8500 TEU Container Ship

Green Ship of the Future

Concept study.

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0.0 Introduction.

The purpose of this container ship conceptual study is to show how the exhaust gas emissions can be reduced for a typical large container ship by using appropriate developed and emerging technologies for reduction of exhaust emissions.

The goal at the outset of the study was to achieve emission reductions in comparison with today’s container ships of as shown below. These goals for the reductions were settled as the overall target for the project “Green Ship of the Future”:

- $\text{CO}_2$: - 30 %
- $\text{NO}_x$: - 90 %
- $\text{SO}_2$: - 90 %

This container ship study is one of two studies supported by the Danish Maritime Fund and is part of the many projects under the Danish project “Green Ship of the Future”.

Emission restrictions coming in force internationally or regionally in ECA’s (ECA = Emission Control Areas).

The coming international rules for sulphur (SOx) content in fuel oil as decided by IMO will be as shown in Fig.1 below:

![SOx emission limit schedule according to IMO (Int. Maritime Organisation)](image)

Fig.1: Future IMO requirements for maximum allowable sulphur content in fuel oil.
Concerning Emission Control Areas, ECA areas, there is a tendency to extend these areas worldwide.

Lately EPA (US Emission Pollution Agency) has put forward a proposal that will extend the ECA area to 200 nautical miles from the coast of Canada and USA. It contains demands concerning use of fuels with less than 0,1% sulphur from 2015 and 80% NOx reduction from 2016. Instead of using low sulphur HFO this proposal calls for exhaust gas cleaning devices (“scrubbers”) which can remove the Sox from the exhaust gas. This method can be beneficial as the demand of low sulphur HFO most probably will exceed the total production worldwide in the future.

An EU directive limits the sulphur content of fuels to 0.10% or less in EU ports from January 2010!

California CARB requirements limit sulphur content of fuels to 0.50% or less in Californian ports and within 24 nautical miles from the Californian coastline from May 2009 – i.e. already in force.

The rules coming in force concerning NOx emissions is internationally controlled by IMO and to some extent by local national governments stating separate demands for NOx within ECA areas.

Concerning CO2 it is expected, that rules will come in force in the near future for ships both as internationally and regionally. As stated by the Marine Environment Protection Committee (MEPC) it is time
for action. A recent study has shown, that international ship trade in 2007 contributed about 2,7% of the world’s CO\textsubscript{2} emission and also state that emission reductions are feasible through technical and operational measures including introduction of market-based reduction mechanisms (MEPC 59\textsuperscript{th} session, July 2009). Different studies have stated CO\textsubscript{2} reduction of 10 to 30% over the coming years under different assumptions. What is sure is that the CO\textsubscript{2} will be reduced either by market based instruments or by introduction of technical requirements for new ships as stipulated by the introduction of the so-called Energy Efficiency Design Index (EEDI) or by a combination of these two measures.

The potential of the Green Ship of Future partnership.

The following companies are partners in this Green Ship of the Future project – all participating are offering different ways to achieve the emission reduction goals.

Fig.3: Green Ship of the Future partners.
The following table shows, what these companies have reported different technologies can offer of improvements concerning emission reductions if installed on a ship – in general terms.

