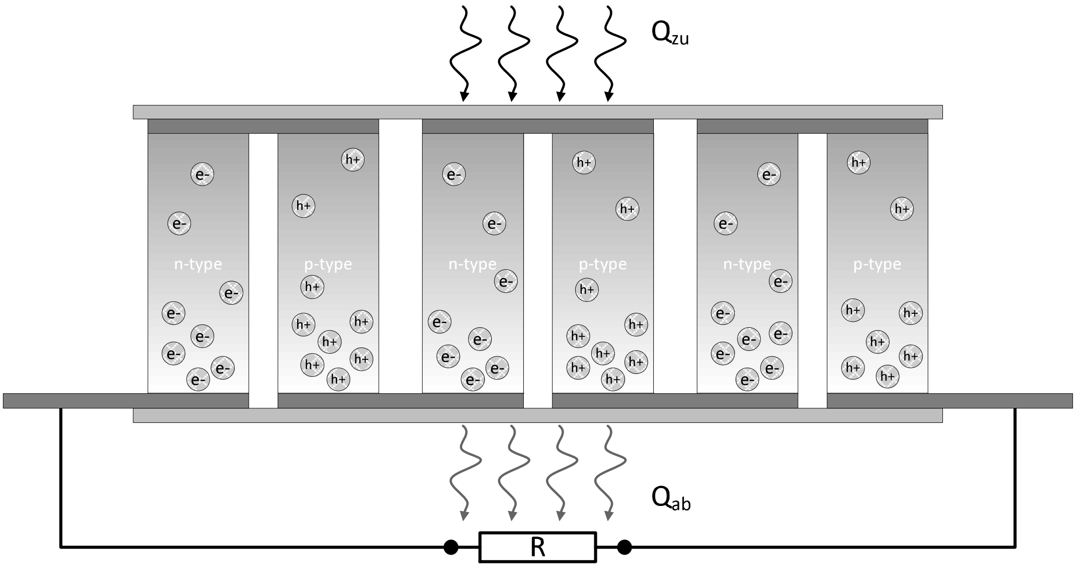

Figure 3: *Thermoelectric Generator Module*

2.1 Thermoelectric effects

The thermal and electric forces, which occur in semiconducting materials, can be described with three fundamental effects, the Seebeck effect, the Thomson effect and the Peltier effect [4, 10].

Seebeck effect

The Seebeck effect describes the electric voltage depending on the temperature difference occurring at the arms of a TEG. The voltage can be expressed as

$$U_{Seebeck} = \alpha_{n,p} \cdot (T_H - T_C) \quad (1)$$

with the Seebeck coefficient α for the n- and the p-conducting arm and the absolute temperatures at the hot and cold side T_H and T_C.

Peltier effect

An electric current floating through a pair of connected semiconducting materials leads to an exchange of heat energy with the surrounding environment, which can be expressed as

$$\dot{Q}_{Peltier} = \alpha_{n,p} \cdot I \cdot T \quad (2)$$

with the electric current I.

Thomson effect

The Thomson effect describes the thermal flow, which appears if a temperature gradient is applied to a semiconducting material and an electric current is floating through the material at the same time. The Thomson effect is often neglected due to its minor impact compared to the Peltier effect.

2.2 Materials

The semiconducting material is essential for the degree of efficiency of the TEG. The materials can be evaluated with the temperature depended ZT value which is most relevant to the efficiency (3,4). Moreover, for industrial and mobile applications, the environmental compliance and the availability of the material have to be taken into account. Up to now there are only a few materials ready for serial production and mobile applications, like Bi_2Te_3 and SiGe. Research for new materials with high ZT values is taking place in the material research right now and some reports have been made about promising materials [11, 12, 13].

$$ZT = Z \cdot \Delta T = \frac{\alpha^2 \rho}{\kappa} \cdot \Delta T \tag{3}$$

$$\eta = \frac{\sqrt{1+ZT}-1}{1+ZT+\frac{T_C}{T_H}} \cdot \frac{T_H - T_C}{T_H} \tag{4}$$

With the resistivity ρ and die thermal conductance κ.

