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THERMAL AND ENVIRONMENTAL ASSESSMENT OF A CONCEPTUAL WASTE HEAT RECOVERY SYSTEM FOR AUTOMOTIVE APPLICATION

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Abstract

Global energy consumption projections for the period 2001-2025 indicate a growth from 4.26×10^{14} to 6.57×10^{14} MJ, an increase of almost 54% [1]. Carbon dioxide emissions are also expected to grow at the same rate increasing from 23,563 million metric tons in 2001 to 37,124 million metric tons in 2025. Growth of CO_2 emissions from mobile and stationary sources can be mitigated by technology improvements to increase fuel economy; however this is unlikely to have a noticeable effect as fuel economy of vehicles are projected to improve only slightly above the reference year level. Thermoelectric heat-to-electricity conversion is a possible solution to the recovery of part of the large waste heat streams in heat engines thereby moderating CO_2 emissions by the transportation sector. In the context of the design process, this possibility is presented in the paper as an alternative conceptual design to the traditional on-board power unit (alternator). As a design exercise it does not follow a prescriptive model and deals mainly with the environmental implications of an alternative conceptual design. This limits its applicability to illustrating the methodology an environmental engineer may use to assess the environmental impact of alternative design ideas in a classical design process model. The analysis shows tangible improvements in both fuel economy and environmental impact.

Keywords: Environmental, conceptual design, thermoelectrics, vehicle

1. Introduction

As a result of steady increase of electronic content of motor vehicles the demand for onboard electrical energy has grown from 500 W in 1970 to over 2000 W in recent times. In order to accommodate further growth of electrical power requirement in motor vehicles, expected to exceed the 10 kW mark in some models by 2010, the automotive industry is considering a move from the 14 V system to 42 V electrical system. The present day alternators can produce up to 2.0 kW and with upgraded power can be boosted to 3.5 kW. Integrated starter alternators (or flywheel-alternator-starter) systems, currently under development, may be able to deliver up to 12 kW of power, which will allow a number of electrically driven fuel-saving new technologies to be added to future vehicles. However, with the advent of the e-car featuring vision enhancement systems, heads-up displays, navigation systems and enhanced safety and communication systems in addition to power hungry systems such as electromechanical engine valve actuators, electrically assisted power steering and heated windshield the added power can easily be used up. One way to meet any additional demand is to add an auxiliary power unit. Fuel cell systems incorporating on-board fuel reformers are being investigated as possible auxiliary power units. The main disadvantage of the proposed solutions to the increased electrical power requirements of future motor vehicles is that an alternator is mechanically driven by shaft power and fuel cells convert fuel to electricity, both resulting in an increase of fuel consumption and emissions. Waste heat recovery by direct thermoelectric conversion of heat to electricity could provide a suitable solution to this problem. The waste heat in internal combustion engines, caused by the irreversibility of the various engine cycle processes, is potentially a good source of additional onboard energy. There is a significant body of research on the use of thermoelectric generators as a means of recovering the waste heat in the exhaust gases [1-6], but none on the possibility of recovering other losses in internal combustion engines. Figure 1 shows the energy balance in a typical naturally aspirated spark ignition engine and the variations with speed and load. Of the total energy in the fuel, 18 to 22% only is converted to shaft power with the remaining energy lost to the coolant, exhaust and miscellaneous losses including radiation and incomplete combustion. Current and future vehicle electrical systems envisage continuous reliance on engine driven alternators, which further reduces the shaft power available for propulsion. Eliminating the alternator or reducing its size by utilizing the engine waste heat to generate electricity will result in reducing fuel consumption at best and avoiding the need to boost engine power to compensate for the power consumed by the electrical system at worst.

In addition to improving the figure of merit of existing materials and boosting the thermal conversion efficiencies of thermoelectric generators, environmental concerns associated with power generation must be addressed if this technology is to be promoted as "green".

Very little is reported in the literature on the environmental implications of thermoelectric generator applications [8-9], hence the need for the development of a method to critically approach the environmental impact of thermoelectrics in waste heat recovery applications.

The current paper presents an analysis of the environmental impact of replacing the alternator in a motor vehicle by a thermoelectric waste heat recovery system (WHRS). Discussed is not only the effect of reducing fuel consumption and emissions of carbon dioxide (CO_2) on global warming, but also the overall impact of the WHRS on the environment within the concept of industrial ecology. One of the tools of industrial ecology is environmental Life Cycle Analysis (eLCA), which allows to quantify the overall impact of any industrial activity on the environment from "cradle to grave", or more appropriately, from "cradle to reincarnation". This involves the stages from material extraction, product manufacture, transport, use of the product and end of life (reuse/ recycling/disposal).

