# Waste Heat Regeneration

## Scope

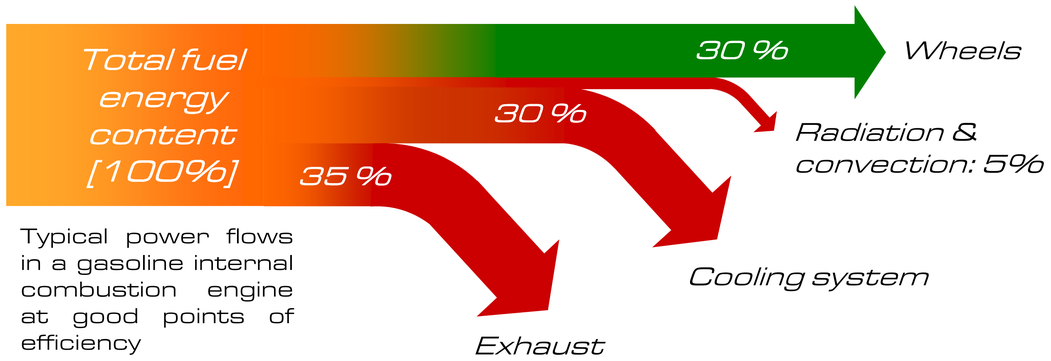
The scope of waste heat regeneration is to use the heat that is normally thrown away into the atmosphere in a dedicated machine in order to transform it into a usable form of energy.

Usually this is the same form of energy that is generated by the machine that also generates the waste heat but this is not always an absolute requirement.

The goal is to reduce the speed of primary energy consumption.

Combustion engines are known to have very limited efficiency as a lot of power flows away as heat through the exhaust and the engine cooling system.

The following diagram represents the power flows for a gasoline engine in a near optimal working point.



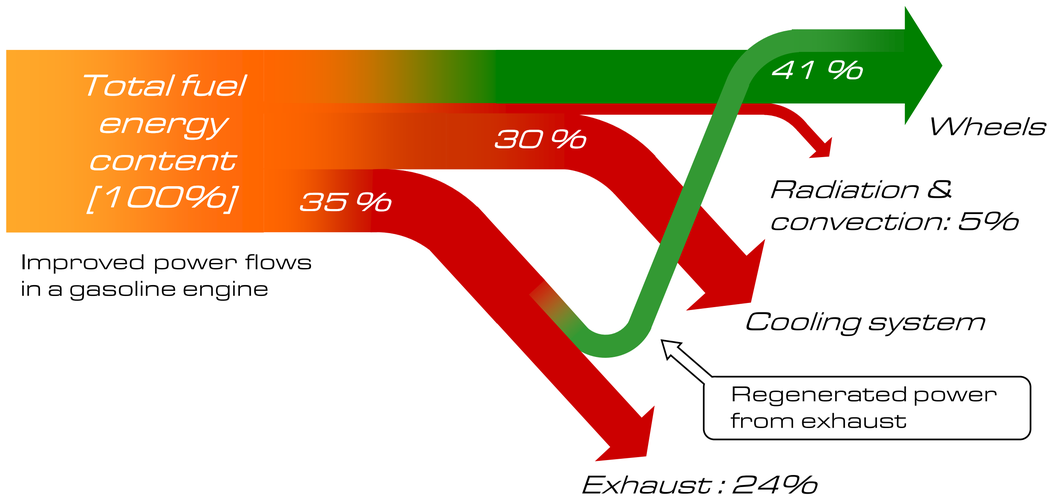

Typical power flows in a gasoline internal combustion engine at good points of efficiency

The power flow through the cooling system is of relatively low temperature and has small potential for powerful waste heat regeneration.

Many systems exist to transform heat into usable power (torque). The ones with the most interest from the IC engine industry for waste heat regeneration are the Organic Rankine Cycle (ORC) and thermo-electricity (TE).