2.3 Design

The arms of the TEG material are connected to each other by conductors, e.g. plates of copper, which are soldered directly on the semiconducting elements. For insulation and isolation of the elements the TEG is normally pressed or glued into an isolation material, e.g. ceramic plates or graphite foil, which should insulate the single arms from each other but conduct the heat as good as possible. This leads to a classic conflict of goals. All these parts – arms, solder, conductors, glue, and isolation (Figure 4) – have to be taken into account in a simulation of the thermoelectric module (TEM).

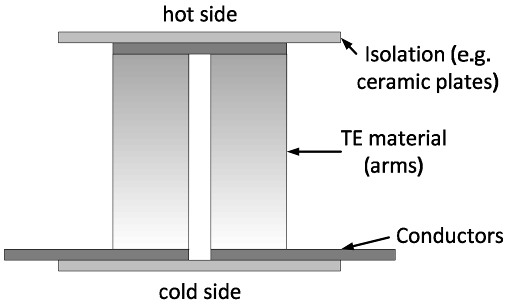

Figure 4: *Design of a TEM*

3. Application

For a thermoelectric generator system (TES) in an exhaust waste heat recuperating context, additional aspects have to be taken into account, which can be easily seen by considering figures 1 and 2. The heat energy from the exhaust gas needs to be conducted to the TEM (hot side) by a heat exchanger and the TEM has to be cooled on the cold side. The electric power output has to be integrated into the electric network of the application and, for an optimum efficiency, it has to be controlled. The actual configuration of the systems strongly depends on the boundary conditions.

3.1 Automotive

In this work TES in automotive applications are not discussed in detail, but two concepts are described in order to give a short overview and a classification.

Classic powertrain concept

In this context the classic powertrain concept means a mechanical traction force transmission from the combustion engine to the wheel by gear, coupling, shafts, etc. The electric power supply is for charging the battery, lights, multimedia, climate control, sensors, wipers, etc. and the maximum constant electric power demand is about 2 kW for premium class cars. In this concept the power demand limits the size of the TES, and hence the reduction of fuel consumption is also limited. In this case an integration of the TES in the exhaust gas recirculation (EGR), where a cooling of the exhaust gas is anyway necessary may be a suitable solution [14].

Hybrid powertrain concept

In this work the hybrid powertrain concept includes all variations of hybrid cars with combustion engine, were the traction force transmission is electrically supported or purely electric. In this case the electric power demand of the vehicle is normally above 5 kW. Therefore an integration of the TES in the main exhaust line of the vehicle, where one can find the highest amount of waste heat energy, should be considered. Certainly the impact on the exhaust back pressure has to be taken into account, which can negatively influence the power of the engine.

3.2 Diesel electric high power vehicle

The diesel electric high power vehicle is a vehicle with an electric traction power transmission and an engine performance of several hundredth kilowatts, e.g. mobile harbor cranes, hybrid busses, ships, diesel electric trucks or locomotives [15, 16, 17]. Here a generator is directly flanged to the diesel engine. Generator and diesel engine form a unit, the so called "genset". This powertrain configuration has a long tradition in railway technologies, where the nonexistence of a coupling which can transmit the traction force made other solutions necessary (Figure 5).