2. The Alternative Conceptual Design

A typical spark-ignition engine utilises no more than 25% of the energy in the fuel as useful mechanical energy at the flywheel decreasing to about 15% at the driving wheels. The remaining energy is lost in the form of waste heat in, mainly, the cooling system and exhaust gases (Figure 1). Proof of concept by research is first briefly outlined followed by the conceptual design as a case study.

2.1 Proof of Concept Research

Feasibility (proof of concept) and optimisation of small-scale waste heat recovery systems were carried out over a period of time at Monash University. A WHRS incorporating six thermoelectric modules (14 W at 200^{o}C temperature difference) was designed according to the manufacturer's specifications and tested in a stationary industrial type diesel engine (Figure 2). The work showed that optimum performance was possible with careful assembly and sufficient temperature gradient across the modules. The latter was achieved by locating the WHRS as close to the exhaust manifold as possible and regulating the heat flux in the system by changing engine load.

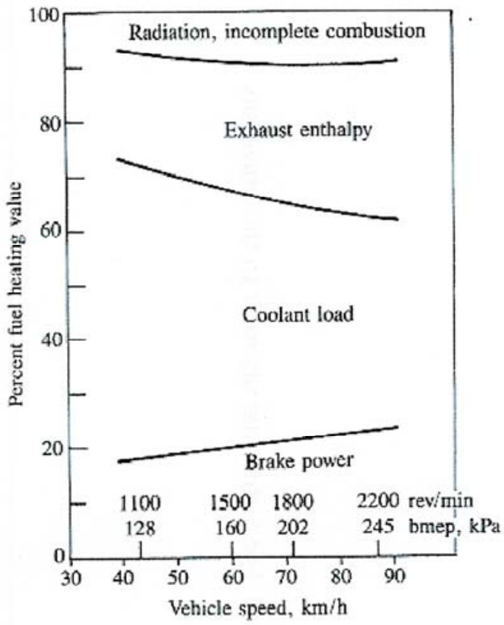

Figure 1 Brake power, energy of the coolant and exhaust gases, and miscellaneous energy losses in automotive spark ignition engine [7]

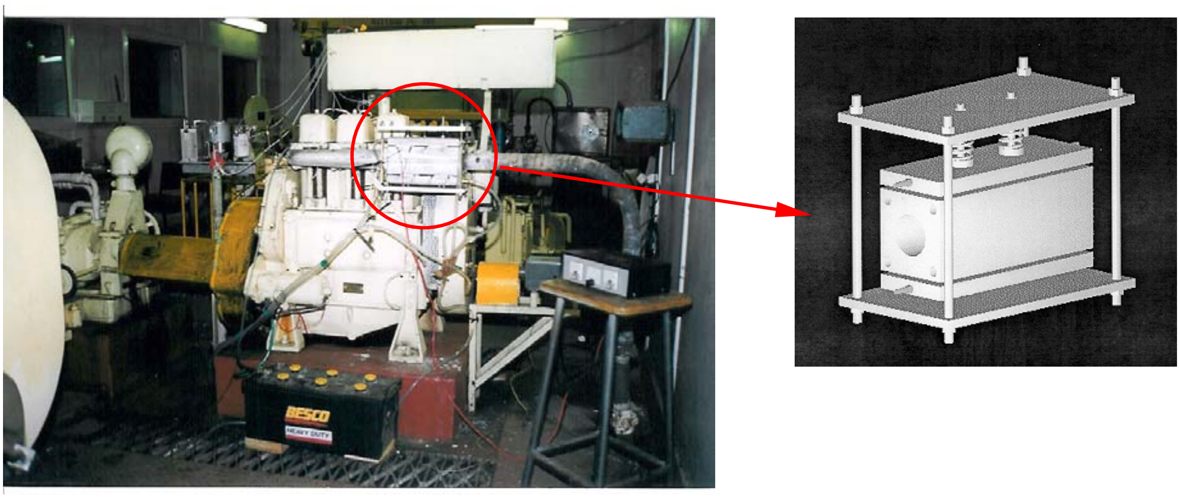

Figure 2 WHRS in the exhaust stream of a stationary diesel engine

Optimisation work on a small boiler fired by natural gas and a WHRS with a single thermoelectric module (Figure 3) lead to some very useful design guides as to the performance of different cooling systems and electric insulator plates between the electrically conducting thermal spreader and the module. Figure 4 shows a family of curves that allow the prediction of the electrical power output from the module as a function of the available temperature difference across the module and cold side temperature. These curves take into account the effect of the thermal resistances at all the interfaces (Figure 6), which were estimated using inverse heat transfer analysis.

