Mohsen Namakian

Mild Hybrid System in Combination with Waste Heat Recovery for Commercial Vehicles

Supervisors
Jan Dellrud: Scania Technical Center
Edris Safavi: Linköping University

Examiner
Johan Ölvander: Linköping University

May 2013
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ABSTRACT

Performance of two different waste heat recovery systems (one based on Rankine cycle and the other one using thermoelectricity) combined with non-hybrid, mild-hybrid and full hybrid systems are investigated. The vehicle under investigation was a 440hp Scania truck, loaded by 40 tons. Input data included logged data from a long haulage drive test in Sweden.

All systems (waste heat recovery as well as hybrid) are implemented and simulated in Matlab/Simulink. Almost all systems are modeled using measured data or performance curves provided by one manufacturer. For Rankine system results from another investigation were used.

Regardless of practical issues in implementing systems, reduction in fuel consumption for six different combination of waste heat recovery systems and hybrid systems with different degrees of hybridization are calculated. In general Rankine cycle shows a better performance. However, due to improvements achieved in laboratories, thermoelectricity could also be an option in future.

This study focuses on “system” point of view and therefore high precision calculations is not included. However it can be useful in making decisions for further investigations.
ACKNOWLEDGEMENT

This study could not be completed without helps from others. I would like to take this opportunity to record my sincere thanks to those who supported me, those who shared, willingly and without expectation, their knowledge and experience with me.

First and foremost I wish to acknowledge Jan Dellrud (senior technical advisor at Electric System Development, Research and Development, Scania). As my supervisor, he provided a great deal of theoretical and technical support during the project. I appreciate his patience while answering my questions and willingness to spend time with me, helping me passing many challenges occurred during the investigation.

I am highly indebted to Johan Linderyd, head of Advanced Engine Systems, Research and Development, Scania, and his colleague Jonas Aspfors for their valuable advice, guidance and information regarding to Rankine cycle, engine performance and also driving cycle data.

I would also like to thank Johan Falkhäll, development engineer at Hybrid Systems Development, Research and Development, Scania, for his assistance in hybrid part of the project, in particular issues regarding to Matlab/Simulink.

I am really grateful to Gunnar Ledfelt, expert engineer at Electric Power Supply, Research and Development, Scania, for his precious support in mathematical modeling and numerical approach. He also provided me valuable information regarding to power demand of auxiliaries of a truck. Beside his professional helps, his nice and friendly communication made my working environment even more pleasant and hearty.

I deeply appreciate the support from Ola Hall, expert engineer at Cooling and Performance Analysis, Research and Development, Scania, regarding to the heat exchangers and their performance.

I am happy for working closely with Nicklas Enquist, master thesis worker who prepared the battery model. During the project we had a friendly and constructive corporation.

I would like to express my gratitude to Johan Ölvander, head of the Division of Machine Design and Edris Safavi, PhD student, my examiner and supervisor at Linköping University for all I learned from them, not only during this particular project but also through the courses and student projects I have had with them, while studying at Linköping University.

And finally, I would like to thank my wife Fatemeh for her understanding and love during the past few years. Her support and encouragement was in the end what made my study and in particular this thesis possible.
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<tr>
<td>AEDEG</td>
<td>Automobile Exhaust Thermoelectric Generator</td>
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<td>CEC</td>
<td>California Energy Commission</td>
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<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
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<td>DOE</td>
<td>US Department of Energy</td>
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<td>HDV</td>
<td>Heavy Duty Vehicle</td>
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<td>HEV</td>
<td>Hybrid Electric Vehicles</td>
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<td>IPCC</td>
<td>International Panel on Climate Change</td>
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<td>LDV</td>
<td>Light Duty Vehicle</td>
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<td>MPPT</td>
<td>Maximum Power Point Tracking control</td>
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<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
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<tr>
<td>PMU</td>
<td>Power Management Unit</td>
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<tr>
<td>REP</td>
<td>Electric System Development (Scania, Research and Development)</td>
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<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generators</td>
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<td>TEG</td>
<td>Thermoelectric Generator</td>
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<td>TEPG</td>
<td>Thermoelectric Power Generation unit</td>
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<tr>
<td>SEPIC</td>
<td>Single-Ended Primary-Inductor Converters</td>
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<td>WHR</td>
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1 INTRODUCTION

1.1 Sustainability in transportation

Transport sector is one of the key factors in economy of development. The mobility, whether people or goods and also the range of accessibility, altogether create the heart of this importance. An efficient transportation system will lead to a higher economic and social opportunities and benefits. In contrast a deficient transport system has an opposite effect.

Having strong and mutual relation between development and transport in mind, global effect of transport sector can be better understood in an “international development” context. In other words, in the globalized world, impacts (with whether positive or negative contribution) on any of key playing factors (transportation, for example) will be globalized. Thus, when it comes to transportation, the way to sustainable development passes through sustainable transport.

In contrast to the term “Sustainable Development”, with its internationally widely accepted definition introduced by Brundtland Commission, “Sustainable Transport” has not found its unique definition yet. A study of sixteen practitioner and research initiatives on transportation sustainability shows many different definitions and notes on the concept, along with six distinct approaches and frameworks to present the roadmap. However, and regardless of these differences, one core statement remains consistent: To reduce all transportation related pollutants and eliminate greenhouse effects.

Although sustainable transport (and hence environmental related issues) includes a broad extent of different concepts ranged from roads, railways, airways, ports, canals, pipelines to infrastructure and energy, for the scope of this report only contribution of vehicles, in particular hybrid vehicles with diesel internal combustion engines and waste heat recovery systems are taken into consideration.

1.2 Environmental impacts caused by vehicles

Greenhouse gasses are the main reason for global warming which has several undesirable influences on the planet. A comprehensive assessment conducted at IPCC (International Panel on Climate Change) shows that global temperature increase has caused a number of negative impacts including:

- Decrement in ice cover
- Changes in ecosystems
- Increase in ground instabilities and rock avalanches
- Facing earlier springs
- Changes in structure and quality of water stored in natural resources due to warming
- Changes in migration patterns of migratory animals
- More acidity levels of oceans

Transportation is alone responsible for 13.5% of global greenhouse gas emissions, of which heavy duty vehicles are the second largest source of emissions in transport sector, larger than both international aviation and shipping.

Vehicles powered by internal combustion engines contribute in greenhouse gas emissions, potentially by releasing three major gasses: Carbon dioxide (CO₂) accounted for 98%, while methane (CH₄) and nitrous oxide (N₂O) accounted for the balance. Due to their negligible contribution in fossil fueled vehicles, methane and nitrous oxide is not studied in this report.
Undesirable impacts on environment are not limited to green house gases. Nitrogen oxides, Carbon monoxide, unburned hydrocarbons and also other pollutants are results of combustion of hydrocarbon fuels in internal combustion engines by which most of today vehicles are being powered.

1.2.1 Nitrogen oxides

Nitrogen oxides (NOx) are responsible for creation of highly reactive oxygen atoms that are harmful for membranes of living cells. These oxides are also the cause of a phenomenon called as “acid rains” that, if inhaled in, can damage lung tissues, and in an extreme case cause death. Acid rains are also strongly destructive for the forests and play a role in deterioration of marbles used in antiquities. Nitrogen dioxide partly contributes as well in “smog”, harmful for human (and all other living creatures) health.\(^8\)

1.2.2 Carbone monoxide

Carbone monoxide is a product of incomplete combustion of hydrocarbons due to lack of oxygen. It is a colorless, odorless, tasteless and, in the meantime, poisonous gas. Thus, Carbone monoxide poisoning is very difficult to be detected by people.

Incomplete combustion is most likely due to air-to-fuel ratios in the engines, that happens during conditions like starting (“choked” condition), inappropriate car tuning, and at higher altitudes, where lower amount of oxygen is in air.\(^9\) Diesel engines have a small contribution in Carbone monoxide pollution since there is normally extra oxygen during the combustion process.

1.2.3 Unburned hydrocarbons

Similar to Carbone monoxide, unburned hydrocarbons also result when fuel does not burn or burns partially. Hydrocarbons, in reaction with nitrogen oxides and sunlight, form ground-level ozone, a major component of smog. Ozone is harmful for the living creatures’ health, with potential to cause cancer in some cases. Unburned hydrocarbon pollution is considered to be the major air pollution problem in cities.\(^10\)

In diesel engines, in particular, particles released due to incomplete burned hydrocarbons are believed to be one of the most dangerous air pollutants.\(^11\) These very fine particles contain toxic pollutants and if inhaled can reach to the deepest parts of lungs and then bloodstream.\(^12\)

1.2.4 Other pollutants

Impurities in fuels, mostly sulfur, are a source of emission of some pollutants. Sulfur trioxide, caused by oxidation of sulfur impurities in fuels during combustion and then reaction with air, can react with water vapor and form sulfuric acid that is a major component of acid rain.\(^13\)

1.3 A picture of future, need for green vehicles

High developing growth rates suggests a rapid increase in vehicle ownership. It is predicted that the number of world total vehicles will be approximately 1.5 times higher in 2020 than in 2008.\(^14\) Longer terms anticipations show even more rates; 2.5 times greater in 2030 than in 2002, increasing to more than two billion vehicles.\(^15\) It can be therefore seen the importance of moving towards lower emitting vehicles as well as higher tank-to-wheel efficiencies, which is anticipated to be in the range 21.7 to 29.8% in 2020, for advanced diesel and hybrid diesel vehicles, in highway driving condition.\(^16\)

Considering all environmental adverse impacts caused by vehicles, moving towards “green cars” is not just an option, it is an absolute necessity. That explains huge amount of intensive activities in order to
improve efficiencies in ranges of fractions of only one percent; accumulative resultant of this apparently small improvement will be significant, when it is seen in a larger scale.

1.4 Modern transportation

There are different factors contributing in the quite small tank to wheel vehicle efficiency, of which engine losses, idle losses, driveline losses (transmission), accessories, rolling resistance, aerodynamic resistance, inertia and braking losses are the most important contributors.

In order to eliminate the losses, different scenarios are being followed by major vehicle manufactures. Drag reduction techniques are used to reduce losses due to air pressure. Hybrid vehicles are developed to take advantage better functionality of two different energy converters (e.g. internal combustion engine and electric machine) each covers weakness points of the other one. Waste heat recovery systems, though have not been completely developed, are aimed to harvest part of the energy that is dissipated to the air in form of heat. Hybrid vehicles and waste heat recovery systems are investigated in this report.

1.5 Background

The idea of using thermoelectricity in power generation dates back to 1945, when Arthur C. Clarke suggested “an indefinitely prolonged operating period for artificial satellites”17. Since late 1951s, radioisotope thermoelectric generators (RTG), in which heat released by decay of a radioactive material is converted to electricity by thermoelectric generators, has been used in different projects, more widely in aerospace technology18,19. Many unmanned lighthouses and navigation beacons were constructed using RTGs by the Soviet Union of which some are still in use20. Thermoelectricity has also been used to generate power at some remote or off-grid locations21.

Nevertheless, thermoelectric based devices have also found their way for home-use applications. It is used, for example, to charge gadgets using heat produced by stoves22,23, to run a barbeque fan using the heat24, to harvest waste heat from microprocessors25 and for cooling down or warming up in small scales26 (when it is used as cooler/heat pump).

Attempts to use thermoelectric generators, fed by waste heat, in vehicle industry can be traced back to 1963 when Bauer27 stated that thermoelectric generators implemented on vehicles have potential to act as an auxiliary power source. Further investigation was suggested by him.

One year later, in 1964, Tomarchio proposed28 a thermoelectric-based waste heat recovery design that theoretically could supply alternator load when the vehicle was driven at speeds more than 80 km/h.

In terms of practical activities John C. Bass et al.29 have been pioneers in deploying thermoelectric generators for recovering waste heat from diesel engines. This was started in 1987 as one of the inventory programs at the US Department of Energy (DOE), with a goal to harvest 200 Watts from waste heat of diesel engines.