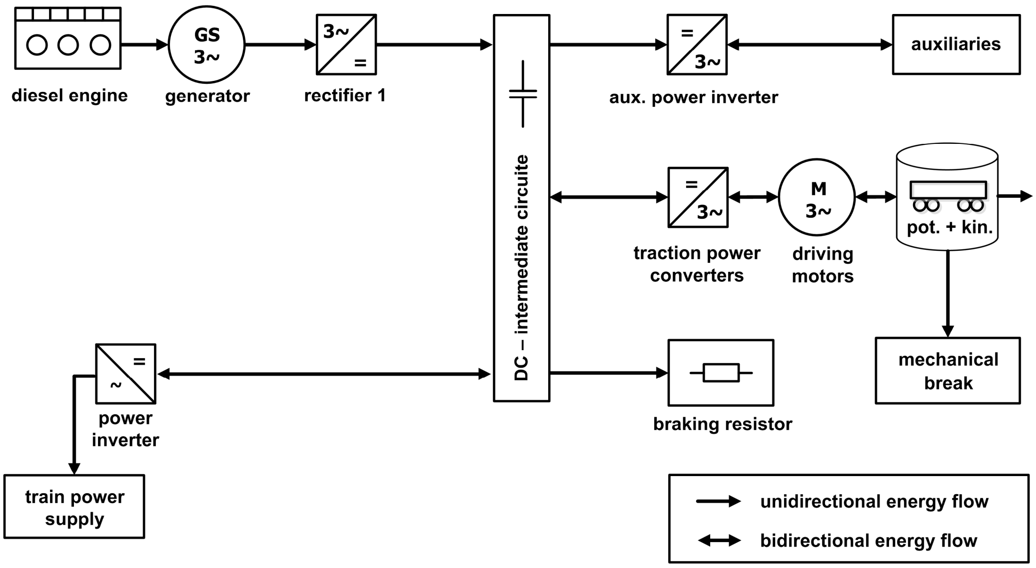

Figure 5: *Schematic representation of a diesel electric locomotive powertrain*

Similar to the hybrid powertrain concept the demand of electric energy is very high. In addition the absolute demand of power is typically larger at the factor ten and more, compared to the automotive vehicle. This is the reason why a TES has to be designed at a much larger scale to have a significant impact on the fuel consumption and a directly into the exhaust line integrated TES is problematic because of the limited space. To solve this problem a new system approach with a thermal oil intermediate circuit was designed (Figure 6), which has three main advantages: First, the amount of necessary heat energy for the aspired system power can be conducted from the exhaust with a smaller heat exchanger. Second, the thermal oil acts as heat storage (in analogy to an electric intermediate circuit capacity) and smoothes the temperature on the hot side, which leads to less thermal cycles and therefore extends the lifetime of the module. Third, it is possible to collect the heat of other available heat sources, e.g. the heat energy of the breaking resistor.
The cold side of the TEM is water-cooled by a wind cooling chiller. For vehicle speeds near to zero, the water is pumped over a backup-cooling cycle which is cooled by the cooling tower of the locomotive. This solution smooths the temperature on the cold side as well.