Stirling engines are well known for transforming heat into torque but have a low specific power which make this concept unsuitable for vehicle applications.

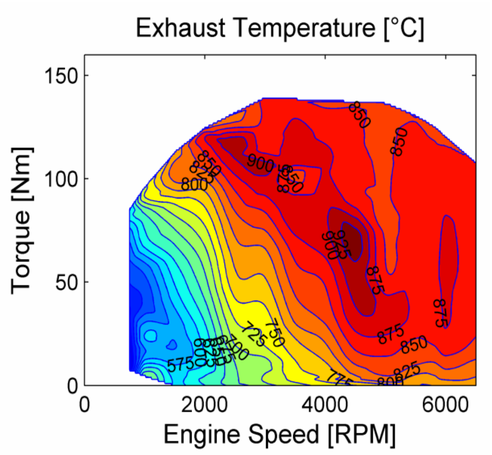
**heat2power** has invented a system for regenerating exhaust heat directly into torque. This system was conceived for combining high efficiency of regeneration and high specific power which is required for vehicle applications.

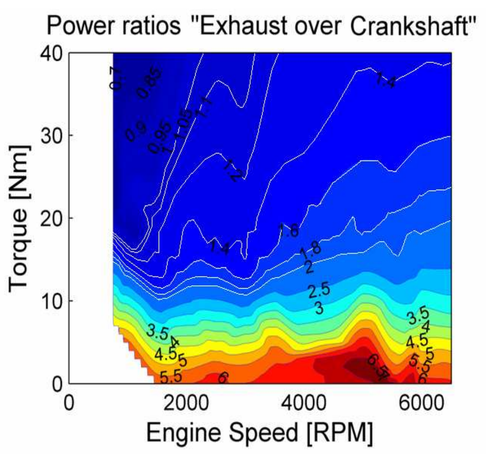



Improved power flows in a gasoline engine

The exhaust temperatures after catalyst and relative power flow shown below were obtained with data acquisition on bench of a mainstream 1600cc gasoline ICE.

The values of exhaust temperatures in diagram are 50°C higher than those measured after the catalyst for taking into account the effect of additional thermal insulation on the exhaust itself.




Though the exhaust temperatures after catalyst are highest near full load, a given ratio of regeneration can give a very good efficiency improvement of the engine due to the high ratio between exhaust power and crankshaft power.

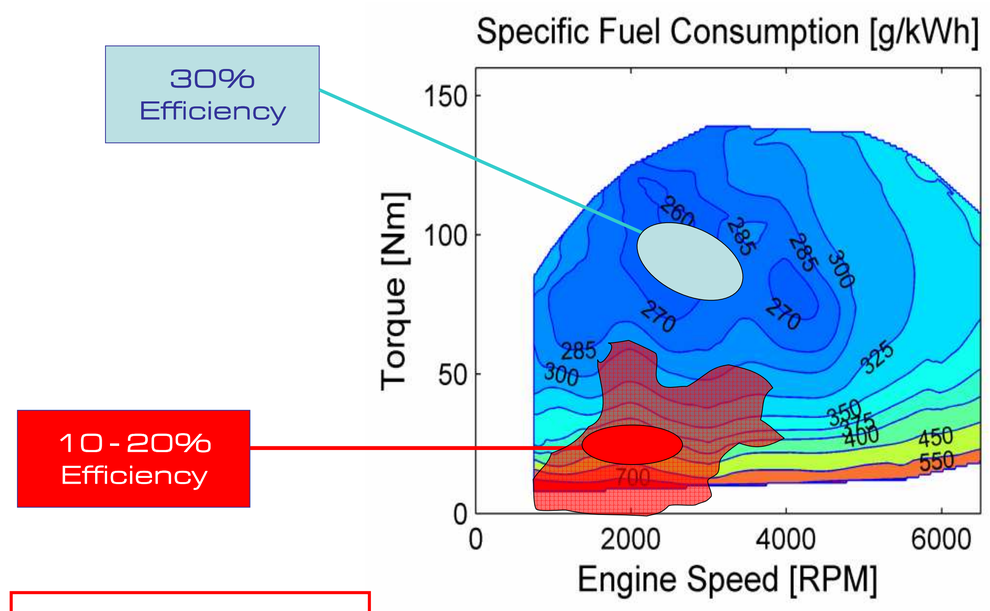
In the torque range of up to 10% of the maximum torque the ratio of exhaust power over crankshaft power can be as high as 2 to 5.