As the next step of the 200 W project, a phase I design of a 1kW waste heat recovery system, to be installed on diesel engines was later finished in 1990. This project was continued by phase II to which lasted until 1992. This project was also supported by the DOE associated by California Energy Commission (CEC). The design was tested in 1993-1994, when various modifications were applied on heat transfer system within the generator30. In this design (figure 1) seventy-two Hi-Z bismuth-telluride modules, arranged in eight groups of nine modules was used to convert energy in exhaust gasses to electricity. Each group of modules was cooled by a single water cooled heat sink. The
module and heat sink assemblies were positioned on the octagonal outer surface of a cast steel center support structure. In order to force the exhaust gas flow close to the surface of the support structure, a hollow displacement body was placed in the center of the generator. Modifications were mostly regarded to boundary layer problem which was solved, in two stages, by changing fin design (on the support structure) and adding swirl fins (on the center body, figure 2), which resulted in an increase in output electric power from 400 to 1000 Watts.

A continuation of the mentioned project was later launched in late 2000, with a major goal “to design, fabricate and road test 1 to 3 kW for class 8 Heavy Diesel Trucks”\(^3\). Modules were manufactured by the newly patented technology (HZ-14). In order to remove lateral movements of modules seen in the previous project, they were epoxy bounded on both sides. Thermally conductive grease was also applied on the TEG assemblies to improve conductance. The assembly in general followed the same idea of its predecessor with improvements in individual parts. It was found that TEG power output was strongly dependent on engine load and less on engine rotational speed. The final status of this project and whether 3kW power generation goal was achieved or not, is not reported.

There have also been other similar investigations during the last decade of twentieth century. Menchen el al.\(^3\), for example, concluded that theoretically 1 kW could be produced and speculated that a thermoelectric generator might replace the truck’s alternator. Takanose and Tamakoshi\(^3\) installed a TEG system on a passenger car and could generate up to 10 to 130 Watts (depending on the road and driving conditions). In the meantime attempts to recover some energy from an automotive radiator have also been made. Crane et al.\(^3\) showed that it is probably possible to replace the alternator with a low penalty associated by increased radiator size and pumping power.

In 2002, using a model created in Matlab/simulink, developed by DOE’s National Renewable Energy Laboratory (NREL), Terry J. Hendricks and Jason A Lustbadar\(^3\) conducted an investigation in order to simulate, analyze and optimize integrated effects of heat exchanger and thermoelectric device performance in light and heavy duty applications. It was shown that the interaction of heat exchanger performance and TEG device conversion performance creates critical system impacts on maximum power output and cold side cooling requirements. According to this study powers up to 900 Watts was possible to be generated in LDP (Light Duty Passenger) vehicles if Thermoelectric Power Generation unit (TEPG) is placed on the vehicle catalytic converter. The expected range for power generation would be reduced to 700 Watts if TEPG unit is placed downstream of the vehicle catalytic converter. It was also seen that there are certain \(T_h\) and \(T_c\) regimes that maximizes performance of the TEPG.

Terry J. Hendricks and Jason A Lustbadar\(^3\) also quantified effects of important system design parameters on system performance and maximize system power output. It was shown that:
1. TEG device cross sectional area is strongly dependant on exhaust mass flow rate, and it increases as exhaust gas temperature increases.
2. Optimum TEG element area, segment lengths and number of couples are sensitive to exhaust gas temperature near the maximum power ridge.
3. Required mass flow rate to maintain thermal stability and maximum power output can be very sensitive to cold side interface resistances, so cold side design is a critical aspect.
4. Heavy duty vehicles have higher TEG power generation potential than LDP vehicles by about a factor of 5, with 5-7 kW of electrical energy production possible, but they also have more stringent system design requirements.

In a practical attempt, Thacher et al.\textsuperscript{37} an exhaust thermoelectric generator was installed on a 1999 model GMC Sierra (figures 3 and 4). The test was performed in a climatic wind tunnel under controlled ambient conditions. In this test powers up to 125 W could be extracted however more power was anticipated that could be generated if a larger unit and also a more efficient heat exchanger were used. Since the test was done under well monitored conditions, valuable data regarding to several design parameters could be achieved. It was concluded that thermal management i.e. insulating the exhaust and lowering the coolant temperature is of the high importance. It was observed that cooling load imposed by the system on the vehicle’s coolant system was not significant. However losses due to additional pumping load that is required for extra coolant loop also the weight of the TEG system is observed considerable. Finally an improvement in vehicle fuel efficiency on the order of 1-2 percent depending on speed was achieved.

Figure 3. Arrangement of HZ-20 modules and heat exchangers in the AETEG\textsuperscript{37}. 
A performance model in ADVISOR led by BMW showed 6-10% increased vehicle efficiency is expected in a BMW next generation in-line 6-cylinder engine in a 530i model. Thermoelectric materials with ZT values ranging from 0.85–1.25 were used in this study to reflect current and near-term available material systems. Subsystem components of this system architecture was later, in December 2006, built and tested. The BMW Group roadmap indicates commercialization of a TEG system, integrated in its products in about 2022. Figure 5 shows how this system would look like in future.

A simulation study work at Honda R&D showed that with applying exhaust system insulation and forming the appropriate combination of elements with differing temperature properties inside the TEG could yield an enhancement of about 3% in fuel economy. Effects of implementing a new system in fuel economy were taken into account, such as power generation, increased weight and backpressure. It was also shown that by using different TEG elements having optimized working temperature at upstream and downstream of the system, efficiency was increased by about 30%.

In a report Meisner described a project led by General Motors (GM), in which three TEG prototypes using improved materials (Skutterudites) were implemented. The prototypes were demonstrated on a vehicle and several tests were accomplished. According to the report, GM aims to Achieve 10 % improvement in fuel economy by 2015 without increasing emissions.

Renault Trucks in corporation with Volvo Group has been investigating TEG application on LDV and HDVs. A four year 4M€ project named “RENOTER Project” was launched in 2008, aimed on 100-
300w for passenger diesel cars, 500w for passenger gasoline cars and 1Kw for heavy duty vehicles\textsuperscript{44}. At the time of writing this report (May 2013), no track of the results could be found.

Scania has been following the idea of waste heat recovery using TEG, since 2009. In a feasibility study\textsuperscript{45} conducted by Henrik Schauman, a small prototype of a waste heat recovery unit was built and tested. Using a simulation, verified by tests in low range temperatures and extrapolated over higher temperatures, it was predicted that powers in range of 400 to 1400 Watts could be expected, depending to different driving cycles and also the place the TEG system is placed (EGR or exhaust pipe).

In 2010, in another project supervised by Scania, Adham Shawwaf constructed a numerical model in Matlab/Simulink to analyze DC-DC convertors\textsuperscript{46}. The model was then verified by a prototype made at Scania. It was also shown that by using a DC-DC converter, more power would be generated even if less number of TEG cells is used. However the converter is designed for powers in range of less than 100 Watts and, according to the report of this study, more efficient converters adopted for higher output powers needed to be implemented.

Later in 2012, two more advanced DC-DC converter equipped with Maximum Power Point Tracking control (MPPT) was studied by David Jahanbakhsh\textsuperscript{47}. Single-ended primary-inductor converters (SEPIC) were simulated in this study. The simulation followed two different algorithms (P&O and INC algorithms) in order to track maximum power, and also a prototype was constructed. Performance of these two algorithms were compared and it was concluded that in general INC shows better functionality. It was also shown that efficiencies in order of 80-85\% for converters could be expected.

In the same year (2012) another study was launched by Scania, in order to investigate the effects of different TEG connecting configurations in the output power generated by a waste heat recovery system\textsuperscript{48}. In this study Björn Andersson showed that Serial-Parallel switching could be discarded as a realistic alternative to a DC-DC-converter. He concluded that a direct connection with a switching network can definitely be competed with a DC-DC converter based solution, and in some cases it may even be a better choice.

1.6 Hybrid Electric Vehicles (HEV)

Taking advantage of high energy-density of petroleum fuels, internal combustion engines (ICE) provide a good performance in terms of long operating range. Today a regular passenger car having a fuel tank as large as 60 liters can typically travel around 1000 km which is significantly higher than the corresponding value for an electric car, typically in range of 60-100 km. In fact, it can be realistically assumed that ICEs give an “infinite operation range” since they can be refueled very quickly and almost anywhere. In contrast, refueling of an electric car takes several hours and at limited locations. There are still other factors that make electric cars unfavorable compared to ICE based ones, factors like initial and maintenance costs, lifetime (specifically for batteries) etc.

However ICEs suffer from low efficiencies (at its best, around 40\%) and a limited working range that their maximum efficiency can be achieved. They are also highly polluting machines, in particular during city driving, when many start-stops might occur. ICEs have many moving parts in contact with each other (friction) which in turn means maintenance costs and also noise. ICEs have a lower power to volume ratio. All of the above mentioned disadvantages are not seen, or seen at a much lower level in electric vehicles.

A hybrid system, in general, combines advantages of ICEs and another distinct power source and covers some of disadvantages of each by the other one. If the second power source is an electric
system, the system is called as a hybrid electric vehicle (HEV). There are also other versions of hybrid vehicles of which fuel cell vehicles can be referred as an example\(^49\).

### 1.6.1 Major hybrid functions

Depending to design requirements and considerations there can be a wide range of functions to be implemented in a HEV. Some the most common functions can be listed as follows:

#### Energy saving while braking (regenerative braking)

In conventional brakes a large amount of kinetic energy is wasted to heat via friction. It also causes maintenance costs due to wearing down in brake disks and pads. This wearing down has a significant environment impact since it causes some toxic metals to be released to the environment\(^50\).

Energy saving while braking is aimed to convert this kinetic energy to electricity and save it in storage (battery). In city driving, in particular, when there are many stop-starts, this function can result approximately 10% percent reduction in fuel consumption.

#### Zero emission idling

There are situations in which the vehicle needs to be in idle. One of the most common cases is city driving with a traffic jam. Therefore a hybrid function could be shutting down the ICE and turn it on in a suitable time (usually called as start-stop function). Depending to degree of hybridization, this function can be combined with regenerative braking, to provide fast restarting the ICE using energy saved during the braking. It can be further advanced so that the vehicle is accelerated to a suitable speed by electrically supplied power train and then switch to ICE, when ICE functions at a suitable efficiency.

#### Zero emission driving

Zero emission driving is achieved when the power train is supplied only with electric energy for longer times. It lowers harmful emissions (in urban driving, for example) and also provides a no-noise driving condition. However a higher degree of hybridization and larger storages (batteries) is needed.

#### Maximum ICE efficiency

By deploying and implementing a suitable energy strategy, a hybrid vehicle can be designed in such a way that its ICE functions (almost) always at its maximum efficiency. If powers more than what is supplied by ICE is required, electric side of power train comes to the picture and delivers the amount of extra power that is needed. If, however, powers less than what is supplied by ICE is needed, the extra power generated by ICE is used to charge the batteries.

#### Boosted power

For specific situations when extra power is needed (high acceleration rate, for example), power from ICE can be amplified by power delivered by electric motor.

#### Other functions

Hybrid functions are not limited to what mentioned above. Other functions like open-clutch driving, fast gear shift, electric devices temperature control, battery charging strategies and other functions can also be implemented in a hybrid vehicle, with one ultimate goal: to improve performance of the vehicle, in terms of efficiency, environmental impacts etc.
1.6.2 Degree of hybridization

In a variety of different power train configurations, ranged from only ICE propelled vehicle to a fully electric driven one (without an ICE), different degrees of hybridization can be defined.

**Micro hybrid vehicle**

Micro hybrid vehicles perform only start-stop function. By some definitions, regenerative braking is also considered as one function in micro hybrid vehicles.

**Mild hybrid vehicle**

Mild hybrid vehicles utilize most of full hybrid functions excluding e-driving, whether pure e-driving or combined by ICE for long ranges. Functions like start-stop, regenerative braking and some levels of power boost can be included in a mild hybrid vehicle.

**Full hybrid vehicle (HEV)**

A full hybrid vehicle is defined as a vehicle that can be run individually by ICE or electric power or a combination of both. E-drive mode is limited to lower ranges (compared to HEVs), typically 2km. Different hybrid functions can be included in a full hybrid vehicle with the ultimate goal to decrease fuel consumption.

**Plug-in hybrid electric vehicle (PHEV)**

PHEVs provides all functions of a fully hybrid electric vehicle, having an extra possibility to recharge the batteries by plugging into an external electric power source. This added feature gives e-drive possibilities for longer distances, typically 20km.