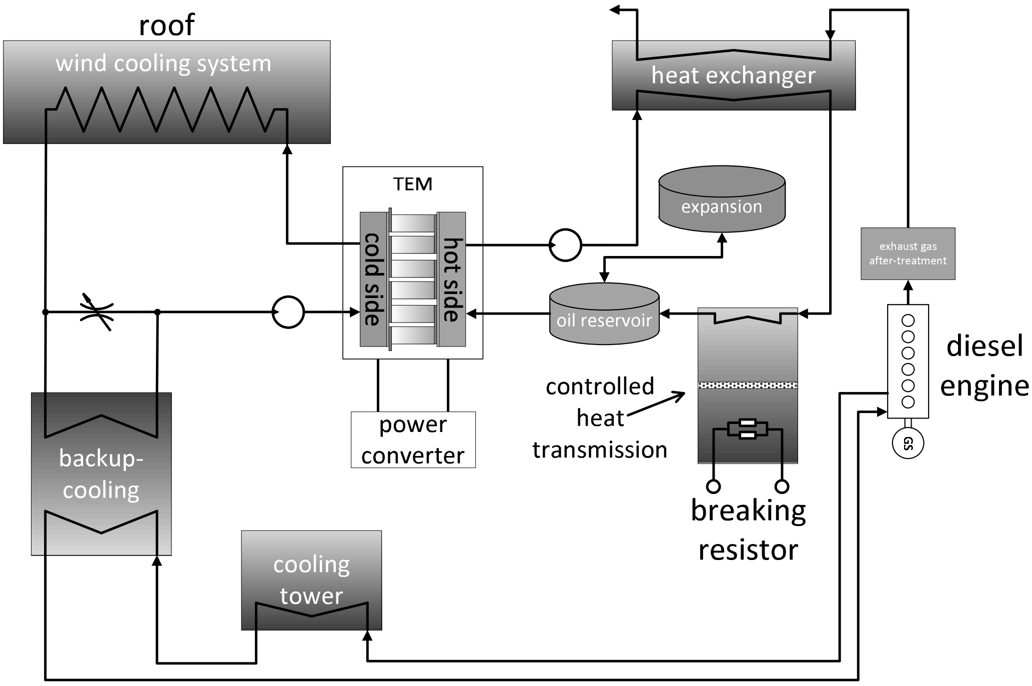

Figure 6: *Thermoelectric generator system with thermal oil intermediate circuit*

4. Simulation

To evaluate the system performance and efficiency a simulation in Matlab/Simulink was done. The intention was to show the achievable power output depending on the thermoelectric material, the connection between the exhaust gas heat exchanger and the TEM heat exchanger, the effectiveness of the temperature smoothing and the reduction in fuel consumption depending on the type of track (e.g. regional train or freight train). For this purpose an appropriate TEG model has to be introduced.

4.1 Simulation of thermoelectric generators

Three different approaches for TEG models have been analyzed: A 1D model with an iterative solution for the coupled equations, a 1D network approach with thermal capacities and the zero dimensional classic model with a direct solution.

1D iteration model

The basic idea is to divide the arms of the TEG into small slides with the length dx and to solve the equations (5, 6, 7) for every slide depending on given boundary conditions, e.g. the temperature on the hot and cold side and the electric current. If the discretisiation is sufficient, it can be assumed that the temperature in every slide is constant [4, 10].

$$T_{i+1} = T_i + \left(\frac{\alpha_i \cdot T_i \cdot j - \dot{q}_i}{\kappa_i}\right) \cdot dx \tag{5}$$

$$\dot{q}_{i+1} = \dot{q}_i + \left[j^2 \cdot \rho_i \cdot \left(1 + \frac{\alpha_i^2}{\rho_i \cdot \kappa_i} \cdot T_i\right) - \frac{j \cdot \alpha_i \cdot \dot{q}_i}{\kappa_i}\right] \cdot dx \tag{6}$$

$$u_{i+1} = u_i - \left(j \cdot \rho_i + \frac{\alpha_i^2 \cdot T_i \cdot j + q_i \cdot \alpha_i}{\kappa_i} \cdot T_i\right) \cdot dx \tag{7}$$

1D network model

Similar to the 1D iteration model the TEG is discretised into slides with the length dx. If the temperature is assumed to be constant for every single slide, then every slide can be modeled as a network consisting of thermal resistors, thermal sources and a thermal capacity (Figure 7). The sources on both sides of the network are representing the hot and cold side of the TEG. The thermal resistors are representing the temperature dependant thermal conductivity of each slide and the capacity its thermal capacity. The sources in between are injecting the Joule heating.

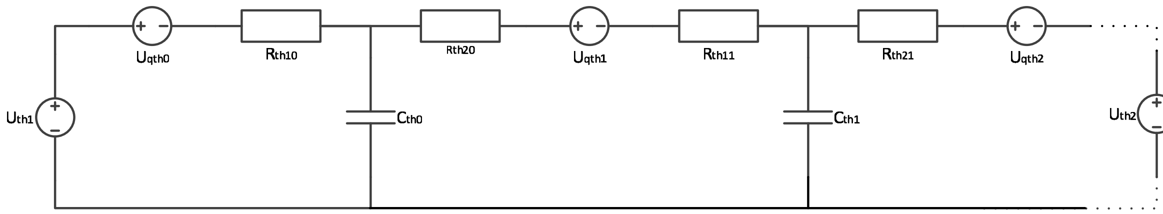

Figure 7: *1D TEG network model*

With this model a calculation of the temperature gradient in the TEM under high dynamic boundary conditions is possible.