<table>
<thead>
<tr>
<th>Measure/Method</th>
<th>CO₂</th>
<th>NOx</th>
<th>SOx</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MACHINERY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual/Multi MCR certification</td>
<td>-1 to -3%</td>
<td>-</td>
<td>-1 to -3%</td>
</tr>
<tr>
<td>Turbo charging and variable nozzle ring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste heat recovery (WHR systems)</td>
<td>-8 to -10%</td>
<td>-8 to -10%</td>
<td>-8 to -10%</td>
</tr>
<tr>
<td>Exhaust gas recirculation (EGR systems)</td>
<td>+2 to 3%</td>
<td>-70%</td>
<td>-19%</td>
</tr>
<tr>
<td>Pump and auxiliary systems</td>
<td>-1,5 %</td>
<td>- 1,5 %</td>
<td>-1,5 %</td>
</tr>
<tr>
<td>Pump- and cooling water systems</td>
<td>-1,5 %</td>
<td>- 1,5 %</td>
<td>-1,5 %</td>
</tr>
<tr>
<td>Automated engine monitoring</td>
<td>-1%</td>
<td>-</td>
<td>-1%</td>
</tr>
<tr>
<td>Scrubber systems</td>
<td>(-3 %)</td>
<td>-</td>
<td>-98 %</td>
</tr>
<tr>
<td>Optimised control for ship cooling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNG powering of a fast ferry</td>
<td>-25 %</td>
<td>-35 %</td>
<td>-100 %</td>
</tr>
<tr>
<td>(Water In Fuel emulsion (WIF) )</td>
<td>+1 to 2%</td>
<td>-30 to -35%</td>
<td>+1 to 2%</td>
</tr>
<tr>
<td><strong>PROPULSION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air lubrication system (ACS)</td>
<td>-5 to -10 %</td>
<td>-5 to -10 %</td>
<td>-5 to -10 %</td>
</tr>
<tr>
<td>Innovative propeller</td>
<td>Not yet known</td>
<td>Not yet known</td>
<td>Not yet known</td>
</tr>
<tr>
<td><strong>OPERATION</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIMAC GSF Student forum</td>
<td>Not yet known</td>
<td>Not yet known</td>
<td>Not yet known</td>
</tr>
<tr>
<td>Performance monitoring of silicone antifouling</td>
<td>-6 %</td>
<td>-6 %</td>
<td>-6 %</td>
</tr>
<tr>
<td>Lab on a ship</td>
<td>0 to - 5 %</td>
<td>0 to - 5 %</td>
<td>0 to - 5 %</td>
</tr>
</tbody>
</table>

Fig.4: Green Ship of the Future reported emission reduction potentials.

The table does not show the effect, when the measures and methods are combined in a ship.

The effect of combinations depend on ship type, size, and finally but not least of the actual combination of technologies used in an actual project.

This very point will be dealt with in this report.
1.0 General.

The container ship study is centered on the Maersk Line’s so-called A-type ships – a ship type which has a capacity of 8500 TEU (TEU = a twenty feet equivalent container unit). This type belongs to the group of ships with 17 container positions across on deck, which comprises about 26 % of the entire post-panamax container ship fleet, in turns of number of ships and the number of TEU positions on board (existing and ordered as of august 2009).

The ships were built at Odense Steel Shipyard in 2003-2004 and are typical designs of the time i.e. fast slender containerships with more or less standard specifications. Most notable feature, however, being that they have complete double hull protected oil tanks, i.e. the oil tanks are separated from the ship side by a double hull construction. The cargo hold design is based on high cube containers i.e. containers with a height of 9,5 feet.

Below the waterline the ships were coated with a tin-free self polishing anti fouling coating.

Fig.5: A.P. Møller – Mærsk A-Class container ship: Anna Maersk.
2.0 Description of the A-class container ship.

The main data for this ship type is:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all</td>
<td>352.25 m</td>
</tr>
<tr>
<td>Length PP</td>
<td>336.40 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>42.80 m</td>
</tr>
<tr>
<td>Depth</td>
<td>24.10 m</td>
</tr>
<tr>
<td>Draught (scantling)</td>
<td>15.00 m</td>
</tr>
<tr>
<td>Deadweight (scantling)</td>
<td>109000 tons</td>
</tr>
<tr>
<td>ISO container positions (capacity)</td>
<td>Approx. 8500 TEU</td>
</tr>
<tr>
<td>Main engine:</td>
<td>Wärtsilä 12RTA96C</td>
</tr>
<tr>
<td>Main engine power output (MCR)</td>
<td>63000 kW</td>
</tr>
<tr>
<td>Revolutions</td>
<td>100 RPM</td>
</tr>
<tr>
<td>Electrical shaft motor</td>
<td>6000 kW</td>
</tr>
<tr>
<td>Diesel generators:</td>
<td>1 x 2590 kW(e)</td>
</tr>
<tr>
<td></td>
<td>3 x 3455 kW(e)</td>
</tr>
</tbody>
</table>

The ship has an 8.9 meter diameter fixed pitch propeller with 6 blades and a conventional semi spade rudder.