1.6.3 Architectures of Hybrid Electric Drive Trains

Depending to how energy flows in different components of a hybrid vehicle, two basic architecture of hybrid electric drive train can be defined: series and parallel.

In a series layout, torque demand from driveline can be supplied only by electric machine (motor-generator). In this configuration there is no physical connection between ICE and transmission. The power from ICE is instead converted to electric power via a generator. Using a power management unit (PMU), This electric power is mixed to the electric power system to supply required power for auxiliaries, control units, charge the battery and also drive line requirements.

In a parallel layout, however, ICE and electric machine can be independently involved in driveline requirements. Electric machine might be belt drive-driven (similar to traditionally belt driven alternators, mounted on the engine) or in a serial physical connection to the crankshaft (placed directly on the crankshaft). The latter, in contrast to its serial physical appearance, represents a parallel hybrid layout, due to its parallel-in-nature energy flow.
With new generations of hybrid vehicles introduced to the market, it was realized that some of them could not be classified into the two above mentioned categories. Hence two more categories were added. All four categories are shown in figure 6\(^5\). 

![Diagram of four different architectural categories for HEVs](image)

Figure 6. Four different architectural categories for HEVs\(^5\).

1.6.4 **Major electric components in a hybrid electric vehicle**

*Electric machine*

Electric machine is basically a two way energy converter, functions in two modes; as an electric motor (converts electrical energy to mechanical) and also as an alternator (converts mechanical energy to electrical).

*DC-DC converter*

DC-DC converter is used to convert a variable input voltage to a regulated output voltage, guarantying a maximum output power. Figure 7 shows the variation of voltage and power versus current in a circuit. As it is seen the maximum power occurs at specific current and a corresponding voltage. A DC-DC converter is programmed in such a way that the output power stays at this maximum power region.

*Inverter*

An inverter is placed between electric machine and the electric circuit. It works as an AC-DC converter (when electric machine works as an alternator), or as a DC-AC converter (when electric machine works as an electric motor). Inverter also regulates the electric power into and out from the electric machine.
A control unit senses all the system parameters and inputs and adjusts all control signals in the system accordingly. It decides, for example, whether the electric power is to be converted to mechanical power and delivered to the power train, or it should be stored in the battery. The control unit is programmed to follow energy strategies in the system.

Battery

Battery is probably the most limiting component in a hybrid system. With the today’s technology, batteries are expensive providing relatively low capacity to price ratios.

1.7 Waste heat recovery systems

1.7.1 Waste heat

Nowadays in diesel engines, where the main part of losses occurs, only trends of around 40% of efficiencies at the best engine running conditions are expected. In other words, approximately 60% of available chemical energy in the fuel is wasted in the engine mostly in form of heat from combustion via exhaust gasses and cooling system (figure 8). There are methods to recover part of this heat and convert it to a useful power. Other than thermoelectric generators which will be discussed more in
Six-stroke internal combustion engine cycle

In this method two extra strokes are added to increase efficiency and reduce emissions. There are some patents\textsuperscript{53}, reports\textsuperscript{54} and published papers\textsuperscript{55} about six-stroke internal combustion engines. However it seems more investigations are needed to bring the idea closer to reality.

Rankine cycle

A Rankine cycle utilizes four major components (boiler, expander, condenser and pump) located in a circuit in which a working fluid being circulated. At boiler heat is applied on the working fluid, causes it to be vaporized. The expander converts the energy (heat and kinetic) of the working fluid to kinetic energy (rotation of a shaft). At condenser the working fluid condenses to liquid form to gain higher efficiencies at pump and finally the pump provides energy required for circulation. In exhaust gasses waste heat recovery application, the boiler is in fact a heat exchanger that extracts energy from exhaust gasses and vaporizes the working fluid. Due to relatively low working temperatures (compared to, for example, steam power plants) working fluids with specific properties (evaporation temperature, slope of saturation vapor curve, etc.) should be chosen.

Turbocharger

A turbocharger is in general a compressor, spun by exhaust gasses. It compresses inlet air to cylinder and therefore increases mass flow rate that leads to more engine efficiency. It also helps a better combustion with reduced particulates released to the atmosphere.

Turbo-compound

Turbo-compound is also a turbine spun by exhaust gasses. The power generated by the turbine is usually delivered mechanically to the crankshaft.

1.7.2 Exhaust Gas Recirculation (EGR)

Part of the exhaust gasses is recirculated to the combustion chamber via EGR unit, to eliminate NO\textsubscript{x} emission. NO\textsubscript{x} is formed when nitrogen and oxygen are subjected to high temperatures. By injecting low oxygen exhaust gasses to the combustion chamber, combustion temperature decreases. As a result it lowers NO\textsubscript{x} formation. EGR, however, has a negative effect on the engine power and also causes more soot, along with some other undesired effects that makes its design a compromise between economy, power and environmental related issues.

1.7.3 Thermoelectric generators (TEG)

Seebeck effect

In 1821 Thomas Johann Seebeck\textsuperscript{1}, a Baltic German physicist, discovered that if two different metals are in a closed circuit as shown in figure 9, subjected to a temperature difference, an electric current is produced in the circuit. The phenomenon is a base for thermocouples that measure the temperature by sensing the produced voltage and convert it to temperature.

Developments in semiconductors technology caused Seebeck effect to be efficient enough for energy conversion (thermal to electrical) purposes. If a positive (P type) and negative (N type) material are placed in the same temperature difference, the produced current will be in the opposite direction in
each material. Therefore the performance will be boosted if a pair of “P” and “N” elements are connected together in parallel thermally and in serial electrically, as shown in figure 10.

In practice, several (typically 64, 127, 128 or more) pairs of thermoelectric elements are connected in serial (to increase the produced voltage) to form a thermoelectric module (figures 11\textsuperscript{56} and 12\textsuperscript{57}).

Since TEG elements are purely solid state components, they offer a range of advantages, including noiseless operation, having no moving part (zero friction, low maintenance costs), no vibration and high reliability. However, with today’s technology low efficiency in range of 5-7\% is achieved.
2 SCOPE OF THE WORK IN THIS STUDY

2.1 General considerations

This study was conducted at REP (Electric System Development at Scania, Research and Development) as one part of predevelopment studies. The goal was to investigate different combinations of hybrid/mild hybrid trucks associated with waste heat recovery systems, mainly thermoelectric generators. It was required to compare these combinations, via simulations, when they are functioning under different driving conditions. It was also required to compare TEG based waste heat recovery systems with results from Rankine cycle based one.

The fact that the project was conducted at a “predevelopment” stage implies that it was aimed on general perspectives, rather than highly accurate formulations with very well validated results. Hence some simplifications were inevitable to be deployed. However and as a consistent strategy, it was carefully kept in concern to avoid possible oversimplifications and hold an acceptable level of accuracy in the defined scope of the project.

2.2 Voltage level of the system

As a rule of thumb, currents more than 200A are expensive to handle. Therefore, corresponding to the chosen voltage level, a region in which power level should remain is calculated.

As an example, if a hybrid power level equal to 15kW is chosen, voltage level must be equal or more than 100V. 48V system might be acceptable, if it is approved by further investigation regarding to the costs.

2.3 Assignment

Impact of a waste heat recovery system (WHR, TEG or Rankine) on fuel consumption, when it is integrated in a variety of different power train systems (hybridization degrees) was investigated. These systems are introduced here.

This study was mainly focused on “system point of view”, which means system simulation as a whole, not very deep attention to every individual component. However special attention was paid to the TEG module, since a TEG model that met requirements of this project was not available.

For a TEG system, a mathematical model and then a model using a manufacturer’s (Hi-Z) data sheet was used. Although with current technology, net powers in range of 600-700 W is expected by TEG system, however experiments in labs suggest more efficient TEG modules. Thus, as a future study, net powers in range of 5-10 kW were considered. An extension of the TEG model was therefore created to handle powers in this region. A DC-DC converter ensures the maximum available power to be sent to the power train at the right voltage level.

For the Rankine system, results from another investigation were used in this project. In general a maximum mechanical power equal to 15 kW (for a typical driving cycle) is possible to be generated by a Rankine based WHR. The power obviously varies between zero to this maximum limit, depending to the exhaust gasses temperatures and also mass flow rate. Mechanical power generated by Rankine cycle might be sent to the power train in different ways; mechanical, electrical or a combination of both. These three options are investigated in this project nevertheless only the case when all the mechanical power is converted to electricity is illustrated in the figures. In this particular case, an AC-DC converter is placed after the generator.
Both TEG and Rankine system might be placed at EGR or downstream of the exhaust after treatment system (after the catalytic converter). EGR offers higher gas temperatures however at lower mass flow rates. The temperature at EGR varies in a wider range with higher frequency. At EGR there is a minimum time delay between power demand and temperature raise (probably no need to store the recovered energy in a battery). In contrast, at downstream of the exhaust after treatment there is a higher mass flow rate, at a more consistent but lower gas temperatures. Due to several masses placed in between the engine and the downstream (like silencer, catalytic converter etc.) which work as thermal energy reservoirs, there is a longer delay between high engine power demand and high temperature level. This might urge the design to have a battery as energy storage.

Electric system (represented by olive colored boxes) includes a regular 24V battery and all electrical auxiliaries.

Investigations regarding to the battery, was conducted in another study in parallel to this study\textsuperscript{58}. Since the battery model and the whole system simulation were needed to be used in both investigations (i.e. the present study and the battery modeling) simultaneously, close collaboration between these two projects was necessary.

In all power train variants, a 440 hp truck driving on a driving cycle was simulated. The truck had a gross weight of 40 tons. The driving cycle is explained in section 2.4 Driving cycle data.

2.3.1 System I

WHRs are connected to a full hybrid system (represented by blue color), with hybrid power level 120kW working at 650 V (figure 13). This system takes advantage of a large battery and an efficient energy strategy, which consumes the energy in the best way. However it is costly (only components are estimated to cost 500,000 Swedish Krona\textsuperscript{59}) and its advantage for long haulage driving is questionable. The battery, that has a large economical impact on the design, is probably not sized to an optimal size for this application. Moreover, lower efficiency for converters (since they are to work as step-up transformers as well) is another disadvantage. Nevertheless, economical profitability of application of a full hybrid system in long haulage is not judged in this study.

![Figure 13. WHR (Rankine or TEG) is connected to a full hybrid system, 120 kW, 650 V. Electric system is connected to the high voltage line via a DC-DC converter.](image-url)
2.3.2 System II

It is the same as the previous system, but the electric system is directly connected to the WHR (figure 14). A DC-DC converter that works in both directions is placed in between the WHR and the full hybrid system.

[Diagram of System II]

Figure 14. WHR (Rankine or TEG) is connected to a full hybrid system, 120 kW, 650 V. Electric system is connected to low voltage line, a two direction DC-DC converter connects high and low voltage side of the system.

2.3.3 System III

It is the same as system 1, with a smaller hybrid battery, for economical reasons (figure 15).

[Diagram of System III]

Figure 15. WHR (Rankine or TEG) is connected to a full hybrid system, 120 kW, 650 V. A smaller battery with lower voltage level is used.
2.3.4 System IV

The WHR is connected to a mild-hybrid system with power level limited to maximum 5kW, working at 24 volts (figure 16). Low voltage set for this system implies that high power ranges (more than 5kW) could not be deployed. Thus Rankine system is not considered here and also a lower maximum TEG power is used.

![Figure 16. TEG system is connected to a mild-hybrid system, 5 kW, 24 V.](image)

2.3.5 System V

It is the same as the previous system, with an extra storage (battery) and a control unit to manage the energy flow into or from the battery, also to regulate the voltage level (figure 17). Since the system voltage level is 48 V, higher hybrid power levels is possible to be used. The extra storage is used in order to save the power produced by the WHR, when there is power generated by WHR but no power demand in the power train, for example while braking. It can also add some levels of regenerative braking feature to the system.

