Cost to benefit ratio of an exhaust heat recovery system on a long haul truck
Exoès at a glance
Our skills

EXOES is an engineering company providing its customers with:

- Prototypes
- Calibrated Simulation
- System design
- Test rigs
- Vehicle integration

Prototype technologies:

- Swashplate
- Crankshaft
- Scroll
- Valvetrain
- Pump
Experienced in demo-vehicles

References:

Demotruck:

- EXOES, Renault-Trucks and Faurecia
- a 2-year program
- Waste heat recovery
- Integration of an EXOES expander
- Real life driving and roller test bench
Is there a business case for WHR on long haul trucks?
Exhaust heat recovery typical layout

- Heavy commercial vehicles – typical class 8 truck
- Focus on exhaust heat recovery only
- Ethanol based working media

```
1: Main radiator
2: ICE
3: After-treatment
4: Exhaust bypass valve
5: Exhaust evaporator
6: Expander Bypass valve
7: EVE - Expander
8: Condenser
9: Filter
10: Feed pump
11: Cooling pump
12: Expansion vessel
13: Control valve

→ to be controlled
```
Challenges for the ORC

Ethanol bottoming Rankine cycles are facing the following challenges to enter OEM development programs:

- **Safety case**
  - Flammable working fluid
  - Extensive risk analysis done by TÜV SÜD / FPT for IVECO
  - System supplier or OEM responsibility

- **Business case**
  - Ratio cost / benefit
  - Prove the fuel savings
  - Reduce the component and integration costs

- **Durability case**
  - Prove the component reliability
  - Alcoholate corrosion
  - Fluid ageing: lubricant and ethanol breakdown
Target cost of the system

- Link between payback time, fuel saving and system cost

**Sales price of the ORC system for a 2-year payback assuming 3% fuel saving**

**Assumptions:**

<table>
<thead>
<tr>
<th></th>
<th>Europe</th>
<th>USA</th>
<th>China</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mileage</td>
<td>130,000</td>
<td>110,000</td>
<td>150,000</td>
<td>km/y</td>
</tr>
<tr>
<td>Fuel</td>
<td>1</td>
<td>0.65</td>
<td>0.8</td>
<td>€/L</td>
</tr>
<tr>
<td>Consumption</td>
<td>35</td>
<td>44</td>
<td>35*</td>
<td>L/100km</td>
</tr>
<tr>
<td>ORC Maintenance</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>€/y</td>
</tr>
</tbody>
</table>

*: projected in 2025 with new regulation implementation
Our costing method

- Costing method applied by Exoès supported by external cost killers:

**Part cost**
- Bill-of-materials
- Detailed cost on 20% of parts that make 80% of costs
- Simplified estimation of 80% of references
- Make/Buy strategy

**Assembly cost**
- Assembly process
- Factory and assembly line

**Sales cost**
- R&D cost depreciation
- DCF for profit

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**Valorized Expander BoM**

<table>
<thead>
<tr>
<th>Part number</th>
<th>Cost [% of product cost]</th>
<th>% cost per part</th>
<th>% cost per part number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-30</td>
<td>0-10</td>
<td>0-10</td>
<td>0-10</td>
</tr>
<tr>
<td>31-60</td>
<td>0-10</td>
<td>0-10</td>
<td>0-10</td>
</tr>
<tr>
<td>61-90</td>
<td>0-10</td>
<td>0-10</td>
<td>0-10</td>
</tr>
</tbody>
</table>

**Cost breakdown of Expander sales cost**

- Profit, Tier 2
- R&D amort
- SG&A Tier 2
- Buildings, Utilities & Maintenance
- Labor
- Purchase Parts and Services
Manufacturing scheme

Sales scenario:

- Relatively low volumes. It implies as little investment as possible:
  - 100% buy strategy (Tier1s buy parts and “only” assembles them)
  - No fully-automated assembly lines

<table>
<thead>
<tr>
<th></th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
<th>Y5</th>
<th>Y6</th>
<th>Y7</th>
<th>Y8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sales per year</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unit/y)</td>
<td>5000</td>
<td>10000</td>
<td>15000</td>
<td>25000</td>
<td>32500</td>
<td>42500</td>
<td>52500</td>
<td>67500</td>
</tr>
<tr>
<td><strong>Cumulated sales</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(units)</td>
<td>5000</td>
<td>15000</td>
<td>30000</td>
<td>55000</td>
<td>87500</td>
<td>130000</td>
<td>182500</td>
<td>250000</td>
</tr>
</tbody>
</table>
Built-up of a valorized BoM

- **A valorized Bill-of-Materials:**
  - Manufacturing process
    - Casting / Forging / Machining
  - Raw material cost
    - London Stock Exchange rate
  - Weight
    - According to a design
  - Coatings and thermal treatments
    - Ex: ~2€/kg surface treatment baths
  - Labor
    - 40€/h +20% overhead, incl. utilities
  - Machine rate
    - Ex: 30€/h CNC, Lathe, Horizontal
  - Transport
    - 3%

- Part
Built-up of the system cost

- **Component sales price:**
  - Assembly line
    - Ex: 1,000,000€ for a semi-automatic line – 3 stations
  - Tools
    - Ex: 300,000€ casting die
  - Purchased parts and services
    - Valorized BoM
  - Component sales price

- **System sales price:**
  - **sum of components + OEM margin (+80%)**

- **Assembly labor**
- **SG&A – Profit**
  - +30%
  - Or Discounted cashflows
Expander design and cost
Exoès piston expander technology