The design speed, 26.5 knots in calm weather, with a power requirement exceeding the service rating of 85% MCR of the main engine - the total propulsion power requirement is therefore supplemented by extra power from an electric shaft motor (PTI = power take in).

To obtain the 26.5 knots the main engine delivers 56000 kW and the electric shaft motor 6000 kW, in total 62000 kW. To drive the shaft motor a total of 6771 kW auxiliary diesel power is needed taking transmissions losses etc into account.

The specific oil consumptions of the main engine and the auxiliaries are 165.3 g/kWh and 191.0 g/kWh respectively under ISO conditions, when using diesel oil with a calorific value of 42.8 MJ/kg. These are so-called catalogue values otherwise used throughout the report.

Electric balance show in average a load of 2960 kW(e) at sea.
The total oil consumption for the 26.5knots is thus:

\[(56000 \times 165.3 + (6771 + 2960/0.95) \times 191.0) \times 24/1000000 \text{ tons/day} = 268 \text{ tons diesel oil/24 hours equal to 283 tons HFO/24 hours}

This fuel consumption will based on heavy fuel oil with typical sulphur content of 3% give an emission outlet of, if the engine complied to Tier I requirements:

- CO\(_2\): 878 tons per 24 hours
- NO\(_x\): 26 tons per 24 hours
- SO\(_2\): 17 tons per 24 hours
- Particulates: 3 tons per 24 hours

The purpose of this study is now to see, how much these emissions can be reduced by adding energy saving and emission reducing technologies.

3.0 General arrangement.

Fig.6: A-Class container ship sized for 8500 TEU containers – Profile and cross section.
4.0 Machinery arrangement.

The machinery arrangement for the A-class container ship is concentrated around the main engine with all the ancillary systems distributed on the different decks from tank top to casing.

![Machinery Arrangement Diagram](image)

**Fig.7:** A-class container ship: Shaft tunnel arrangement with electric shaft motor to boost propulsion.

The electric shaft motor is installed to supplement the propulsion power if high speed is required—(behind on sailing schedule, bad weather or fouling on hull and/or propeller).
Fig. 8: A-Class container ship: Tank top arrangement in engine room with main engine and misc. ancillary machinery equipment.
Fig. 9: A-Class container ship: Auxiliary engine deck arrangement with 3 (out of 4) auxiliary engines.
Fig. 10: A-class container ship: Engine room deck arrangement with 4th auxiliary engine.
Fig. 11: A-class container ship: Profile view of engine room and superstructure.
The design of this series of container ships started in 2002, where focus was on high speed and low fuel consumption - NOx certification of engines was stated in 2000 due to new NOx regulations (MARPOL Annex VI) and therefore the main engines were purchased with guaranteed SFOC and full NOx compliance according to Tier I.

In general these vessels are designed as very flexible ships. If high speed is required additional auxiliary diesel generator power can be transferred to the boost propulsion via the electrical motor placed in the shaft line and if low speed is in demand the main engine itself will be able to deliver sufficient power for propulsion.

Following green ship technologies have already been incorporated in these container ships:

- Exhaust boiler utilizing main engine exhaust heat to generate service steam.
- Water cooled reefer containers in cargo holds
- Waste water treatment according to IMO / SOLAS requirements.
- In board fuel tanks to minimize fuel spill in case of grounding or collision.
- Jacket water heated fresh water generator.
5.0 Basic ship data.

5.1 Electrical balance
A typical post-panamax container ship of this size has an electric power demand as follows:

Normal service at sea excl. shaft motor, excl. reefers: 1820 kW(e)
Normal service at sea incl. shaft motor, excl. reefers: up to 8590 kW(e)
Normal service at sea excl. shaft motor, incl. 50% reefers: 4100 kW(e)
Normal service at sea incl. shaft motor, incl. 50% reefers: up to 10650 kW(e)
Normal service at sea incl. shaft motor, incl. 100% reefers: up to 12870 kW(e)
Harbour load excl. reefers: 890 kW(e)
Harbour load, incl. 50% reefers: 3150 kW(e)

Following electrical load figures are used in the calculations for an average sea going and for average harbour condition incl. 25% reefers:

Sea going, average, excl. shaft motor: 2960 kW(e)
Harbour condition, average: 2020 kW(e)

The installed auxiliary diesel generator power for the basis ship is 12955 kW(e). In case of high reefer intake the power to the shaft motor can be reduced such that more electrical power is supplied to the reefer containers.