Figure 3 WHRS in a small steam generator with a single thermoelectric module (TEM)

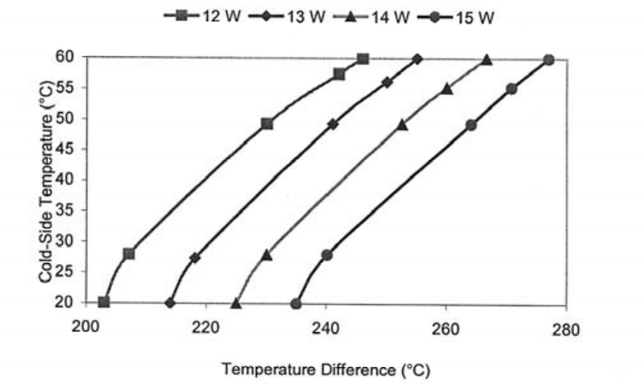

Figure 5 Nomograph of cold-side temperature and temperature difference for constant electrical power outputs

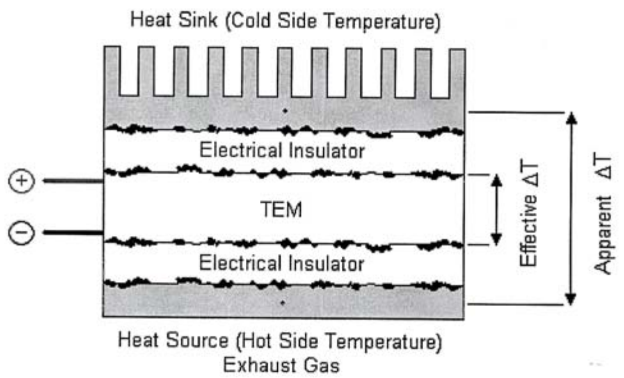

Figure 6 Schematic diagram of the WHRS showing locations of four interfaces

2.2 Conceptual WHRS for a Car

Figure 7 shows a schematic diagram of a conceptual combined engine-WHRS arrangement utilizing the waste heat streams of the exhaust gases and the cooling system. For each unit of the energy liberated from the combustion of the hydrocarbon fuel in the engine the losses in the exhaust and cooling streams are x and y, respectively. The remaining part $(1-x-y)$ is converted to $\eta_m\ (1-x-y)$ mechanical shaft work, where η_m is the mechanical efficiency of the engine. The required onboard electrical energy $(\eta_a z)$ is generated by the alternator at a conversion efficiency of η_a. These processes are shown in the dashed box in Figure 3 and represent the classical engine-alternator arrangement.

With waste heat recovery, two parallel thermoelectric generators can be installed in the waste streams to generate $(x\eta_{e1}\eta_{t1}+y\eta_{e2}\eta_{t2})$ of power, where η_{e1}, η_{t1} and η_{e2}, η_{t2} are the effectiveness and thermal conversion efficiency of the heat exchanger and TE generator of the exhaust gas and cooling streams, respectively. Depending on the required onboard electrical energy and the available recoverable waste heat, the power generated by the WHRS can supplement or replace the power generated by the alternator. In the former case, the total onboard power will be $[(x\eta_{e1}\eta_{t1}+y\eta_{e2}\eta_{t2})+z\eta_a]$, and in the latter $(x\eta_{e1}\eta_{t1}+y\eta_{e2}\eta_{t2})$.

The next section will deal with the assessment of the environmental effect of replacing the alternator by a WHRS in a 1996 four-wheel drive vehicle powered by 4.0-litre, 140 kW engine. The vehicle is assumed to operate at an average speed of 60 km/h travelling approximately 19700 km per annum at an average fuel consumption of 7.23 km/litre [10]. The electrical load in this vehicle is assumed constant at 0.91 kW; therefore, the alternator drive will draw a maximum power z = 1.82 kW from the output shaft at an alternator conversion efficiency of η_a = 50%. A WHRS utilising the exhaust gases is more than sufficient to produce the required output for the speed range shown in Figure 2. Theoretically, a WHRS combining exhaust and cooling wastes can produce up to 13 kW of electrical power at a TEG thermal conversion efficiency of 5% which makes it suitable for use in future cars with high electrical on-board demand.