![Figure 17. WHR (Rankine or TEG) is connected to a mild-hybrid system, 5-15 kW, 48 V. A small battery and a control unit is added.](image)
2.3.6 System VI

The WHR is connected to a non-hybrid system (figure 18). WHR (TEG) only supports electric system, via a control unit. If there is enough power generated by TEG, alternator is shut down and electric system is fed by TEG. Maximum TEG power is set to be 715 W, an approximate value for auxiliary power under normal condition. TEGA-ATS, and TEGA-EGR are used, with considerations mentioned in section 4.1.6 TEG power, used in a non-hybrid system.

![Diagram of WHR (TEG) system](image)

**Figure 18.** WHR (TEG) is connected to a non-hybrid system.

2.4 Driving cycle data

Data logged from a driving test, run in Södertälje-Norrköping-Södertälje route was used in this investigation. Data are logged in every second, longed in total 9,843 seconds (2h44m3s). Data includes engine RPM, engine power, braking power, fuel consumption, mass flow rates at EGR and exhaust pipe and hot gas temperatures at EGR inlet and downstream of the exhaust after treatment. There are other data logged, but not used in the present study.

2.5 EGR or exhaust after treatment

To extract energy from waste heat dissipated from a diesel engine, there are four locations that WHR system can be installed; EGR, exhaust after treatment, retarder oil and cooling system. Benefits and disadvantages of each location is investigated by Henrik Schauman providing a comprehensive comparison list. However, for the purposes of the present study, only EGR and exhaust after treatment is considered.
3 MODEL DESCRIPTION, METHOD AND ASSUMPTIONS

3.1 Engine

Fuel map of a 440 hp engine (the same engine used in the drive cycle) was used to calculate fuel consumption of the simulated system. The map gives the fuel consumption per unit of time (hour) at any power-RPM combination. The current power is subtracted by extra power delivered by hybrid system (including WHR) and this reduced power is sent to the fuel map along with the current RPM to obtain reduced fuel consumption (figure 19).

![Figure 19](image19.png)

Figure 19. The extra power provided by hybrid system (Hybrid) is subtracted from the power demand. A fuel map (Combustion_Engine) is used to calculate reduced fuel consumption.

The map gives the fuel consumption (kg) per unit of time (hr). In order to have the absolute fuel consumption (kg) for the whole driving cycle, it must be divided by 3600 and then integrated.

3.2 Hybrid defined functions

The hybrid system (figure 20) takes care of regenerative braking and the power generated by the WHR. Thirteen switches are used to control the energy flow. Performance map and torque-RPM curves of the electric machine are scaled to the desired power level from Matlab workspace, using a

![Figure 20](image20.png)

Figure 20. Block diagram of hybrid system, simulated in Simulink
variable.

The inputs to the hybrid model (figure 20) include engine RPM, engine power, braking power, results of TEG model and results from Rankine simulations. In the figure, signal interface between separate blocks within the model is show by arrows. As it is seen electric machine, control unit and battery have two directional interface, which means they send and receive signals to and from each other. System mode is set by RANKINE_STRATEGY (explained below).

In case of a Rankine cycle, the hybrid system also manages the mechanical power in the best way, to be whether converted to electrical power or delivered directly to the crankshaft. This is done via a function box called RANKINE_STRATEGY (figure 21), commanded from the Matlab workspace.

![Figure 21. RANKINE_STRATEGY sets the system to function in one of three different modes.](image)

If the Rankine cycle is simulated, the simulation can be run in three modes.

**Mode 1**: When all the mechanical power generated by the Rankine cycle is converted to electrical power and delivered to the system. This design overcomes difficulties in transferring mechanical power to the power train (larger space) and takes advantage of electrical coupling and better possibilities for storing the power (in a battery) compared to mode 2. However there will be losses in electric machine and part of the power will be lost.

**Mode 2**: When all the mechanical power is directly delivered to the power train. Since there are no electrical components (i.e. electric machine, converters etc.) this design will be more efficient compared to the mode one if regenerative braking is excluded. However it needs larger space which is always a problem. Another disadvantage of this design is regarding to difficulties in storing the energy when there is no power demand in the power train, which is not included in simulations done in this study.

**Mode 3**: This mode combines both previous modes. If there is enough power demand in the power train, the generated power is delivered mechanically to the crankshaft. Otherwise (no power demand) the mechanical power is sent to the hybrid system and then converted to electrical power. This design offers more efficiency but needs more mechanical components to handle energy flow in two directions (towards crankshaft or hybrid system). This design keeps also all disadvantages of the second mode.
3.3 Energy strategies

Hybrid system is responsible for applying the best energy strategy via a control unit. The control unit is in fact a function box called CONTROL_UNIT (figure 22) that at any instance senses some system parameters and makes corresponding decisions. As a result it turns seven switches on and off depending to the situation. The main principle of the energy strategies is to consume the stored energy in the battery as soon as possible. In other words it tries to keep the battery as empty as possible (lower limit of the state of the charge).

The control unit has seven input signals as follows:

- **TEG_Rankine** is electrical power generated by either TEG or Rankine system (converted from mechanical power to electricity) depending on the kind of WHR system, and the Rankine mode that is chosen.

- **EnginePower** is the power delivered by the engine at any instance that is read by the simulation as logged data. This power varies from zero to a maximum value during this specific driving cycle.

- **SOC** is state of charge of the battery, used in the hybrid system. In order to optimize life time of the battery, SOC should remain in a certain range specified by **SOC_min_limit** and **SOC_max_limit**. If SOC of the battery reaches to its maximum limit, control unit stops charging the battery. On the other hand if SOC reaches to its minimum limit, control unit stops discharging the battery.

- **Max_Power_Batt_discharge** is the maximum power that can be delivered at any instance by the battery to the system. It partly depends to the state of the charge and partly to the battery’s specification. At higher state of charges more power can be delivered by the battery. However this power is limited to a maximum limit in order to increase the life time of the battery.

- **Recoverable_Braking_Power** is the part of the braking power that can be converted to electricity by electric machine. The more hybrid power is chosen, the more braking power can be regenerated.

![Figure 22. CONTROL_UNIT commands seven switches, by detecting the system situation at any instance.](image)

![Figure 23. Torque-RPM curves for the electric machine, in two function mode: motor and alternator.](image)
3.4 Electric machine

Electric machine is the component that converts mechanical power to electrical power (alternator) and vise versa (motor). Measured data for a 120kW electric machine, was used to simulate the machine. Torque-RPM curves (figure 23) were used to calculate maximum power delivered by (mechanical in motor mode and electrical in alternator mode) the machine at any RPM (at any instance, from road data). Losses map (figure 24) was also used to implement losses.

For any hybrid power chosen for the simulation, the original electric machine data are downscaled to the desired level. Downscaling was done by keeping RPMs intact and applying a scale factor on torques as well as losses.

3.5 TEG system

A TEG system (figure 25) consists of a set of TEG modules, an extended surface (heat exchanger) at the hot side, a heat exchanger at the cold side (as a part of a cooling system) and a DC-DC converter. There might be a bypass pipe included in the system.
3.5.1 **Extended surface**

The thermal energy carried by exhaust gasses is extracted from the flow by an extended surface. For the purposes of this project a model based on the first law of thermodynamic combined by data sheets provided by one manufacturer was deployed in order to estimate the amount of energy extractable from the gasses. This model will be explained in the next section.

3.5.2 **TEG modules**

A set of TEG modules electrically connected to each other is used to convert the thermal energy carried by exhaust gasses to the electrical energy. To model extended surface and TEG modules, two approached were followed in this study: mathematical modeling and using data sheet provided by manufacturers.

**Mathematical modeling:**

In this method governing equations of one TEG elements (a pair of P- and N- type) is solved by given boundary conditions and initial values. Governing equations include energy balance equations in each leg and also equations covering electrical behavior of the element. Boundary conditions include thermal interfaces between heat exchangers and the TEG element at hot and cold sides. Initial values are temperature profile of both P- and N- legs that is constant, equal to ambient temperature.

The problem was then solved by numerical methods. Finite difference method in space domain and explicit forward difference method in time domain were used as solution methods, implemented into a Matlab code.

As a verification method, a test was planned and executed. Although there were signs of matching results in calculations and practical test, the code could not be completely verified due to lack of precise information regarding to material properties in the TEG modules that were used in the test.

Mathematical modeling offers more flexibility, in particular when parametric study is on-going. However without a reliable verification, a mathematical model might lead to disastrous conclusions and therefore should be avoided.

For more information about the mathematical model and the verification method, please see appendices A and B.

**Modeling using manufacturers’ data sheet**

Compared to the mathematical model, this approach offers more reliability. However special attention is needed in the case when future study (TEG modules with more efficient materials) is conducted.

Data sheets of a set of manufacturers were investigated. For the purposes of this study, data provided by Hi-Z\(^{61}\) company was observed to be the most comprehensive one. In the data sheet issued by Hi-Z, performance of different TEG modules in terms of hot and cold side temperatures and corresponding heat flux through the module and electrical power generated at matched load is given. Having these data available, the first law of thermodynamics was used to model the system.

Figure 26 schematically shows the energy flow through a TEG module. Part of the thermal energy applied on the module is converted to electricity and the rest is dissipated to the coolant at the cold side. Attempts are made to increase efficiency of the modules. Efficiency of a module is defined as:
Performance of the latest product of Hi-Z (called Hi-Z20) is shown in Figures 27 to 29. Although the curves show hot side temperatures more than 250 degrees centigrade but working at temperatures more than 250 degrees will decrease the lifetime of the module and therefore it is not recommended.

As it is seen, with the current technology a maximum efficiency in the order of 6% can be achieved at a maximum hot side temperature of 250 degrees centigrade. Simulation showed (will be discussed later in this report) that this range of the efficiency does not justify the application of a TEG system, however reports of experiments in labs shows a promising future in terms of efficiency and also hot side temperature limit (figure 30).

Figure 26. Energy flow through a TEG module. With current technology a small portion of the heat flux is converted to electricity.

Figure 27. Electrical power generated by TEG modules Hi-Z20.
Improved modules

Since part of the study was to simulate the system based on the higher efficiency TEG modules that are expected to be found in the market in future, an extended TEG module was simulated by applying an efficiency factor (to increase the efficiency) and also extrapolating data regarding to Hi-Z20 TEG modules (to cover temperatures more than 250 degrees centigrade).

Figure 30 shows module efficiency versus hot side temperatures for TEG modules made by current technology, new technologies (QW) that are anticipated to come to the market (developed now at labs) and also new materials. As it is seen, current technology offers maximum efficiencies in the range of 6-7% that agrees with figure 29. It is also seen that efficiencies of approximately 25-30% is achieved.
During experiments at laboratories, with hot side temperatures in the range of 350-400 degrees (region for exhaust gasses of diesel engines).

Figures 31 to 33 show the expected behavior of a TEG module with new materials, as an extended version using Hi-Z20 data as a base and also the blue curve in figure 30 as a sample pattern.

Figure 30. TEG modules behavior, using current technology and new materials. Figure by Hi-Z company.

Figures 31 to 33 show the expected behavior of a TEG module with new materials, as an extended version using Hi-Z20 data as a base and also the blue curve in figure 30 as a sample pattern.

Figure 31. Electrical power generated by an improved version of TEG modules Hi-Z20.
 Configuration one represents TEG modules placed along a cylindrical heat exchanger. Temperature of the gasses is decreased while passing each stage (figure 34). This configuration needs smaller space, however has a disadvantage of causing more back pressure (ignored in the model), which in turn reduces the overall efficiency of the system.

The model is based on part of the thermal energy content of the exhaust gasses at any time step (one second) that passes through the TEG, satisfying the first law of thermodynamics.

According to the first law of thermodynamics change in the internal energy of any closed system is equal to the amount of the heat supplied to the system plus the work done by the system. The law can be formulated as follows:
Or if time derivation of the terms is written:

\[ \delta U = \delta Q + \delta W \]  

(3)

Figure 35 shows exhaust hot gasses at instance “t”, in an insulated box, in touch from one side to one TEG module. The insulated box implies that there is no other energy interference than with the TEG module. It also means that the pressure drop during the process is ignored; hence no work is done by the gasses. The equation 3 can be therefore simplified as:

\[ \delta U = \delta \dot{Q} \]  

(4)

Variation of internal energy of a ideal gas at constant pressure is calculated by:

\[ \delta \dot{U} = \dot{m}C_p \delta T \]  

(5)

Where \( \dot{m}, C_p \) and \( \delta T \) are mass flow rate, specific heat of air and variation in temperature respectively. Substituting in equation 4 gives:

\[ \delta \dot{Q} = \dot{m}C_p \delta T \]  

(6)
In other words, if a heat flux equal to $\delta Q$ is removed from our imaginary box (figure 35), temperature of the gas inside the box will decrease by the amount of $\delta T$.