5.2 Load profile
For a post-panamax container ship of this size a typical main engine load profile is shown in figure 12:

![Fig.12: Operational main engine load profile at sea for a typical post panamax container ship.](image-url)
This load profile is valid for nearly 75% of the year and the remaining 25% time is harbour operation. The continuous service rating (CSR) described in the table is equal to 90% MCR.

5.3 Basic ship emissions based on MAN Tier 1 engine.
The basis post-panamax as described above and with selected MAN main engine type 12K90ME9 engine installed is taken as basis for this study.

**Basis engine SFOC and emissions at Tier I.**

Engine SFOC and emission figures are based on derated 12K90ME9 Tier I main engine without WIF, EGR and WHR. The emission figures are listed in table 1 as a function of the engine load (%MCR).

**Table 1: 12K90ME9 Reference SFOC and emission data.**

<table>
<thead>
<tr>
<th>Load %</th>
<th>Power kW</th>
<th>SFOC g/kWh</th>
<th>Specific emissions Tier I CO2 g/kWh</th>
<th>SOx g/kWh</th>
<th>NOx g/kWh</th>
<th>PM mg/Nm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>62230</td>
<td>167,7</td>
<td>556.2</td>
<td>10.6</td>
<td>17.0</td>
<td>2.00</td>
</tr>
<tr>
<td>95</td>
<td>59110</td>
<td>166,4</td>
<td>551.8</td>
<td>10.5</td>
<td>17.0</td>
<td>1.95</td>
</tr>
<tr>
<td>90</td>
<td>56000</td>
<td>165,3</td>
<td>548.3</td>
<td>10.4</td>
<td>17.0</td>
<td>1.90</td>
</tr>
<tr>
<td>85</td>
<td>52890</td>
<td>164,3</td>
<td>545.2</td>
<td>10.4</td>
<td>17.0</td>
<td>1.85</td>
</tr>
<tr>
<td>80</td>
<td>49780</td>
<td>163,6</td>
<td>542.6</td>
<td>10.3</td>
<td>17.0</td>
<td>1.80</td>
</tr>
<tr>
<td>75</td>
<td>46670</td>
<td>163,0</td>
<td>541.1</td>
<td>10.3</td>
<td>17.0</td>
<td>1.75</td>
</tr>
<tr>
<td>70</td>
<td>43560</td>
<td>162,7</td>
<td>539.8</td>
<td>10.3</td>
<td>17.0</td>
<td>1.70</td>
</tr>
<tr>
<td>65</td>
<td>40450</td>
<td>163,2</td>
<td>541.1</td>
<td>10.3</td>
<td>17.0</td>
<td>1.65</td>
</tr>
<tr>
<td>60</td>
<td>37340</td>
<td>164,1</td>
<td>543.3</td>
<td>10.3</td>
<td>17.0</td>
<td>1.60</td>
</tr>
<tr>
<td>55</td>
<td>34220</td>
<td>165,3</td>
<td>546.4</td>
<td>10.4</td>
<td>17.0</td>
<td>1.55</td>
</tr>
<tr>
<td>50</td>
<td>31110</td>
<td>166,7</td>
<td>549.9</td>
<td>10.5</td>
<td>17.0</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Table 1 shows the specific oil consumption and emission data used as basis for comparison with the ship with advanced emission technologies. It is remarkable, that the original engine installed on the A-class had a SFOC of 165,3 g/kWh at the 90% load, as a fuel optimized engine. The guarantied NOx compliance SFOC was according to SFOC =168,6 g/kWh when issued in 2002.
5.4 Engine with WIF and EGR technologies.

The MAN engine has a possible rating window up to 68.760 kW at 94 rpm and is a two stroke engine with a bore of 900 mm and a stroke of 2870 mm.

The A-class container ship has a 8,9 meter 6-bladed propeller designed for 100 rpm. As the new engine has a rpm of 94 this gives the possibility to increase the propeller diameter to 9,2 meter – which will increase the propeller efficiency accordingly.