## Engine efficiency...

## ...a relative meaning

In the every day use of an IC engine in a vehicle the operating point is generally far off the lowest specific fuel consumption. This is particularly the case for larger engines. The ratio of power lost through the exhaust compared to what actually goes to the crankshaft is high.

The aim of WHR technologies is not only to improve the best efficiency points of the engine but also and perhaps more importantly the efficiency in lower torque band and lower to medium RPM band.




80 - 90% is LOST

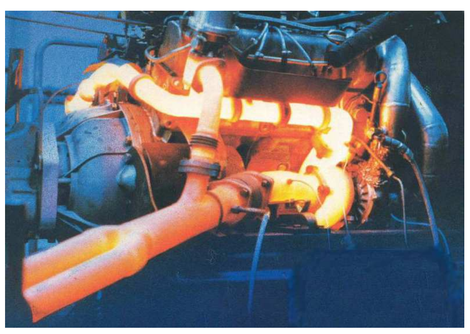
A big part of these 80 - 90% goes to the exhaust

Exhaust WHR makes sense

Optimizing fuel economy at the most efficient working point of an engine is not always the most desired effect.

Optimizing fuel economy in frequently used working points can prove to be more attractive. The optimal WHR technology can be different for these two areas of working points.

Where turbomachines are good at regenerating power at medium to higher outputs of the IC engine, other WHR technologies are better adapted for the lower output ranges.



The right WHR technology can improve efficiency both in the medium to high power outputs but in the lower power outputs as well. Percentage wise the improvements can be significant at the lower power end due to the high level of lost heat.

The frequent occurrence of low power output should have a strong influence in the choice for the WHR technology other than those base on turbomachines.

Applications of IC engines in hybrid configuration with an electric motor result in less frequent lower power outputs which will have an impact on the choice of the most appropriate WHR technology.

# Waste Heat Regeneration

## Power flows in an IC exhaust

Besides the heat flow in the exhaust there are also other power flows that can be used for waste energy re-use.

These are :

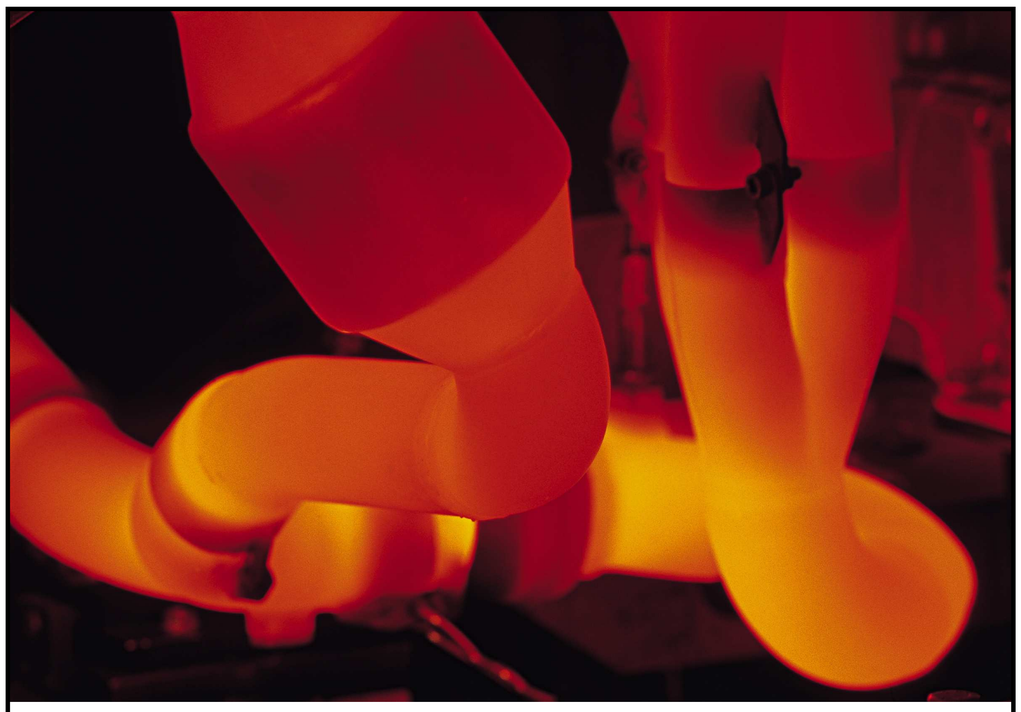
1. Thermal power flow
2. Kinetic power flow
3. Chemical power flow (non-combusted Hydro- carbons, Carbon-monoxide and Soot)
4. Upper latent heat flow