- **EVE-T2**: Single acting swashplate technology – 3 pistons
- Inlet poppet valves, and exhaust ports and valves
## Expander Datasheet

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EVE-T2</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Speed range</strong></td>
<td>1,000 - 4,530 RPM</td>
</tr>
<tr>
<td><strong>Shaft power range</strong></td>
<td>&lt;12 kW</td>
</tr>
<tr>
<td><strong>Eff. Is. efficiency range</strong></td>
<td>Typ. 55 - 65%</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>&lt; D200xL200mm</td>
</tr>
<tr>
<td><strong>Weight without coupling</strong></td>
<td>15kg</td>
</tr>
<tr>
<td><strong>Oil circulation rate</strong></td>
<td>Typ. 10%</td>
</tr>
<tr>
<td><strong>Outlet pressures</strong></td>
<td>1 - 4 barA</td>
</tr>
<tr>
<td><strong>Inlet pressures</strong></td>
<td>&lt;40 barA</td>
</tr>
<tr>
<td><strong>Nominal pressure ratio</strong></td>
<td>15 – 20 for ethanol</td>
</tr>
<tr>
<td><strong>Nominal gear ratio</strong></td>
<td>1.5 – 2.5 for trucks</td>
</tr>
<tr>
<td><strong>Transmission</strong></td>
<td>Freewheel</td>
</tr>
<tr>
<td><strong>Bypass valve</strong></td>
<td>Integrated</td>
</tr>
</tbody>
</table>
Expander tests and model calibration

Effective Isentropic Efficiency measured* vs calculated

Effective Isentropic Efficiency comparison
@ 2000rpm, 1barA outlet, 30°C superheat

Effective isentropic efficiency:
\[ \eta_{eff,is} = \frac{\dot{W}_{shaft}}{\dot{M}(h_{in} - h_{out,is})} \]

*Measured = calculated based on measured values
Future expander generation

- Compliant Scroll – Volume ratio 4.6 – Capacity 139cm³

<table>
<thead>
<tr>
<th></th>
<th>EVE-T2 - piston</th>
<th>EVE-T3 - scroll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed range (RPM)</td>
<td>1,000 - 4,530</td>
<td>1,000 – 6,000</td>
</tr>
<tr>
<td>Shaft power range</td>
<td>&lt;12 kW</td>
<td>&lt;15 kW</td>
</tr>
<tr>
<td>Eff. Is. efficiency range</td>
<td>Typ. 55 - 65%</td>
<td>Typ. 60 - 75%</td>
</tr>
<tr>
<td>Size</td>
<td>&lt; D200xL200mm</td>
<td>&lt; D200xL130mm</td>
</tr>
<tr>
<td>Weight w/o coupling</td>
<td>15kg</td>
<td>16kg</td>
</tr>
<tr>
<td>Oil circulation rate</td>
<td>Typ. 10%</td>
<td>Typ. 5%</td>
</tr>
</tbody>
</table>
Efficiency & cost forecast

- Higher efficiency expected
- Projected cost for 50,000 pcs/year
  - 350€ ±50€ sold to OEM

Efficiency comparison with Ethanol 95.5%mass
@ 2000rpm, 1bar outlet, 30°C superheat (EVE-T1 and T2)
@ 3600rpm, 1bar outlet, 20°C superheat (EVE-T3)
Pump design and cost
# Pump Datasheet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PHP-T1</strong></td>
<td></td>
</tr>
<tr>
<td>Speed range</td>
<td>750 – 6,000 RPM</td>
</tr>
<tr>
<td>Max flow</td>
<td>7 L/min</td>
</tr>
<tr>
<td>Fluid</td>
<td>Ethanol – Water mixtures</td>
</tr>
<tr>
<td>Size</td>
<td>D100mm x L200mm</td>
</tr>
<tr>
<td>Weight</td>
<td>&lt;5kg</td>
</tr>
<tr>
<td>Required subcooling</td>
<td>~5°C</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>1 – 4 barA</td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>&lt;40 barA</td>
</tr>
<tr>
<td>Optional : motor</td>
<td>24Vdc Electric motor integrated</td>
</tr>
<tr>
<td>Communication: CAN</td>
<td></td>
</tr>
<tr>
<td>Other options:</td>
<td>Filter</td>
</tr>
<tr>
<td></td>
<td>Relief valve</td>
</tr>
<tr>
<td></td>
<td>Pressure &amp; Temperature sensors</td>
</tr>
</tbody>
</table>
Conclusion
Estimated system price

- Estimated sales price: 2,700€ (± 300€)

- Some assumptions:
  - Exhaust WHR (No EGR recovery)
  - Radiator carried over
  - Mechanical feed pump
  - Mechanical coupling of expander
  - OEM costs and profit = 80% of components costs
  - ~50,000 unit/year; 250,000 units over 8 years
Business case

- Fuel savings:
  - measured on demovehicle – 11L SCR only engine – 40-ton truck
  - between 2.75 to 3% according to driving cycle
  - Paper to come with detailed results

- Valid business case (at least in Europe)

Sales price of the ORC system for a 2-year payback assuming 3% fuel saving:

- Current fuel prices
- Target ORC sales price
- Current fuel prices

Sales price of the ORC system for a 2-year payback assuming 3% fuel saving:

- Current fuel prices
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Fuel price €/L
Thank you for your attention