The revised lay-out basis for this green ship will then be a main engine with a MCR of 62230 kW at 94 rpm and a CSR of 56000 kW (90%) maintaining 94 rpm for propeller lay-out. The better propeller efficiency reduces necessary added power from the shaft motor to 4000 kW to achieve the required ship speed of 26,5 knots. The propulsion efficiency gain by using a bigger propeller is abt. 3 %.

The rating 62230 kW of the main engine is selected as MCR and the engine is optimized for 90 % MCR as standard and as a compromise between with Tier 1/0 NOx requirements, and regards to WIF, EGR and WHR systems. MAN has proposed the following data which have been used for the evaluation and lay-out of WHR, power turbine (P/T) & steam turbine (S/T) generator unit and scrubber system etc.:

Table 2: 12K90ME9

<table>
<thead>
<tr>
<th>Load %</th>
<th>Power kW</th>
<th>SFOC g/kWh</th>
<th>Mass Flow EGR kg/h</th>
<th>Temp. EGR in Dg. C</th>
<th>Mass Flow T/C kg/h</th>
<th>Temp. T/C out Dg. C</th>
<th>EGR Bl. Power kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>62230</td>
<td>173,9</td>
<td>151230</td>
<td>457</td>
<td>352870</td>
<td>285,6</td>
<td>760</td>
</tr>
<tr>
<td>95</td>
<td>59110</td>
<td>172,4</td>
<td>155168</td>
<td>440</td>
<td>329732</td>
<td>278,8</td>
<td>780</td>
</tr>
<tr>
<td>90</td>
<td>56000</td>
<td>171,1</td>
<td>158304</td>
<td>431</td>
<td>307296</td>
<td>273,4</td>
<td>790</td>
</tr>
<tr>
<td>85</td>
<td>52890</td>
<td>169,9</td>
<td>160416</td>
<td>424</td>
<td>285184</td>
<td>269,4</td>
<td>800</td>
</tr>
<tr>
<td>80</td>
<td>49780</td>
<td>168,9</td>
<td>161576</td>
<td>418</td>
<td>263624</td>
<td>266,8</td>
<td>810</td>
</tr>
<tr>
<td>75</td>
<td>46670</td>
<td>168,2</td>
<td>161600</td>
<td>415</td>
<td>242400</td>
<td>265,6</td>
<td>810</td>
</tr>
<tr>
<td>70</td>
<td>43560</td>
<td>167,7</td>
<td>152760</td>
<td>407</td>
<td>229140</td>
<td>265,8</td>
<td>760</td>
</tr>
<tr>
<td>65</td>
<td>40450</td>
<td>168</td>
<td>143560</td>
<td>400</td>
<td>215340</td>
<td>267,4</td>
<td>720</td>
</tr>
<tr>
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<td>134040</td>
<td>395</td>
<td>201060</td>
<td>270,4</td>
<td>670</td>
</tr>
<tr>
<td>55</td>
<td>34220</td>
<td>169,7</td>
<td>124120</td>
<td>390</td>
<td>186180</td>
<td>274,8</td>
<td>620</td>
</tr>
<tr>
<td>50</td>
<td>31110</td>
<td>170,9</td>
<td>113800</td>
<td>387</td>
<td>170700</td>
<td>280,6</td>
<td>570</td>
</tr>
</tbody>
</table>
The electric power for the exhaust gas recirculation blower shall be noticed – EGR NOx reduction requires that the recirculation percentage remains high – between 30 to 40%.

The engine data in table 2 are the basis for the waste heat recovery system lay-out and the selection of exhaust boilers and P/T & S/T generator for this study.