0D model

In this model the TEG is condensed on one point and the temperature depending parameters are defined at the mean temperature (8) over the generator [4].

$$T_M = \frac{T_H + T_C}{2} \tag{8}$$

The heat flow on the hot and cold side for the n- and p-arms of the TEG is calculated with equations (9) and (10).

$$q_{H,p/n} = -\frac{1}{2} \cdot R_{el} \cdot i^2 \pm \alpha_{p/n} \cdot i \cdot T_H + \frac{\kappa_{p/n} \cdot A}{h} \cdot (T_H - T_C) \tag{9}$$

$$q_{C,p/n} = +\frac{1}{2} \cdot R_{el} \cdot i^2 \pm \alpha_{p/n} \cdot i \cdot T_C + \frac{\kappa_{p/n} \cdot A}{h} \cdot (T_H - T_C) \tag{10}$$

Conclusion

Both, the 1D iteration and the 1D network model need more computational time to solve than the 0D model, but give a more precise solution if the temperature dependant parameters (Seebeck coefficient, thermal conductivity and electric resistance)

vary within the given temperature range. The more the variation is, the worse are the results of the 0D model.
For the given system the 0D model is sufficient because of three reasons:

1. The temperatures of the hot and cold side are almost constant.
2. The temperature difference of the hot and cold side is quite low (no high temperature application).
3. If necessary, the variation of the temperature dependant parameters can be assumed with an adjustment of the mean temperature because of the nearly constant temperatures on both sides of the module.

4.2 System simulation

To evaluate the performance of the presented TEG system a multi domain energy simulation in Matlab/Simulink was done for the Regional Express track from Hamburg to Cuxhaven in Germany with a Bi_2Te_3 TEM (Figure 8). Even though the efficiency of the TEG in the temperature window is only 6% or less, the reduction in fuel consumption is 0.7%. With a TEM adapted on the occurring system temperatures (and improved modules) a higher reduction in fuel consumption is possible.