The kinetic power flow is in many occasions already used for increasing the engine output via a turbocharger.

The chemical power flow is converted in heat inside the catalyst converter.

Upper latent heat flow is not used and leaves the exhaust. This power flow represents about 11% of waste energy.

The thermal power flow could thus best be tapped after the catalyst in order to make use of its exothermy .



Hot exhaust : a too big potential for fuel economy not to be used

## Choosing the right WHR system

The automotive WHR solution needs the following characteristics:

- Operate within the waste heat temperature range of the ICE's exhaust gases
- Compact
- Lightweight
- High specific power
- Best possible efficiency level in all working points
- Easy to adapt in an industrial equipment
- Easy to adopt (no hazardous materials, chemicals)
- Free of particular maintenance
- Cost effective

Apparently interesting technologies have serious drawbacks :

- In a too early phase of development (Thermo-tunneling)
- Too expensive (Thermo-electricity based on Seebeck effect)
- Insufficient fuel economy (Turbo compounding on part load, thermo-electricity)
- Too difficult to put in place (Organic Rankine Cycle, endothermic vapo-cracking)
- Too bulky (Lithium-hydride cycle, Stirling engine)
- Very complex to integrate in an existing industrial processes (Proe cycle)

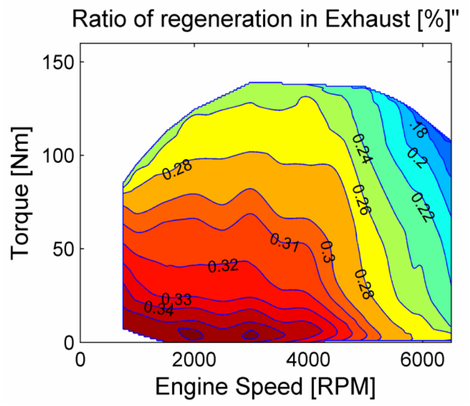
We had to come up with our own solution that combines all the required characteristics. This led us to the heat2power concept

## The heat2power principle

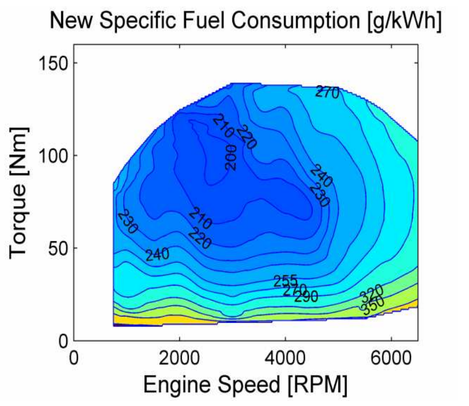
This concept combines all the requirements for application in series produc- tion of cars and trucks :