MAN informs the following emission figures for an engine with WIF & EGR systems:

**Table 3: 12K90ME9 - Concept Ship engine with WIF and EGR – SFOC and specific emission data.**

| Load % | Power kW | SFOC g/kWh | CO2 SOx NOx PM mg/Nm³ |
|--------|----------|-------------|----------------------|---------------------|
| 100    | 62230    | 173.9       | 575.4 7.5 3.4 1.00   |
| 95     | 59110    | 172.4       | 570.5 7.4 3.4 0.98   |
| 90     | 56000    | 171.1       | 566.1 7.3 3.4 0.95   |
| 85     | 52890    | 169.9       | 562.1 7.3 3.4 0.93   |
| 80     | 49780    | 168.9       | 558.9 7.3 3.4 0.90   |
| 75     | 46670    | 168.2       | 556.5 7.2 3.4 0.88   |
| 70     | 43560    | 167.7       | 554.9 7.1 3.4 0.85   |
| 65     | 40450    | 168.0       | 555.9 7.1 3.4 0.83   |
| 60     | 37340    | 168.7       | 558.2 7.2 3.4 0.80   |
| 55     | 34220    | 169.7       | 561.5 7.2 3.4 0.78   |
| 50     | 31110    | 170.9       | 565.5 7.3 3.4 0.75   |

From table 3 it is seen the NOx values fulfil IMO Tier III level. SOx emissions have been reduced by 25% and particulates (PM) by 50%. All these emission reductions have been achieved by introduction of WIF and EGR technology. If a scrubber system is installed, after the waste heat recovery system in the casing, the total SOx and PM emission can be reduced with more than 90%.

6.0 Developed energy saving and exhaust gas cleaning technologies

The following developed technologies and methods have been selected for the concept study to evaluate the effect on emissions, electric balance (and fuel consumption), space requirements, budget costs and cargo intake for this container ship design if all these advanced technologies are introduced:
- EGR (exhaust gas recycling on main engine) – MAN technology
- WIF (water in fuel) – MAN technology
- PT & ST (power turbine and steam turbine) generator unit – MAN Turbo technology
- WHR (waste heat recovery) exhaust boilers – Aalborg Industries technology
- Exhaust gas scrubber system – Aalborg Industries technology

6.1 Change of main engine incl. EGR and WIF

The basic concept of the exhaust gas recirculation (EGR) technology is that the heat capacity of the re-circulated exhaust gas is higher than for normal combustion engine. This lowers the peak combustion temperature in the combustion chamber, which suppresses the formation of thermal NOx. The lower oxygen content (compared to the ambient air) in the re-circulated exhaust gas lowers the chemical reaction rate for the combustion of the fuel, and by that, also the peak combustion temperature becomes lower.

Why adding water to the fuel?

WIF is believed to decrease the NOx formation because the peak temperature is lowered due to the higher heat capacity of water vapor (compared to ambient air) and the heat absorption by water vaporization. It has also been observed, that the formation of PM is lowered when WIF is used, which can be explained by the phenomenon of micro-explosions or secondary atomization of emulsified fuel. This occurs, because the boiling point of water is lower than that of the surrounding fuel oil. The overall effect of the improved mixing of fuel with the combustion air is a decrease of the final CO, THC and PM concentrations. The improved mixing is also due to an increased momentum of the vaporized fuel jet (the mass is increased due to addition of water), which also improves the mixing. The presence of water in the fuels leads to a potential ignition delay, which means that more time for premixing of fuel and air is available. The last effect of WIF is an increased amount of hydroxyl radicals due to the higher water concentration. Hydroxyl radicals are essential in the oxidation of CO and THC.

In short:

EGR: recirculation of exhaust gas increases heat capacity and lowers O\textsubscript{2} content

WIF: water vapor in combustion chamber increases heat capacity and lowers O\textsubscript{2} content

\[ \rightarrow \text{High heat capacity and low O}_2 \text{ in scavenge air gives low combustion temperatures} \]

\[ \rightarrow \text{Low combustion temperatures give low NOx emissions} \]
Water in fuel (WIF) system.

The normal fuel system installed on the A-class container ship is a combined fuel system serving both main engine and auxiliary engines. This system has to be divided into separate systems for main and auxiliary engines, because the auxiliary engines can’t run with water in fuel without derating these engines.

The WIF fuel system for the main engine will look like this diagram – new components are water in fuel measuring device, homogenizer, dumping tank, safety fuel oil supply pump for securing pressure in the fuel system. In order to control the fuel / water mixtures and correct viscosity the temperature must be higher than normal (180 deg C) meaning that a heater is needed with higher pressure, than the normal 6 – 7 bar steam.