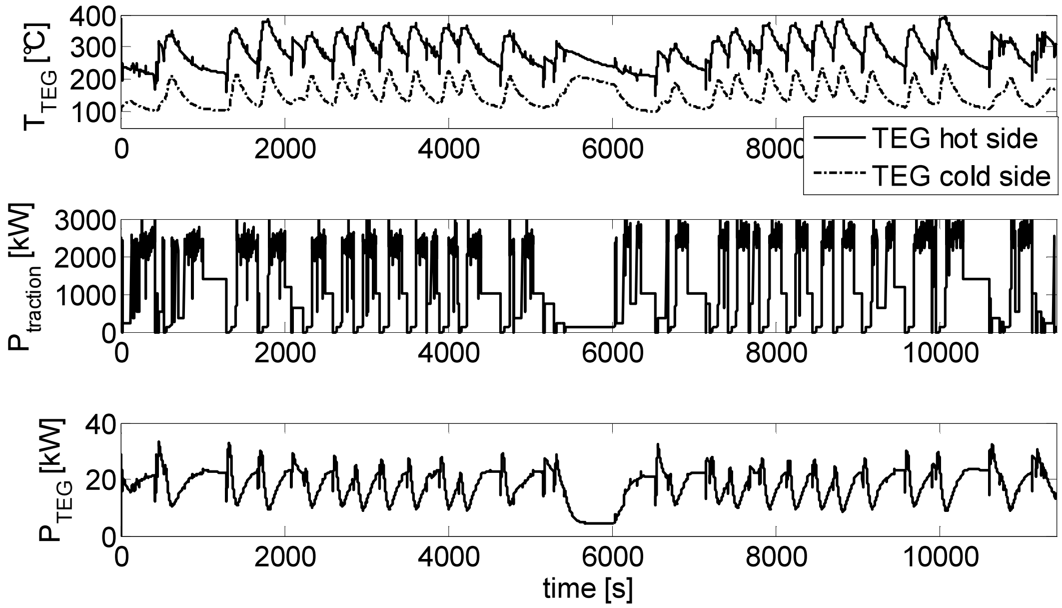

Figure 8: *Simulation result Hamburg-Cuxhaven*

5. Conclusion and outlook

Thermoelectric generator systems (TES) are one promising option to face the needs for reducing energy consumption and environmental protection. This work introduced three simulation models for thermoelectric generators, each for a different purpose, and a new TES suitable for high power diesel electric vehicles. It has been introduced by an example of a diesel electric locomotive, which was evaluated by a multi domain energy simulation. The results show that a significant reduction in fuel consumption for regional tracks is possible, if a thermoelectric material for the desired temperature range is available for industrial applications, which is one goal of the BMBF HiTEG project.

Next steps are a further improvement of the simulation and the evaluation of different track types like freight traffic. Other types of diesel electric vehicles would also be possible to investigate, e.g. diesel electric trucks, busses or mobile harbor cranes. A scaled prototype of a TES is planned in order to validate the concept and the simulation.

Literature

[1] Schimke, R.; Zimmermann, G.; Beitelschmidt, M.: *Life Cycle Cost Calculations of Diesel-Electric Locomotives with Electrochemical Storage Systems*, Energy Efficient Vehicles Technology I, Proceedings to EEVC 2011, Dresden, 30.06.-01.07.2011, S. 57-67.

[2] Brehm, H.; Heckenberger T.: *Anforderungen an thermoelektrische Generatoren zum Einsatz im Abgasstrang von Automobilen,* IAV-Thermoelektrik Konferenz, Berlin, 2008.

[3] Eder, A.; Liebl J.: *Thermoelectric Waste Heat Recovery,* IAV-Thermoelektrik Konferenz, Berlin, 2008.

[4] Rowe, D.M.: *Thermoelectrics Handbook: Macro to Nano,* CRC Press, Boca Raton (USA), 2006.

[5] Voith Turbo Marine SteamTrac B.V.: *Increased power and less fuel consumption,* Twello, 2011

[6] Miller, J.: *Propulsion Systems for Hybrid Vehicles*; London; 2004.

[7] Guzzella, L.; Sciaretta, A.: *Vehicle propulsion systems: introduction to modelling and optimization*; Zürich, 2005.

[8] U.S. Department of Energy: Waste Heat Recovery: *Technology and Opportunities in U.S. Industry*; USA; 2008.

[9] Böttner, H.: *Schwerpunkte und Trends der Thermoelektrik: ein nationaler und internationaler Überblick,* IAV-Thermoelektrik Konferenz, Berlin, 2008.

[10] J. Christine: *Analyse thermoelektrischer Module und Gesamtsysteme (Dissertation)*, Braunschweig, 2010.

[11] Federov, M. I.; et al.: *Highly effective Mg2Si1-xSnx thermoelectrics*, Physical Review 74, 2006.

[12] Shi, X.; et al.: *Low thermal conductivity and high thermoelectric figure of merit in n-type BaxYbyCo4Sb12 double-filled skutterudites*, Applied Physics Letters 92, 2008.

[13] Subramanian, M. A.; et al.: *Thermoelectric Properties of Indium Filled Skutteridites*, Chemistry of Materials 18, 2006.

[14] Pfeiffer, P.; *Integration eines Thermoelektrischen Generators in den Kühlkreislauf eines Verbrennungsmotors*, IAV-Thermoelektrik Konferenz, Berlin, 2008.

[15] Beitelschmidt, M.; Schimke, R.; Tempelhahn, C.; Müller, J.; Reiß, R.: *Effiziente Energierekuperation in dieselelektrischen Hafenmobilkranen*, Tagungsband zur 18. Internationale Kranfachtagung, Bochum, 2010.

[16] Lehmann, M.; Zauner, F.: *Elektromobilität bei schweren Nutzfahrzeugen*, 23. Verkehrswissenschaftliche Tage, Dresden, 2012.

[17] Ådnanes, A. K.: *Maritime Electrical Installations and Diesel Electric Propulsion*, Olso, 2003.