On the other hand for the TEG module (figure 25):

$$\dot{Q}_{in} = P + \dot{Q}_{out} \quad (7)$$

Where $\dot{Q}_{in}$, $P$ and $\dot{Q}_{out}$ are heat flux entering the module, electric power and heat flux leaving the TEG module respectively.

Combining equations 6 and 7, considering the fact that $\dot{Q}$ leaving the box (figure 35) enters the TEG module (as $\dot{Q}_{in}$) gives:

$$P|_{T_c}^{T_h} + \dot{Q}_{out}|_{T_c}^{T_h} = \dot{m}C_P(T_G - T_{G,new}) \quad (8)$$

Where $T_h$, $T_c$ and $T_{G,new}$ are TEG module hot side temperature, TEG module cold side temperature and temperature of gas inside the box after the process.

Depending to the conductive coefficient of the material used for the extended surface (heat exchanger), $T_h$ is less than $T_G$ at any instance. In this study it was assumed to be 20 degrees centigrade (although the code gives the option to change this value). $T_c$ was also considered to be 80 degrees centigrade (the reason for this is explained in the next section).

Equation 8 can be rearranged for $T_{G,new}$ as follows:

$$T_{G,new} = T_G - \frac{P|_{T_G}^{T_{G,20}} + \dot{Q}_{out}|_{T_G}^{T_{G,20}}}{\dot{m}C_P} \quad (9)$$

$P$ and $\dot{Q}_{out}$ are calculated using Hi-Z20 data sheet, at corresponding hot and cold side temperatures. Equation 9 gives the temperature of gas inside the imaginary box (exhaust gasses flow at instance t) if one TEG module is attached to the box. Now this process can be repeated several times until there is no energy extractable by TEG module remained in the box. The total power generated by system at instance t, is the sum of individual electric powers calculated in each loop, number of loops gives the number of TEG modules deployed in the TEG system and sum of $\dot{Q}_{out}$ calculated in each loop is the heat flux to be removed by cooling system.

Due to high pressure drop created by excessive number of TEG modules (i.e. a large hot side heat exchanger) the loop cannot be continued until all internal energy in the exhaust gases is extracted. On the other hand, small temperature differences between hot and cold side, results in very low TEG efficiencies. Thus the loop should be stopped using some limiting criteria. These criteria will be explained later in this report.

On the other hand, hot side temperature should not be more than maximum temperature limit defined for the TEG modules. This high temperature in practice shortens the modules’ lifetime and in calculations results in overestimation of the power. Hence, as one more limiting factor, calculations are made base on a defined maximum hot side temperature.

The process described in this section was repeated (via a Matlab code) for every second of the driving cycle and for two locations (EGR and downstream of the downstream of exhaust after treatment) in order to have the electric power generated as a function of time. Values of the electric power was saved in data files and was used in the next step as inputs of the hybrid simulation.
**Verification**

To verify the model, comparison with two independently done calculations (focusing on the extended surfaces) was made (configuration two). The mean value of the electric power was a bit larger that what the other investigations suggest, but in an acceptable range. Further investigation showed that the TEG modules’ data used in this model were more efficient than what was used in two other calculations. That explained well why higher rates of electric power are calculated by the model which was used in this project.

In the meantime, results for configuration one were also compared with other similar practical and theoretical attempts (mentioned in section 1.5 Background). It was again observed that estimated power extracted using this configuration also lies, with good correlation, in the same region as the other investigations show.

**TEG system, configuration two**

In this configuration (figure 36) cells (each contain four TEG modules) are placed in a plane normal to the gas flow direction. Mass flow passing through each cell is therefore the total mass flow rate divided by the number of cells. This configuration offers lower pressure drop, however special attention needs to be paid to heat transfer characteristics of each cell.

![Figure 36. TEG modules placed in configuration two.](image)

The model follows the same theoretical principle as the previous model (configuration one), with a different energy flow pattern. This pattern is shown in figure 37.

Following the same derivation method as what was done for configuration one gives:

\[
T_{G,\text{stage two}} = T_G - \frac{2 \times (p_{10}^{T_{G,20} - 20} + Q_{\text{out}}^{T_{G,20}})_{\text{m}}}{\text{number of cells} \times \eta_{P}} \tag{10}
\]

Once hot and cold side temperatures of TEG modules (placed in both stages) are calculated, the electric power generated by each cell can be calculated using Hi-Z data sheets or its improved (high efficiency) version.
3.5.3 TEG cooling system

Cold side of the TEG system should be cooled down at certain temperatures to guarantee a maximum output electrical power generated by TEG system. This can be done by a heat exchanger, fed by engine cooling water or cooling water circulated in a separate cooling circuit.

The circuit (figure 25) includes the heat exchanger, radiator, fan, water pump, pipes and coolant (water). To model this circuit, data from investigation conducted at Scania was collected and used. Since the calculations are made assuming the fan is running at idle fan speed it consumes no extra power. Thus the power required for cooling is only the power consumed by the pump.

In order to model the required power for the pump, heat flux that should be removed from the TEG surface and the temperature at which this heat flux is taken must be known. The temperature of the coolant is assumed to be in the range 40-50°C (to achieve 80°C as the cold side temperature of the TEG module). Heat flux passing through the TEG is calculated by the TEG model. Calculations showed that the power required to circulate the water in the circuit can be neglected.

3.6 Battery

Investigations regarding to the batteries was the subject of another study conducted in parallel with this study. Therefore detailed information can be found in the corresponding report58.

Application of a battery in a WHR system combined with mild-hybrid system is of importance for two reasons; Time delay in WHR power generating and regenerative braking.

3.6.1 Time delay in WHR power generating

An HDV climbing up-hill and then driven down is shown in figure 38. While the truck is climbing up, high power demand is needed to overcome the extra grade tractive force. As a result a drastic temperature raise occurs at the exhaust manifold. Depending on how many components with how large specific heats exist in between the exhaust manifold and after treatment, there will be a delay until the gas temperature at outlet of after treatment rises. If there is a long positive grade road, temperature of the gasses at outlet of after treatment also increases and therefore more power from WHR is expected.
Now the situation of downhill driving is considered, there is no power demand but there still exists high gas temperatures at after treatment. There will be a time delay until temperature at the outlet of after treatment decreases depending to overall specific heat of the components located in between the exhaust manifold and after treatment. In other words, there is potentially some energy in the exhaust gasses that can be extracted by WHR system, while there is no power demand from the road. This energy can therefore be stored in a battery to be used later, when there is a power demand.

![Figure 38. An HDV in two situations: climbing uphill, going downhill.](image)

### 3.6.2 Regenerative braking

The battery can also be used to create a degree of hybridization, most importantly regenerative braking. In trucks, in particular, regenerative braking can cause relatively more fuel saving compared to passenger cars. The reason for this is that in trucks the brakes are used more often. A combination of regenerative braking and the time delay (discussed in previous section) might lead to use a small size extra battery.

### 3.7 Comparison

Comparisons were made using fuel map of the engine. Percentage of fuel reduction was calculated using equation 11.

\[
\text{Fuel reduction (\%) = } \frac{\text{fuel consumed}_{\text{original}} - \text{fuel consumed}_{\text{hybrid-TEG-Rankine}}}{\text{fuel consumed}_{\text{original}}} \times 100
\]

Output of the engine fuel map (kg/hr) was divided by 3600 (kg/s) and then integrated (kg) to calculate total mass of the fuel that is consumed.

Although practical data regarding to the fuel consumption was available from logged data, this data was not used in comparison, due to a slight difference from calculated fuel consumption using the fuel map. Since fuel map could only be used for calculating fuel consumption in hybrid, TEG or Rankine mode, practical data regarding to fuel consumption was not used for a better comparison.

### 3.8 Assumptions

- Efficiency of AC-DC and DC-DC converters were assumed to be constant. Typical values equal to 97% (for low step-up values) and 0.93% (for high step-up values, full hybrid) were used.
- Belt efficiency (mild-hybrid) was assumed to be 96%.
- Due to the electric machine used in the simulation (maximum power delivered at 1200 RPM, equal to a mean value for diesel engines) a pulley ratio (connects crankshaft to the electric machine) equal to 1 was chosen.
Since data regarding to the engine power (along with other data) for the driving cycle was available, Energy interface between electric system (24V battery and auxiliaries) and hybrid or mild-hybrid system was assumed to be included in the engine power (an alternator was in practice coupled to the engine). In other words the electric machine used in the simulation does not cover the power required by auxiliaries. A simple investigation showed that this simplification does not alter the final results in a large extent.

Data (measured by hybrid department in Scania) for one single electric machine (120kW), was downscaled to the desirable power levels. This, of course, adds some errors to the simulation results however it is believed the errors remain in an acceptable region.

Back pressure, created by an extra obstacle (the WHR) placed in the exhaust pipe, was ignored. Back pressure means a need for more power from the engine which in turn means more fuel consumption. However, it is believed that with a proper design for the heat exchanger, combined with a probable resign of the whole exhaust system, this effect could be well eliminated.

Proper insulation of the exhaust pipe, will positively affect the performance of the WHR system, however this effect is not considered in this study.

Exhaust gasses are assumed to behave as an ideal gas.

The power required for the control unit is neglected.
4 RESULTS AND DISCUSSION

4.1 General considerations

4.1.1 Impact of the battery

Since investigations regarding to the battery, was concept of a parallel study, conducted by Nicklas Enquist\textsuperscript{58}, it was decided to exclude effects of the battery used in simulations here, when it was possible. As a result, where system included a battery, one battery type (lead-acid) was chosen in all cases. If a change in the battery specification was necessary, one single parameter (out of many) was played with (number of cells in parallel). Of course, in practice, there are many factors affecting the design. Impacts of the battery (including the size, battery type, battery configuration etc.) on the same systems investigated here can be found in Nicklas’s report.

4.1.2 Data handling

All original data were provided in excel files, needed to be read and rearranged in a right way, suitable to be used in simulations. It is also faster to read data from Matlab .m files instead of Excel files in particular when data is going to be used in loops. Therefore separate Matlab codes were scripted for this purpose, and data were saved as .m Matlab files.

To calculate the energy generated by TEG system over the driving cycles (time function), results from configuration two was used.

For Rankine cycle, due to different physical requirements, energy can be extracted simultaneously from EGR and exhaust after treatment and therefore in the data used, sum of the power from both locations is considered.

4.1.3 Data analysis

Thermal energy carried by exhaust gasses is proportional to product of mass flow and temperature (formula 5, section 3.6.2 this report). For the engine, EGR and road data used in this study, it was observed that thermal energy content of exhaust gasses at after treatment outlet is 2.6-3.7 times larger than EGR gasses, depending to the driving cycle that is chosen.

On the other hand, temperature at EGR varies in a wider range (90-731°C), compared to outlet of after treatment (101-424°C). In the mean time, for different driving cycles, gasses at EGR have higher average values (332-385°C) compared to gasses at outlet of after treatment (300-337°C).

It can be therefore concluded that more energy can be expected if WHR is located at outlet of after treatment. However (as is discussed in section 3.6.2, TEG modules) higher temperatures at EGR might lead for TEG modules to work at higher efficiencies, resulted in more recovered energy.