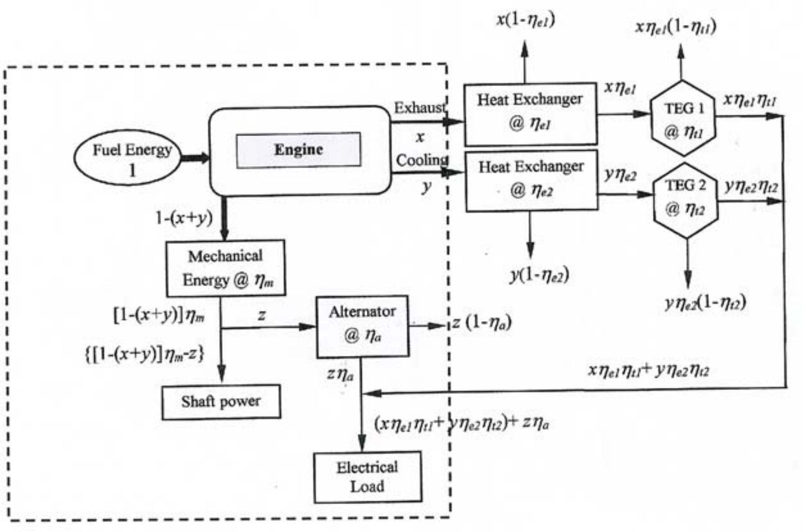

Figure 7 Combined engine-WHRS system for two waste energy streams

3. Environmental Life Cycle Assessment

A software package called SimaPro 5.0 (Pre Consulting, the Netherlands) was used for the environmental life cycle assessment of the conceptual WHRS using thermoelectric generators versus the standard alternator.

2.1 Goal and Scope Definition

Comparison was made on the basis of operation of the vehicle over its lifetime (taken as ten years) under normal driving conditions. The materials used and their manufacturing methods in the two systems are shown in Tables 1 and 2. A two-bank WHRS was assumed for the current study each bank carrying 36 HZ-14 modules on a hexagonal shaped thermal spreader (Figure 8). The design, based on the previously described small-scale systems developed at Monash University [11-12], was an all aluminium thermal spreader with anodised aluminium plates as electrical insulators and aluminium water-cooled heat sinks. The 72 Bismuth Telluride TE modules have a combined mass of 5.9 kg. The databases in the software do not include inventory tables for Bi_2Te_3 or its constituent elements; therefore, the impact of the TE modules on the environment during material extraction and manufacturing processes was ignored.

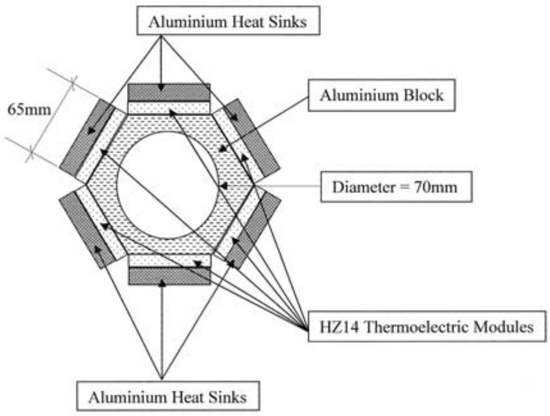

Figure 8 Schematic diagram of the WHRS

During use, the alternator's contribution to fuel consumption was estimated at 60 litres per annum. Replacement of the alternator was then assumed to reduce fuel consumption of the vehicle by the same amount, which was equivalent to a decrease of travelling distance by 4338 km over the 10-year assessment period.

Table 1 Alternator materials and manufacturing processes

Parts	Material	Mass, kg	Process
Windings	Copper	0.730	Drawn, Machine Assembled
Stator	Iron	0.745	Cast
Cooling Fan	Tin	0.190	Pressed
Outer Housings	Recycled Aluminium	0.780	Cast
Windings Clips	Plastic	0.010	Moulded
Rotor	Steel	1.670	Cast, Pressed, Machined
Various Plastic Components	Plastic	0.060	Injection Moulded
Brackets	Recycled Aluminium	0.110	Cast, Drilled, Machined
Various Bolts	Steel	0.190	Drawn, Rolled

By itself, this saving looks modest; however, if similar savings are projected on the global vehicle fleet, the impact on the environment, particularly on global warming, could be very significant. Effect of maintenance during use is not included in the analysis. The Product retirement stage includes recycling of metals and disposal of non-metal components according to European disposal scenario for both systems. As for the TE modules, it is assumed they are fully recycled at

Table 2 WHRS materials and manufacturing processes

Parts	Material	Mass, kg	Process
Thermal Spreader	Recycled Aluminium	14	Machining
Electrical Insulators	Aluminium Sheet	1.0	Machining
Heat Sink	Recycled Aluminium	28.8	Cast work
HZ-14 TE Modules Total 72	Bismuth Telluride	5.9	No Data
Various Plastic Components	Plastic	0.2	Injection Moulded

the end of their lifetime. This implies zero environmental impact of end of life of these modules and is justifiable on the currently available Bismuth Telluride recycling technologies [8].