- Heat regeneration efficiency of 18 up to 35 % (including at part load)
- Combining this with high specific power
- Cost effective (less than 25$ per percent fuel economy making it competitive with diesel engine technology)
- Compact (easy packaging)
- Uses conventional technology
- Novel thermodynamic cycle using air as working medium (easy for maintenance, handling in manufacturing process and aftersales)
- Various configurations possible (simple or optimized)
- Compatible with all fuel types (Diesel, gasoline, ethanol, CNG, LPG, etc.)
- Possible as an Add-In system and as an Add-On system
- Add-in solution maintains high specific power
- Add-in solution maintains similar mass and packaging
- Entry ticket for industrialization similar to a variant of an existing engine Is easy to build in existing engine plants
- No negative impact expected for compatibility with EU6 emissions regulations
- Complementary with Hybrid Electric Powertrain concepts (with gain on extra-urban)
- Concept has been patented in September 2006.

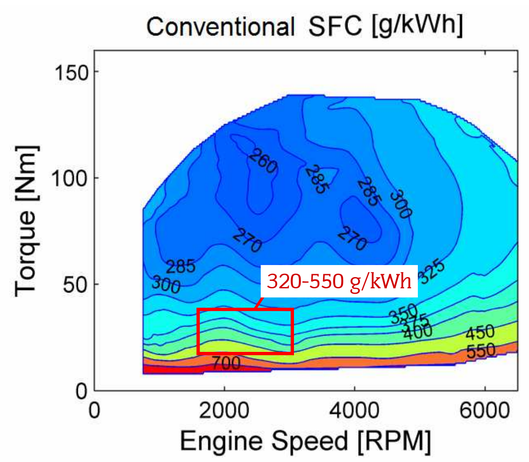
Heat regeneration efficiencies currently obtained are in the 18 to 35% range depending on RPM and mean effective pressure levels.

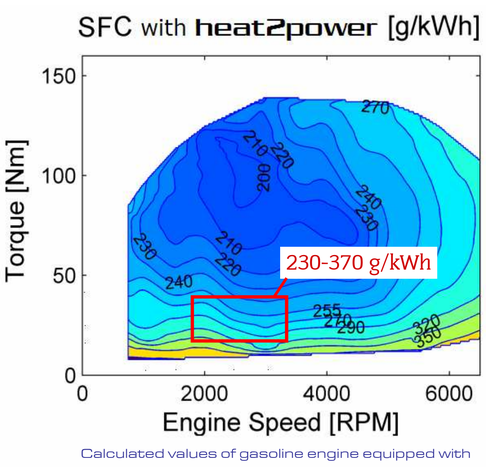



The ratio “exhaust power / crankshaft power” allows us to draw a new specific fuel consumption diagram:




The potential of WHR with a regeneration simulated efficiency on typical NEDC cycle points of operation :




Calculated values of gasoline engine equipped with heat2power system.

Diagrams are based on a gasoline engine. Improvement for torques < 30% are interesting for bigger engines (US market)

# The markets for WHR

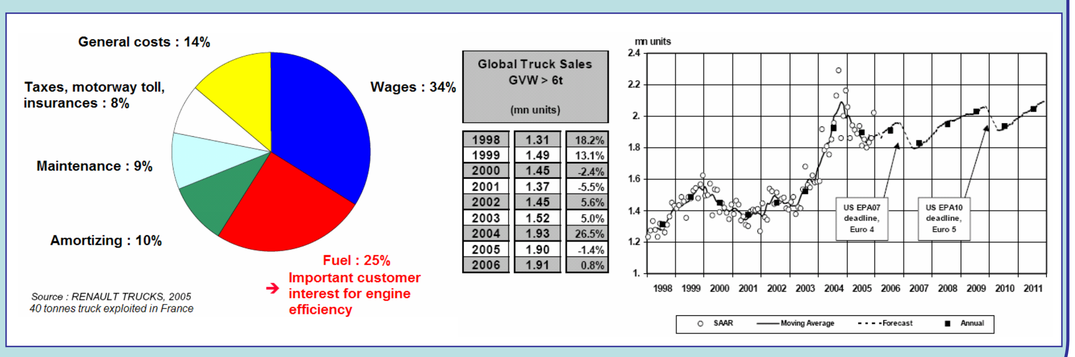
## Market segments with highest interest in WHR