4.1.4 Voltage level adjustment

As it was discussed (in section 2.2. Voltage level of the system), corresponding to the power level chosen for the system, voltage level should stay in specific limits. The following logic (implemented by Nicklas Enquist\textsuperscript{58}) was applied to set the voltage level of the system:
Table 1. Voltage level of the system, depending on the hybrid power level

<table>
<thead>
<tr>
<th>Power level</th>
<th>Voltage level</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 kW</td>
<td>24 V</td>
</tr>
<tr>
<td>10 kW ≤ Power level ≤ 15 kW</td>
<td>48 V</td>
</tr>
<tr>
<td>15 kW &lt; Power level ≤ 35 kW</td>
<td>100 V</td>
</tr>
<tr>
<td>35 kW &lt; Power level</td>
<td>650 V</td>
</tr>
</tbody>
</table>

4.1.5 TEG power level

To fulfill TEG power requirements of this project, Hi-Z20 modules were used in the simulated TEG system when they are installed following configuration two (section 3.6.2, TEG modules). After simulating the TEG system (located at outlet of after treatment) over the driving cycle, it was seen that using Hi-Z20 and modified Hi-Z20 modules, it is possible to generate maximum powers equal to 1.1 kW (named TEGA-ATS), 5 kW (named TEGB-ATS) with mean values equal to 510 W, 2.25 kW respectively. It was also seen that if a larger TEG system with improved modules is used a maximum power equal to 10kW (named TEGC-ATS) with a mean value equal to 3.9 kW can be reached. Although, due to large space required for the heat exchanger, the latter system is oversized and does not seem to be realistic, however the results of simulation is presented for comparison reasons. In figure 39 electric power generated by the first TEGA-ATS, when it is placed at outlet of after treatment and simulated using logged data for the driving cycle (Södertälje-Norrköping-Södertälje) is shown.

Figure 39. Electric power generated by TEG system (maximum power 1.1 kW), when it is located at outlet of after treatment. Driving cycle: Södertälje-Norrköping-Södertälje.

These three TEG systems were chosen as reference for the TEG system, and then the same TEG systems is placed at EGR and simulated (called TEGA-EGR, TEGB-EGR and TEGC-EGR respectively).

As another alternative, it was assumed that TEG systems are placed simultaneously at outlet of after treatment and EGR. i.e. two systems are installed on the vehicle. The systems are called TEGA-TOT, TEGB-TOT and TEGC-TOT.
Once the data file containing power generated by TEG system at any instance (for two TEG system locations) was created, the data files were then used in hybrid simulation as inputs.

### 4.1.6 TEG power, used in a non-hybrid system

For a non-hybrid system, TEG system is aimed to supply auxiliary power that for the truck under investigation is approximated to be constant equal to 715 W. If, for example, TEGA-ATS is used (figure 39) generated powers more than 715 W will be wasted. It is possible to adopt a small control system and use a portion of the battery to store this extra power and deliver it later to the electric system, when power generated by TEG system is less than 715 W. This system is called TEGA-EL. Results of simulation of such a design is shown in figure 40.

![Figure 40. Improvement in TEG power delivered to electrical system.](image-url)
4.2 Results and discussion

4.2.1 System I

System is shown in figure 41.

![Figure 41. WHR (Rankine or TEG) is connected to a full hybrid system, 120 kW, 650 V. Electric system is connected to the high voltage line via a DC-DC converter.](image)

WHR systems (Rankine and TEG) are connected individually to a full hybrid 120kW system. Mode two of Rankine system (where all Rankine mechanical power is delivered mechanically to the power train, section 3.3. hybrid defined functions) is in fact a non-hybrid system, however results regarding to this mode is included in this assignment.

Table 2. Application of a Rankine system in a full hybrid system.

<table>
<thead>
<tr>
<th>Rankine mode</th>
<th>Fuel reduction (percent)</th>
<th>System description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode one</td>
<td>4.81</td>
<td>All Rankine power is converted to electricity, and then delivered to hybrid system.</td>
</tr>
<tr>
<td>Mode two</td>
<td>3.55</td>
<td>All Rankine power is delivered directly to the power train mechanically, <strong>non-hybrid system.</strong></td>
</tr>
<tr>
<td>Mode three</td>
<td>5.76</td>
<td>Combination of two above modes.</td>
</tr>
</tbody>
</table>

Results of application of TEG system in a full hybrid system is presented in table 3.
Table 3. Application of TEG system in a full hybrid system.

<table>
<thead>
<tr>
<th>TEG mode</th>
<th>Fuel reduction (percent)</th>
<th>System description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEGA-ATS</td>
<td>1.98</td>
<td>TEG system (1.1 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGA-EGR</td>
<td>1.86</td>
<td>TEG system (1.1 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGA-TOT</td>
<td>2.26</td>
<td>Two TEG units (1.1 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
<tr>
<td>TEGB-ATS</td>
<td>3.05</td>
<td>TEG system (5 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGB-EGR</td>
<td>2.45</td>
<td>TEG system (5 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGB-TOT</td>
<td>3.91</td>
<td>Two TEG units (5 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
<tr>
<td>TEGC-ATS</td>
<td>4.06</td>
<td>TEG system (10 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGC-EGR</td>
<td>3.40</td>
<td>TEG system (10 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGC-TOT</td>
<td>5.85</td>
<td>Two TEG units (10 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
</tbody>
</table>

For a full hybrid system without WHR, simulation shows 1.55% in fuel reduction. In other words 1.55% of the fuel reductions shown in tables 2 and 3 (except Rankine mode two, which is a non-hybrid system), comes directly from braking power that is highly dependent to the road and driving condition rather than engine performance.

It should be reminded that TEGC units (highlighted with red) require a large space and therefore is not a realistic choice. However results are presented for comparison.

Mode one (Rankine system) shows a better performance compared to mode two. There will be losses (typically 60-70%) when mechanical power is converted to electricity via an alternator. But mode one takes advantage full hybrid system in two extents: regenerative braking and the battery, where electrical power can be stored if there is no power demand at power train. Mode three combines advantages of modes one and two including: less losses when the power is mechanically delivered to the power train, regenerative braking and the battery’s capacity from full hybrid system. Thus mode three show a better performance.

TEGB-TOT, improved TEG modules placed at ATS and EGR, shows 3.91% in fuel reduction comparable with 3.55% from Rankine mode two. However TEGB-TOT requires a greater investment due to full hybrid system. Decision will be a compromise between practical as well as economical issues.
4.2.2 System II

System is shown in figure 42.

In terms of simulation and calculation of fuel reduction percentages, this system is identical to system one with an extra DC-DC two directional converter placed in the system. In other words the efficiency of this extra component affects performance of the system. Results for a Rankine and TEG systems are shown in tables 4 and 5, respectively.

Table 4. Application of a Rankine system in a full hybrid system

<table>
<thead>
<tr>
<th>Rankine mode</th>
<th>Fuel reduction (percent)</th>
<th>System description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode one</td>
<td>4.74</td>
<td>All Rankine power is converted to electricity and then delivered to hybrid system.</td>
</tr>
<tr>
<td>Mode two</td>
<td>3.55</td>
<td>All Rankine power is delivered directly to the power train mechanically, <strong>non-hybrid</strong>.</td>
</tr>
<tr>
<td>Mode three</td>
<td>5.69</td>
<td>Combination of two above modes.</td>
</tr>
</tbody>
</table>
Table 5. Application of TEG system in a full hybrid system.

<table>
<thead>
<tr>
<th>TEG mode</th>
<th>Fuel reduction (percent)</th>
<th>System description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEGA-ATS</td>
<td>1.95</td>
<td>TEG system (1.1 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGA-EGR</td>
<td>1.83</td>
<td>TEG system (1.1 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGA-TOT</td>
<td>2.20</td>
<td>Two TEG units (1.1 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
<tr>
<td>TEGB-ATS</td>
<td>2.93</td>
<td>TEG system (5 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGB-EGR</td>
<td>2.36</td>
<td>TEG system (5 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGB-TOT</td>
<td>3.70</td>
<td>Two TEG units (5 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
<tr>
<td>TEGC-ATS</td>
<td>3.81</td>
<td>TEG system (10 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGC-EGR</td>
<td>3.22</td>
<td>TEG system (10 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGC-TOT</td>
<td>5.45</td>
<td>Two TEG units (10 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
</tbody>
</table>

All results (except Rankine mode two) are slightly lower than results in system I. The reason for this is placement of a DC-DC converter in the layout that its efficiency affects the energy flow almost all the time. However this layout make it possible to have a standard unit (WHR compatible with regular electric system) that can be used as a modular unit, with capability to be installed on different trucks.
4.2.3 **System III**

System is shown in figure 43.

![Diagram of System III](image)

**Figure 43.** WHR (Rankine or TEG) is connected to a full hybrid system, 120 kW, 650 V. A smaller battery with lower voltage level is used.

Since in this system, impact of the battery is the main concern, variations in percentage of fuel reduction versus the battery’s capacity (represented by number of cells in parallel) is plotted. It should be borne in mind that these curves must only be used for having a general idea of the impact. For detailed and more precise investigation regarding to the batteries and their impact and also definition of the term “*number of cells*” used here, Nicklas Enquist’s report is recommended.

It is seen (figure 44) that in all cases if the maximum number of cells is reached, results identical to system 1 is obtained.

![Graph of battery impact](image)

**Figure 44.** Impact of capacity of the battery on fuel consumption, for different systems.

It is also seen that a maximum performance can be reached at cells’ number equal to 6. Increasing the number of cells to values more than limit causes a slight negative impact.
4.2.4 System IV

System is shown in figure 45.

Two different TEG systems (1.1 and 5kW) are connected to a mild-hybrid system (5kW). Results are shown in table 6.

Table 6. Percentage of fuel reduction, for a mild-hybrid system connected to TEG systems.

<table>
<thead>
<tr>
<th>TEG mode</th>
<th>Fuel reduction (percent)</th>
<th>System description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEGA-ATS</td>
<td>0.27</td>
<td>TEG system (1.1 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEGA-EGR</td>
<td>0.30</td>
<td>TEG system (1.1 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEGA-TOT</td>
<td>0.56</td>
<td>Two TEG units (1.1 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
<tr>
<td>TEBG-ATS</td>
<td>1.04</td>
<td>TEG system (5 kW) is placed downstream of after treatment</td>
</tr>
<tr>
<td>TEBG-EGR</td>
<td>0.86</td>
<td>TEG system (5 kW) is placed at EGR</td>
</tr>
<tr>
<td>TEBG-TOT</td>
<td>1.77</td>
<td>Two TEG units (5 kW each) is placed downstream of after treatment and at EGR</td>
</tr>
</tbody>
</table>

This system represents a low voltage (therefore low hybrid power) level, with no extra battery. Hence it is not affected by regenerative braking in a great extent. It is also a 24 volt system, compatible with trucks currently in production line. 1.77% can be therefore considered as a good performance.
4.2.5 System V

System is shown in figure 46.

WHRs (Rankine or TEG systems) are connected individually to a 48 V mild hybrid system. Reduction of fuel consumption in every combination is plotted (figure 47) versus the hybrid power level. In order to exclude impact of the battery, an oversized battery was chosen and therefore results in this section are the maximum fuel reduction possible. Again, it must be reminded that these curves are only useful for general understanding of the system. More precise simulations regarding to impact of the battery is found in Nicklas Enquist’s report.

Figure 46. WHR (Rankine or TEG) is connected to a mild-hybrid system, 5-15 kW, 48 V. A small battery and a control unit is added.

Figure 47. Impact of hybrid power level on fuel consumption, in different systems.
As it is seen in figure 47, impact of regenerative braking (no WHR) constantly increases as hybrid power level increases. Since a battery sized for a full hybrid system is chosen, impact of regenerative braking keeps increasing up to 1.55% if hybrid power level reaches to 120 kW (system I).

TEG based WHRs and Rankine mode three system show less improvement as the hybrid power level increases. Moreover, part of the slight improvement comes from regenerative braking that is dependant to the road and driving condition. It is therefore seen that for the mentioned WHRs, hybrid power level might be limited to lower levels.

Rankine mode one, however, shows a different behavior. This is due to higher electrical powers handled by this system. It is seen that hybrid power level for this system can be chosen at higher levels.
4.2.6 System VI

System is shown in figure 48.

Figure 48. WHR (TEG) is connected to a non-hybrid system.

TEGA-ATS and TEGA-EGR systems are used, without modification and with modification in electric system. The modification is described in section 4.1.6 TEG power, used in a non-hybrid system. Results are shown in table 7. As it is seen in the table, improvement in the electric system contributes as small as 0.04%-0.05% in fuel reduction.

Table 7. Reduction of fuel consumption, if TEG systems are used in non-hybrid system.