3.2 Impact Assessment

One of the impact assessment methods included in SimaPro is Eco-indicator 95 (Figure 9). This method classifies and assigns weightings to the emissions from processes according to the following ten environmental effects: global warming, ozone layer depletion, acidification, eutrophication, summer smog, winter smog, pesticides, airborne heavy metals, waterborne heavy metals and carcinogenic substances [13].

The resulting weighted scores can be normalized against the environmental impact of an average European person in one year. The normalised scores say nothing about the hierarchy of the environmental effects, they simply tell us which effects are large and which are small. However, an effect with a low score can cause more damage to the environment than another effect with a much larger score. Hence the need for a further step to evaluate the environmental impact of the different effects in the form of a single score. This is done by setting equivalent damage levels for three criteria: human fatalities, health impairment and ecosystem damage. Weighting factors are then assigned to each effect depending on the current level of an environmental problem and the effort to reduce it to predetermined acceptable damage levels. For example, the highest weighting factor of 100 is given to ozone layer depletion (can cause fatalities) indicating that high priority must be given to reducing emissions causing ozone layer depletion. The factors for pesticides, acidification and global warming are 25, 10 and 2.5, respectively. The resulting Eco-indicator scores (points or millipoints) for the different environmental effects can be added to determine the overall effect of a product, process or any human activity on the environment. Figure 9 shows this process schematically. The higher the final score, the greater the damage done to the environment.

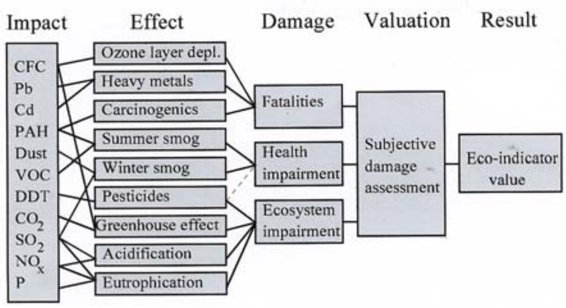

Figure 9 Eco-indicator environmental impact evaluation method [13]

3.3 Assessment Results

The environmental impact assessment was carried out for both the assembly stage (material extraction, processing and manufacture) and the life cycle stage (assembly in addition to use over a period of 10 years and disposal). Figure 10 shows the comparison of the impact of the alternator and the WHRS for the assembly stage. The available data within the databases of the software clearly indicated that the WHRS had a larger negative impact on the environment (0.29 points versus 0.114 points). The difference was mainly due to solid waste resulting from extensive use of aluminium in the fabrication of the WHRS. The comparison of life cycles is shown in Figures 11 and 12 for the two systems. The alternator's impact was almost three times larger than the WHRS with acidification contributing about 0.5 points (44.6%).

Despite the fact that the larger environmental impact of the alternator was due to fuel usage, the contribution to the greenhouse effect was not large, comprising 0.19 points or 17%. For the WHRS the figures were 0.0136 and 3.6%, respectively. These translate into a decrease of CO_2 emissions from 955 kg to 67.6 kg – a 14-fold reduction. Figure 12 clearly shows that the alternator was environmentally much worse than the WHRS with respect to five effects. The WHRS scored worse in just one category – heavy metals. This could obviously have changed if the contributions of the thermoelectric material and manufacturing were accounted for.