Fig.13: MAN water in fuel (WIF) system. The yellow marked components are new added or changed components compared to the normal main engine fuel system for this size of main engine.
Fig. 14: WIF principal pipe diagram – as it can be seen the proposal include two steam heaters for heating the water fuel mix, one for normal steam (6.5 bar) and one to higher temperature steam (15 bar) (MAN).

The WIF system with water in the fuel to cool the combustion to reduce the NOx formation requires - that the ship must have extra fresh water production. The diagram show that a production of abt. 123 tons per 24 hours is needed at the MCR output for this engine – (read more about this in the section 6.6 concerning sizing of FW generators for the demand of fresh water required by these technologies).
Exhaust gas recirculation (EGR).

A typical EGR system will include scrubber, cooler, water mist catcher, blower and NaOH support system with pump and tank.

The MAN proposed EGR system can be seen at this diagram.

![Diagram of MAN proposed EGR system](image)

**Fig.15: MAN proposed EGR system.**

Figure 15 shows an EGR system. An EGR exhaust boiler is added for energy recovery of the heat in the recirculated exhaust gas. This EGR exhaust boiler is designed by Aalborg Industries as described in the WHR system section.

The typical installation for a MAN engine in an engine room can be seen on figure 16.
The components needed for the EGR system take up some space in the engine room, which have to be considered in the overall machinery arrangement (MAN).

Based on the 12K90ME9 engine MAN has sized the EGR components for this engine. Power consumption figures, particularly for the EGR blower, dimensions and weights for the different components are also given by MAN – table 4 and 5.

EGR blower electrical demand.

The EGR system blowers require the following electric power – table 4:

<table>
<thead>
<tr>
<th>ME %</th>
<th>100</th>
<th>95</th>
<th>90</th>
<th>85</th>
<th>80</th>
<th>75</th>
<th>70</th>
<th>65</th>
<th>60</th>
<th>55</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW(e)</td>
<td>760</td>
<td>780</td>
<td>790</td>
<td>800</td>
<td>810</td>
<td>810</td>
<td>760</td>
<td>720</td>
<td>670</td>
<td>620</td>
<td>570</td>
</tr>
</tbody>
</table>

The above variation has to be taken into account in the electric balance calculation for the fuel and emission calculations with the load profile.
Table 5:

**EGR System Installation – 12K90ME9**

<table>
<thead>
<tr>
<th>Component</th>
<th>Dry mass (kg)</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGR Unit (x2)</td>
<td>10000</td>
<td>Length=3750; Height=3143; Width=1580</td>
</tr>
<tr>
<td>Scrubber</td>
<td>3500</td>
<td>Length=3750; Ø = 1150</td>
</tr>
<tr>
<td>Blower + wheel</td>
<td>3000</td>
<td>Length=1650; Height = 1611; Width=1580</td>
</tr>
<tr>
<td>Cooler + housing</td>
<td>4000</td>
<td>Length=1350; Height = 1800; Width = 1580</td>
</tr>
<tr>
<td>Buffer tank (x2)</td>
<td>450</td>
<td>Ø1260; Height=2010</td>
</tr>
<tr>
<td>Electrical cabinets (x4)</td>
<td>50</td>
<td>Length=1400; Width=624; Height=2040</td>
</tr>
<tr>
<td>Water Cleaning unit (x2)</td>
<td>100</td>
<td>Length=2000; Width=1000; Height=1800</td>
</tr>
<tr>
<td>Polishing unit (x2)</td>
<td>100</td>
<td>Length=2000; Width=1000; Height=1800</td>
</tr>
<tr>
<td>NaOH tank (x2)</td>
<td>1000</td>
<td>Length=4300; Width=950; Height=1200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Power consumption(kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blower</td>
<td>See process data</td>
</tr>
<tr>
<td>Seawater pump (x2)</td>
<td>20kW</td>
</tr>
<tr>
<td>Scrubber pump (x2)</td>
<td>15kW</td>
</tr>
<tr>
<td>Water Cleaning/Polishing unit (x2)</td>
<td>15kW</td>
</tr>
<tr>
<td>NaOH pump (x2)</td>
<td>0.2kW</td>
</tr>
<tr>
<td>NaOH heating (x2)</td>
<td>4kW</td>
</tr>
<tr>
<td>Actuators/Sensors</td>
<td>1kW</td>
</tr>
</tbody>
</table>