<table>
<thead>
<tr>
<th></th>
<th>TEGA-ATS</th>
<th>TEGA-EGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original electric system</td>
<td>0.61</td>
<td>0.80</td>
</tr>
<tr>
<td>Modified electric system</td>
<td>0.66</td>
<td>0.84</td>
</tr>
</tbody>
</table>

For better understanding, the system was also simulated assuming 715 W could be constantly generated by TEG system. It was seen that fuel consumption in such a system would be reduced by almost one percent (0.9966%). This value can be considered as the upper threshold or maximum achievable rate for this system.
### Conclusion

Results from simulations of all six systems are presented in Table 8.

#### Table 8. Results

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V Hybrid power level (kW)</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of cells</td>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Rankine, mode 1</td>
<td>4.81</td>
<td>4.74</td>
<td>3.27 4.10 4.86</td>
<td>N/A</td>
<td>2.46</td>
<td>2.89</td>
</tr>
<tr>
<td>Rankine, mode 2</td>
<td>3.55</td>
<td>3.55</td>
<td>3.55 3.55 3.55</td>
<td>N/A</td>
<td>3.55</td>
<td>3.55</td>
</tr>
<tr>
<td>Rankine, mode 3</td>
<td>5.76</td>
<td>5.69</td>
<td>4.23 5.10 5.85</td>
<td>N/A</td>
<td>4.00</td>
<td>4.09</td>
</tr>
<tr>
<td>TEG-TOT</td>
<td>2.26</td>
<td>2.20</td>
<td>0.76 1.57 2.32</td>
<td>0.56</td>
<td>0.68</td>
<td>0.77</td>
</tr>
<tr>
<td>TEGB-TOT</td>
<td>3.91</td>
<td>3.70</td>
<td>2.37 3.20 3.98</td>
<td>1.77</td>
<td>2.09</td>
<td>2.28</td>
</tr>
<tr>
<td>TEGC-TOT</td>
<td>5.85</td>
<td>5.45</td>
<td>4.27 5.12 5.91</td>
<td>N/A</td>
<td>3.56</td>
<td>3.86</td>
</tr>
<tr>
<td>TEG-ATS</td>
<td>1.98</td>
<td>1.95</td>
<td>0.46 1.26 2.02</td>
<td>0.27</td>
<td>0.40</td>
<td>0.48</td>
</tr>
<tr>
<td>TEG-EGR</td>
<td>1.86</td>
<td>1.83</td>
<td>0.45 1.25 1.94</td>
<td>0.30</td>
<td>0.40</td>
<td>0.48</td>
</tr>
<tr>
<td>no WHR</td>
<td>1.55</td>
<td>1.55</td>
<td>0.16 0.98 1.66</td>
<td>0.005</td>
<td>0.11</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Each of the six different systems investigated in this study, are based on fuel economy viewpoints, implemented in different ways depending on what criterion is the most in concern. Like every other engineering problem, decision is always a compromise between costs and benefits. Results of this study clearly approve complexity of the system under investigation, with a multi-parameter nature. Results of this study (table 8) could be used as inputs for economical analysis.

Full hybrid system, as it was expected, shows the best performance (fuel reduction up to 5.8%). However it is costly and therefore a comprehensive economical study is required if development of a full hybrid system is to be decided. Feasibility of a full hybrid system, for long haulage application, also depends on the conditions in which the vehicle supposed to be driven. However, when a WHR is added, full hybrid system might be more feasible.

If practical issues regarding to implementation of a Rankine system is resolved, in general it shows more promising short-term future, whether it is implemented in a non-hybrid (3.55%), mild hybrid (4%) or full hybrid system (5.8%). However it should be kept in mind that Rankine cycle holds a long history in industry and it can be considered as a fully developed concept, with apparently no sign of a significant improvement in the overall efficiency. From this perspective special attention should be paid in long-term planning.

TEG system with current technology does not seem to be beneficial (maximum 2%, mostly, 1.5%, from regenerative braking). However TEG system, compared to Rankine system, is easier to be practically implemented. In the meantime there are claims of better performances achieved at laboratories. The present study shows that in short term plans fuel reductions between 1.5-3% might be assumed, for mild hybrid or full hybrid systems.

Impact of the storage (battery) is significant (figures 43 to 51), and in close relation with the hybrid power level (figures 52 to 59). A limited power level (say 5 kW), limits the battery’s capacity in such a way number of cells in parallel more than 2 only causes 0.2% fuel reduction (figure 52).

On the other hand, the battery might limit the performance of the system, in a way that increase in hybrid power level does not help any more (figure 53) or even a negative impact due to increased losses in electric machine (figure 54).
6 FUTURE WORK

Since the present investigation was conducted in a pre-development stage, this study aimed on simulating the system in a general level of simulation precision. It was planned to make simplifications and avoid in detailed engineering calculations for different components. Therefore results can only be used as a road map for future. Nevertheless during the project and while facing different challenges, a list of suggestions was created and completed, as follows:

- More precise model for TEG modules could be made, representing high efficiency modules working at higher temperatures. In order to create these kind of model both mathematical method and using data sheets could be followed. However, in both cases, it is important to combine heat transfer (energy equations) with Seebeck effects (electrical equations) and solve the problem to cover transient behavior of the TEG module.
- A better arrangement of different TEG modules, placed in the heat exchanger could be investigated. TEG modules have different “best performance” working points. Hence placement of Different TEG modules in different stages of heat exchanger might lead to a better overall efficiency.
- An economical analyse for hybrid and also WHR systems gives a clearer picture and paves the path for making final decisions. Investigations include profitability of high rate investing on these systems in compromise with fuel expences as well as polution reduction necessities.
- The way that thermal energy is extracted from the exhaust gasses could be investigated. Higher ratios of heat flux to back pressure, the temperature at which the heat flux is delivered and also methods to increase efficiency of the heat exchanger might be parts of the investigation. A better model for the heat exchanger can be made afterwards.
- Intelligent cooling system might be investigated in order to keep the cold side temperature of TEG modules at its best value, compromising the output power and water pump power requirements.
- More accurate performance maps could be investigated for all hybrid components, to be used in the simulation. Hybrid components include: electric machine, DC-DC and DC-AC converters, inverter, battery and control unit.
- Gathering logged data from driving cycles having power required by auxiliaries excluded from the engine power, might lead to more accurate results from the simulation.
- Simulating the system over different driving cycles, gives better understanding regarding to in which condition what system performs better.
- Investigations regarding to impact of insulating the exhaust pipe, might give a better understanding of more efficient WHR systems, due to increased thermal energy carried by the gasses where WHR is installed.
REFERENCES


A mathematical model for thermoelectric generators

A mathematical model for thermoelectric generators, if it is well-developed and verified, could be very useful for at least two reasons.

Firstly, it makes the model more generalized, independent of data provided by suppliers. Suppliers usually provide the most important characteristic specification under specific conditions. These data is adequate for developed applications where other performance data is available. However, when a parametric study with a set of uncertainties is to be conducted, more flexibility is needed.

Secondly, since the model is based on material properties it is more reliable and also convenient for future study. New materials are tested in labs and reports are published containing material properties. These data can be used to anticipate what might happen in future.

In contrast, mathematical models can be used only if they are approved by a trustable verification process, otherwise mathematical models might cause disastrous misleading.

Figure a.1 illustrates one TEG elements (a pair of P and N type) placed in a heat source and sink, connected to an electrical load (resistance). Part of the thermal energy carried by exhaust gasses \( Q_{\text{exhaust}} \), is extracted by a heat exchanger \( Q_{\text{in}} \) symbolized by extended surfaces, fins. and is transferred to the TEG elements. The TEG elements are cooled from the other side by a coolant \( Q_{\text{out}} \).

Due to the heat flux passing through the TEG elements, a current \( I \) is created and the energy balance causes hot and cold surfaces of the elements to remain at unknown temperatures \( T_h \) and \( T_c \). In order to use numerical methods, TEG elements are discitized into several small sub-elements (three sub-elements are shown for illustrative purposes).
A.1 Governing equations of TEG elements

Governing equations for p- and n- thermoelectric elements can be derived from energy balance as follows:

\[
\frac{C_p \rho_p}{A_p} \frac{\partial T_p}{\partial t} = k_p \left( \frac{\partial^2 T_p}{\partial x^2} + \frac{\partial^2 T_p}{\partial y^2} + \frac{\partial^2 T_p}{\partial z^2} \right) - \frac{\mu_p}{A_p} I \frac{\partial T_p}{\partial x} + \frac{\varepsilon_p}{A_p} I^2 \quad (a.1)
\]

\[
\frac{C_n \rho_n}{A_n} \frac{\partial T_n}{\partial t} = k_n \left( \frac{\partial^2 T_n}{\partial x^2} + \frac{\partial^2 T_n}{\partial y^2} + \frac{\partial^2 T_n}{\partial z^2} \right) + \frac{\mu_n}{A_n} I \frac{\partial T_n}{\partial x} + \frac{\varepsilon_n}{A_n} I^2 \quad (a.2)
\]

In order to increase efficiency, p- and n- elements are thermally insulated on their side walls and therefore equations a.1 and a.2 can be rewritten in one dimensional form:

\[
\frac{C_p \rho_p}{A_p} \frac{\partial T_p}{\partial t} = k_p \left( \frac{\partial^2 T_p}{\partial x^2} \right) - \frac{\mu_p}{A_p} I \frac{\partial T_p}{\partial x} + \frac{\varepsilon_p}{A_p} I^2 \quad (a.3)
\]

\[
\frac{C_n \rho_n}{A_n} \frac{\partial T_n}{\partial t} = k_n \left( \frac{\partial^2 T_n}{\partial x^2} \right) + \frac{\mu_n}{A_n} I \frac{\partial T_n}{\partial x} + \frac{\varepsilon_n}{A_n} I^2 \quad (a.4)
\]

A.2 Electric circuit equations

Electric power generated in p- or n- legs is can be calculated as:

\[
P_{el} = V \cdot I = \alpha_{pn} \cdot T \cdot I \quad (a.5)
\]

Where

\[
\alpha_{pn} = \alpha_p - \alpha_n \quad (a.6)
\]

Voltage in an open-circuit is calculated by:

\[
V_{\text{open-circuit}} = \alpha_{pn} (T_h - T_c) \quad (a.7)
\]

With a resistive load \((R_0)\), electric current and voltage is calculated as:

\[
I = \frac{V_{\text{open-circuit}}}{R_0 + R} \quad (a.8)
\]

\[
V = V_{\text{open-circuit}} - I \cdot R \quad (a.9)
\]

With

\[
R = \frac{\varepsilon_p L}{A_p} + \frac{\varepsilon_n L}{A_n} \quad (a.10)
\]

A.3 Boundary conditions:

Boundary conditions are determined by heat fluxes and electric energy flow at hot and cold sides of the p- and n-elements:

\[
\dot{Q}_{in} + P_{el-n} h = P_{el-p} \big|_h + \dot{Q}_{conduction-p} \big|_h + \dot{Q}_{conduction-n} \big|_h \quad (a.11)
\]
\[
\dot{Q}_{out} + P_{el-n} c = P_{el-p} \big|_c + \dot{Q}_{conduction-p} \big|_c + \dot{Q}_{conduction-n} \big|_c \quad (a.12)
\]

Since the same electric current is passing through the circuit, equations a.11 and a.12 can be written as follows:

\[
\dot{Q}_{in} = \dot{Q}_{conduction-p} \big|_h + \dot{Q}_{conduction-n} \big|_h \quad (a.13)
\]
\[
\dot{Q}_{out} = \dot{Q}_{conduction-p} \big|_c + \dot{Q}_{conduction-n} \big|_c \quad (a.14)
\]

or

\[
\dot{Q}_{in} = -k_p A_p \frac{\partial T_p}{\partial x} \big|_h - k_n A_n \frac{\partial T_n}{\partial x} \big|_h \quad (a.15)
\]
\[
\dot{Q}_{out} = -k_p A_p \frac{\partial T_p}{\partial x} \big|_c - k_n A_n \frac{\partial T_n}{\partial x} \big|_c \quad (a.16)
\]

Thus the boundary conditions at instance “t” are therefore:

\[
\dot{Q}_{in}(t) = -k_p A_p \frac{\partial T_p(t)}{\partial x} \big|_h - k_n A_n \frac{\partial T_n(t)}{\partial x} \big|_h \quad (a.17)
\]
\[
\dot{Q}_{out}(t) = -k_p A_p \frac{\partial T_p(t)}{\partial x} \big|_c - k_n A_n \frac{\partial T_n(t)}{\partial x} \big|_c \quad (a.18)
\]

A.4 Initial conditions:

At the first instance (t=0) all temperatures (hot and cold side and also along the TEG elements) are given, typically ambient temperature.