Huge market potential on :

- Truck diesel
- Large automotive gasoline engines
- Hybrid powertrain (optimizing IC engine)
- CNG engines (extra low CO2 emissions)

Initial market target : Truck diesel engines

Market driver : Orientation on direct financial benefits by the end customer. 20% fuel economy means a reduction of 5% of his annual cost which doubles the company's profits. Upcoming emissions regulations will stimulate renewal of vehicle fleets.



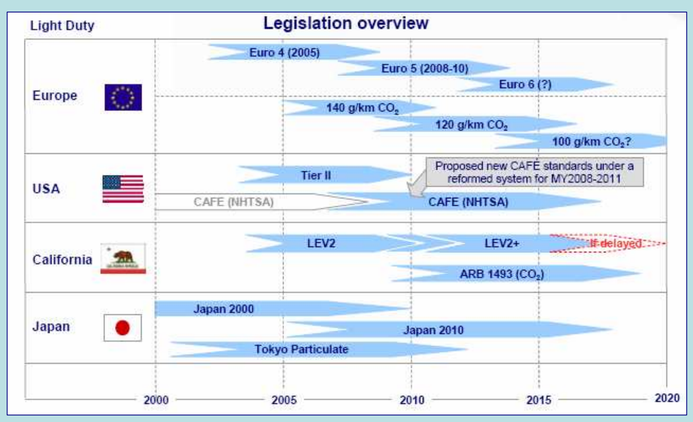

Global Truck Sales GVW > 6t (mn units)

| | | |
|---|---|---|
| 1998 | 1.31 | 18.2% |
| 1999 | 1.49 | 13.1% |
| 2000 | 1.45 | -2.4% |
| 2001 | 1.37 | -5.5% |
| 2002 | 1.45 | 5.6% |
| 2003 | 1.52 | 5.0% |
| 2004 | 1.93 | 26.5% |
| 2005 | 1.90 | -1.4% |
| 2006 | 1.91 | 0.8% |




**Exotic WHR applications on race car engines**
**Driven by new FIA regulations**

Automotive market still reluctant to adopt "costly" solutions.
BUT :
Legislations will push to lower fuel consumption with future Euro6 norm. And governments start to strongly stimulate solutions that reduce pollution and $CO_2$ emissions. WHR will definitely play a role in here.




## heat2power customer relations

### Truck

### Automotive

### Racing

**WHR benchmark studies**

Team up with TIER-1 suppliers for main components (turbos, heat exchangers, exhausts) and co-develop the concept with them towards industrialisation phase

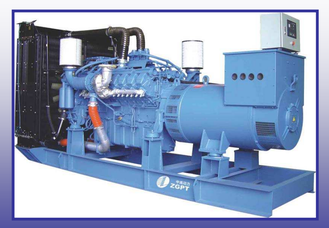
Adapt WHR to Formula one and Endurance racing for fuel economy and less CO2 emissions

Guide OEMs through the various WHR technologies and adapt WHR technologies to their engines

Set up a consortium with an OEM and TIER 1 suppliers to conduct a development program with target of industrialisation.

Derive products to railway, marine and power generation markets.





## And what if ...

**Solar energy**

Niche products that still have a very small market demand today...

But that could one day become a major source of energy

Solar Concentrating power generation with heat engines other than Stirling...