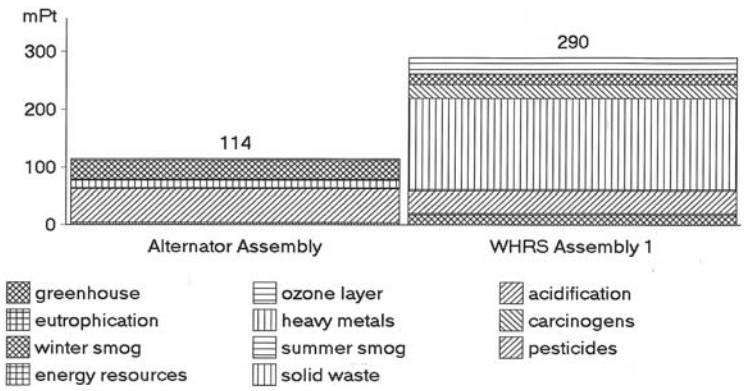

Figure 10 Comparison of assemblies with Eco-indicator 95

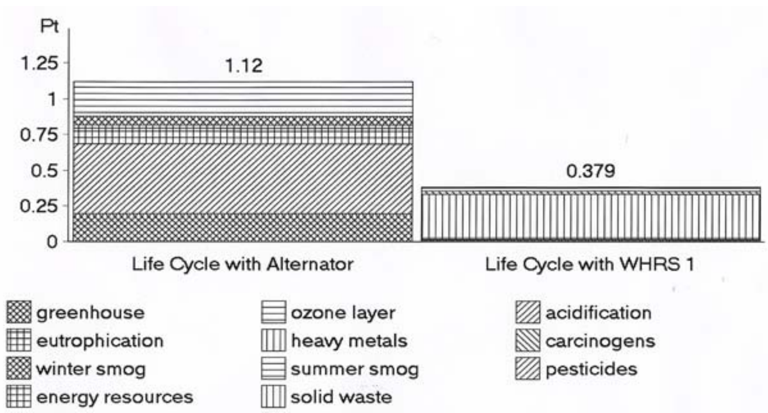

Figure 11 Comparison of life cycles with Eco-indicator 95

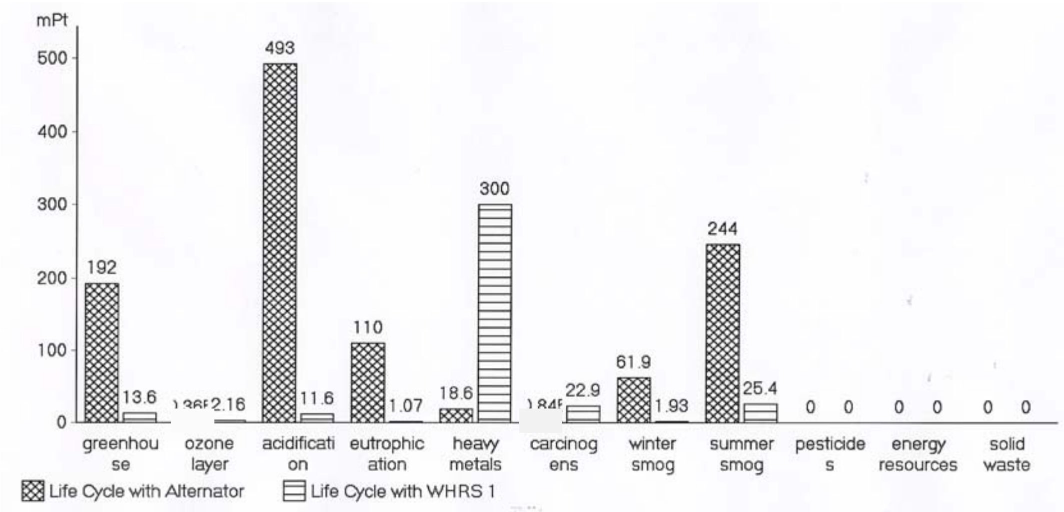

Figure 12 Comparison of the environmental impact of the alternator and WHRS in terms of the environmental effects

4. Conclusions

1. Theoretically, the thermal efficiency of heat engines can be significantly increased by means of combined waste heat recovery design. To this end, thermoelectrics can play an important role even at today's relatively low conversion efficiencies.
2. The most obvious outcome of improvement in engine efficiency is the reduction in greenhouse gas emissions. However, this should not be the only criteria to establish the "green energy" credentials of thermoelectricity.
3. It is imperative to conduct a comprehensive environmental life cycle assessment of any application at the design stage in order to get a clearer picture of the overall impact on the environment, both positive and negative.
4. The simplified eLCA of thermoelectric generators in a waste heat recovery application showed that effects such as acidification, heavy metals and summer smog are more significant than the greenhouse effect.
5. More credible analysis will require the compilation of comprehensive data bases on the environmental implications of extracting virgin materials or recycling scrap materials, processing thermoelectric materials (bismuth telluride, lead telluride and silicon germanium) and manufacturing the thermoelectric modules.

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