A.5 Solution method

As it is seen governing equations a.1 and a.2 form a system of time dependent non-linear second order differential equations which in general can only be solved using numerical methods.

An explicit forward differential approximation in time and central difference method in space is used to solve the system of equations. In order to approximate temperatures along the p and n elements, they are divided up to small parts. The accuracy of results obviously depends to the number of the divided elements.

\[
\frac{\partial T_{p,l}^m}{\partial t} = \frac{T_{p,l+1}^m - T_{p,l}^m}{\Delta t} \quad (a.19)
\]
\[
\frac{\partial T_{n,l}^m}{\partial t} = \frac{T_{n,l+1}^m - T_{n,l}^m}{\Delta t} \quad (a.20)
\]
For each internal node (node number \( m \): \( 2 \leq m \leq \text{number of nodes} - 1 \)), first and second order derivation of temperatures can be approximated as follows:

\[
\frac{\partial T_{p,t}^m}{\partial x} = \frac{T_{p,t}^{m+1} - T_{p,t}^{m-1}}{2\Delta x} \quad (a.20)
\]

\[
\frac{\partial T_{n,t}^m}{\partial x} = \frac{T_{n,t}^{m+1} - T_{n,t}^{m-1}}{2\Delta x} \quad (a.21)
\]

\[
\frac{\partial^2 T_{p,t}^m}{\partial x^2} = \frac{T_{p,t}^{m+1} - 2T_{p,t}^m + T_{p,t}^{m-1}}{\Delta x^2} \quad (a.22)
\]

\[
\frac{\partial^2 T_{n,t}^m}{\partial x^2} = \frac{T_{n,t}^{m+1} - 2T_{n,t}^m + T_{n,t}^{m-1}}{\Delta x^2} \quad (a.23)
\]

Substitution of the above approximations in the governing equations gives:

\[
C_p \rho_p \frac{T_{p,t}^{m+1} - T_{p,t}^m}{\Delta t} = k_p \frac{T_{p,t}^{m+1} - 2T_{p,t}^m + T_{p,t}^{m-1}}{\Delta x^2} - \frac{\mu_p}{\Delta t} \frac{T_{p,t}^{m+1} - T_{p,t}^{m-1}}{2\Delta x} + \frac{\epsilon_p}{\Delta t} I^2 \quad (a.24)
\]

\[
C_n \rho_n \frac{T_{n,t}^{m+1} - T_{n,t}^m}{\Delta t} = k_n \frac{T_{n,t}^{m+1} - 2T_{n,t}^m + T_{n,t}^{m-1}}{\Delta x^2} + \frac{\mu_n}{\Delta t} \frac{T_{n,t}^{m+1} - T_{n,t}^{m-1}}{2\Delta x} + \frac{\epsilon_n}{\Delta t} I^2 \quad (a.25)
\]

Rearranging to calculate \( T_{p,t}^m \) and \( T_{n,t}^m \) in terms of \( T_{m-1}^m, T_m^m \) and \( T_{m+1}^m \) gives:

\[
T_{p,t}^m_{t+1} = \left[ s_p^1 T_{p,t}^{m-1} + s_p^2 T_{p,t}^m + s_p^3 T_{p,t}^{m+1} + u_p^4 \right] \Delta t + T_{p,t}^m \quad (a.26)
\]

\[
T_{n,t}^m_{t+1} = \left[ s_n^1 T_{n,t}^{m-1} + s_n^2 T_{n,t}^m + s_n^3 T_{n,t}^{m+1} + u_n^4 \right] \Delta t + T_{n,t}^m \quad (a.27)
\]

With:

\[
s_p^1 = \left( \frac{k_p}{C_p \rho_p \Delta x^2} + \frac{\mu_p}{2A_p C_p \rho_p \Delta x} \right) \quad (a.28)
\]

\[
s_p^2 = \left( -\frac{2k_p}{C_p \rho_p \Delta x^2} \right) \quad (a.29)
\]

\[
s_p^3 = \left( \frac{k_p}{C_p \rho_p \Delta x^2} - \frac{\mu_p}{2A_p C_p \rho_p \Delta x} \right) \quad (a.30)
\]

\[
s_p^4 = \frac{\epsilon_p}{A_p^2 C_p \rho_p} I^2 \quad (a.31)
\]

And

\[
s_n^1 = \left( \frac{k_n}{C_n \rho_n \Delta x^2} - \frac{\mu_n}{2A_n C_n \rho_n \Delta x} \right) \quad (a.32)
\]

\[
s_n^2 = \left( -\frac{2k_n}{C_n \rho_n \Delta x^2} \right) \quad (a.33)
\]

\[
s_n^3 = \left( \frac{k_n}{C_n \rho_n \Delta x^2} + \frac{\mu_n}{2A_n C_n \rho_n \Delta x} \right) \quad (a.34)
\]

\[
s_n^4 = \frac{\epsilon_n}{A_n^2 C_n \rho_n} I^2 \quad (a.35)
\]
Or in matrix form:

\[ [T]_{p,t+1} = ([S]_p \times [T]_{p,t}^{h,c} + [U]_p) \Delta t + [T]_{p,t} \]  

(a.36)

\[ [T]_{n,t+1} = ([S]_n \times [T]_{n,t}^{h,c} + [U]_n) \Delta t + [T]_{n,t} \]  

(a.37)

With (n.o.n = number of nodes):

\[ [T]_p = \begin{bmatrix}
T_p^2 \\
T_p^3 \\
\vdots \\
T_{p}^{\text{number of nodes}-1}
\end{bmatrix}_{(n.o.n-2)\times 1} \]  

(a.38)

\[ [S]_p = \begin{bmatrix}
s_p^1 & s_p^2 & s_p^3 & 0 & \cdots & 0 \\
0 & s_p^1 & s_p^2 & s_p^3 & 0 & \cdots \\
0 & 0 & \vdots & \ddots & \vdots \\
0 & \cdots & 0 & s_p^1 & s_p^2 & s_p^3 \\
0 & \cdots & 0 & s_p^1 & s_p^2 & s_p^3
\end{bmatrix}_{(n.o.n-2)\times n.o.n} \]  

(a.39)

\[ [T]_{p}^{h,c} = \begin{bmatrix}
T_h \\
[T]_p \\
T_c
\end{bmatrix}_{n.o.n\times 1} \]  

(a.40)

\[ [U]_p = \begin{bmatrix}
s_p^4 \\
\vdots \\
s_p^4
\end{bmatrix}_{n.o.n \times 1} \]  

(a.41)

Corresponding matrixes for “n” element can be obtained by changing “p” subscriptions to “n”

**A.6 Discretizing boundary conditions:**

First ordered derivation at walls, can be discretized as the following:

\[ \frac{\partial T_p(t)}{\partial x} \bigg|_h = \frac{T_h^p(t) - T_h(t)}{\Delta x} \]  

(a.42)

\[ \frac{\partial T_p(t)}{\partial x} \bigg|_c = \frac{T_c(t) - T_{p,n.o.n-1}}{\Delta x} \]  

(a.43)
Substituting the above terms in the boundary condition gives a system of two linear equations, which can be solved for two unknowns $T_h$ and $T_c$.

The model is schematically shown in figure a.2.
Figure a.2. Mathematical model for a TEG element.
A.7 Algorithm

The algorithm used for a Matlab code is shown in figure a.3.

Figure a.3. The algorithm used to implement mathematical model for a TEG module in Matlab.
APPENDIX: B

A test set-up, to measure real-time performance of a thermoelectric generator

Complexities in mathematical modeling of a thermoelectric generator under transient thermal and electrical loads, implies a need to finding reliable verification method.

In the meantime, performance of a waste heat recovery system is highly dependent to its basic component i.e. thermoelectric modules. Although every supplier provides datasheets good enough to make general decisions, tuning the design of a waste heat recovery system which normally works under transient conditions makes it necessary to have more detailed data regarding to performance under simulated working condition.

A well-designed test set-up can therefore be helpful in order to whether verify calculations or create practical data (look-up tables, for example). Due to the same reason and since a mathematical model for thermoelectric generator was first implemented, a test was also conducted. Eventually, however, data from suppliers were used to predict electrical power generated by thermoelectric generator. Nevertheless test set-up and the method used are presented here.

From user point of view, transient performance of a thermoelectric generator is influenced by the parameters listed below:

- Heat flux, entering the module from the hot side
- Temperature at the hot side
- Heat flux, leaving the module from the cold side
- Temperature at the cold side
- Electrical resistance of the load

All the above mentioned parameters might vary in time. In practice there are also interconnections between values of these parameters. Variations of the load resistance, for instance, will affect heat fluxes as well as temperatures. It is therefore important to have real-time simultaneously measured values for the above mentioned parameters.

Test set-up (figure b.1) basically consists of a heat source, two temperature sensors, two heat flux sensors, one TEG module, a heat sink, variable resistance, measuring tools (volt meter, ampere meter, temperature and heat flux indicators) and a clamping system to keep the proper contact pressure (Thermal grease must be used to reduce heat transfer contact resistance).
The test set-up used in this project was a modified-adopted version of the above mentioned set-up. Since heat flux sensors were not available, two more TEG modules were used instead, as is described below. A digital data logger was also used to record all the parameters simultaneously at any instance.

**B.1 Heat flux measurements**

Since heat flux sensors were not available for this project, conductive heat transfer formulas were used in combination with TEG modules, as temperature difference sensors as it is explained below.

Due to basic heat transfer formulas, heat flux passing through an object is approximated by:

\[
\dot{Q} = kA \frac{\Delta T}{\Delta x}
\]  

(b.1)

Where \( k \) is conductive heat transfer coefficient, \( A \) is the area through which heat flux is passing and \( \Delta T \) is the temperature difference along the distance \( \Delta x \). In other words, \( \Delta T \) is a measure of the heat flux for a layer with known properties and dimensions. Therefore a TEG module can be used as a thermocouple in order to 1. Create and measure \( \Delta T \), 2. Let heat flux passes through and 3. Simulate a thin layer on which the simplified heat transfer formula remains valid.

**B.2 TEG calibration, as a thermocouple**

A test set-up (figure b.2) was used to measure open-circuit voltage with respect to temperatures at hot and cold side.

In order to make sure the output voltage created by the TEG and corresponding temperature difference creates a one-to-one correspondence function, the test was planned in such a way that the same temperature differences were created in different temperature regions (100-80°C and 60-40°C, for example, both create 20°C as temperature difference) and the open circuit voltage was measured continuously. As it is seen in figure b.3, open circuit voltage follows has linear relationship with temperature difference. Multiple lines in the middle of the curve represent same temperature differences created in different temperature regions.
Figure b.2. Test set-up to investigate open circuit voltage of a TEG module.

Figure b.3. Open circuit voltage created by the TEG module subjected to different temperature difference.

**B.3 Complete test set-up**

A set-up consisting of one heat source, one heat sink, three TEGs, two temperature sensors, a resistance, data logger and a computer (with corresponding software installed) was utilized to conduct the test (figures b.4 and b.5).
Heat flux entering and leaving the main TEG (the middle one) can be calculated as described in the previous section. Temperatures at hot and cold side of the main TEG is calculated using temperature differences presented by open circuit voltages. Finally the output power is calculated by multiplying the current and voltage measured for the main TEG.

Figure b.4. Schematic view of the complete test set-up.

Figure b.5. The complete test set-up. Electrical heater and tap water were used as heat source and heat sink. The photo is taken in one of primary stages of the test, therefore an anlogue thermometer and two multimeters are seen, instead of a data logger. A digital data logger and a computer were later used in the set-up.

Heat flux entering and leaving the main TEG (the middle one) can be calculated as described in the previous section. Temperatures at hot and cold side of the main TEG is calculated using temperature differences presented by open circuit voltages. Finally the output power is calculated by multiplying the current and voltage measured for the main TEG.