Notice the large size of the different components which increases demand for available space in the engine room.
**NaOH consumption in connection with EGR system.**

Necessary NaOH depends on the sulphur percentage in the fuel and the engine load - the table 6 gives the consumption figures as stated by MAN:

**Table 6: NaOH consumptions based on engine load and Sulphur content in fuel.**

<table>
<thead>
<tr>
<th>Load %</th>
<th>Power kW</th>
<th>SFOC g/kWh</th>
<th>EGR %</th>
<th>NaOH/H₂O solution 1%S l/h</th>
<th>2%S l/h</th>
<th>3%S l/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>62230</td>
<td>176,5</td>
<td>0,3</td>
<td>61</td>
<td>123</td>
<td>184</td>
</tr>
<tr>
<td>75</td>
<td>46670</td>
<td>171,7</td>
<td>0,4</td>
<td>56</td>
<td>112</td>
<td>168</td>
</tr>
<tr>
<td>50</td>
<td>31110</td>
<td>174,5</td>
<td>0,4</td>
<td>38</td>
<td>76</td>
<td>114</td>
</tr>
</tbody>
</table>

With a NaOH price of 2,9 $ per liter the running costs for NaOH, running at 75% main engine load on fuel with 3% sulphur, adds up to 11693 $ per 24 hour! Prices for NaOH/H₂O solution are given by MAN.

It further requires that the ship must have NaOH store tanks installed. Capacity for 30 days based on fuel with 3% sulphur and an average main engine load of 75% require a total stores capacity of 125 m³.

**6.2 Waste Heat Recovery Systems**

Even though a two stroke engine has a very high energy efficiency of 50 % the primary objective is to further increase this number. This can be done by utilizing a waste heat recovery system changing waste heat to valuable electric power to reduce the CO₂ emissions from the ship.

The manufacturers of slow speed engines, such as MAN Diesel as one of the leading manufacturers, have taken up the challenge of reducing the specific fuel oil consumption and the results are that slow speed diesel engines today have a thermal efficiency of approximately 50 %. This high number makes it hard to improve the efficiency further within the engine. Therefore the possibility of installing WHR (Waste Heat Recovery) plants in the vessels to lower the fuel consumption of the ship and further minimise the emission of CO₂, has been investigated and there are large potentials in these systems.
The WHR system consist of an exhaust gas fired boiler supplying steam to a steam turbine. To further boost the electrical output the system can be extended with a gas turbine utilizing the energy in the exhaust gas not used by the turbo charger. To obtain the highest electrical production the optimal solution is to use a dual steam pressure system or even a triple steam pressure system if the engine is equipped with a system for exhaust gas recirculation. The more complex multi steam pressure systems need further supplementary waste heat recovery to heat the feed water. For these systems the available heat in the jacket water and scavenge air is utilized to pre heat the feed water up to just below the saturation temperature.

When designing the systems it has been found beneficial that the engine, the exhaust gas fired boiler and the turbines are optimized in a coordinated manner. An example is that the temperature of the steam can be raised significantly in a superheater situated on the pressure side of the gas turbine or the turbo charger. This position of the super heater influences the design of the engine, boiler and turbines.

**Obtainable electric power output.**

Single steam pressure WHR systems are relatively simple and the total power production in % of the main engine shaft power is limited; however adequate for some kind of vessels – Bulk Carriers and Crude Oil Tankers. For these systems the available electric power production without gas turbine is approximately 5 % and when a gas turbine is added the electrical power output can be as high as 9 - 10 % of the main engine shaft power.

For dual steam pressure WHR systems the available electrical power output can be increased to 11 – 12 % of the shaft power when a gas turbine is included and approximately 7 % without the gas turbine.

For systems where NOx is reduced by means of exhaust gas recirculation there is an opportunity to increase the power output due to the high exhaust gas temperature in the EGR string of the WHR system. For these systems it is found to be beneficial with a triple steam pressure system. Investigations have shown that a power production of up to 14 % of the engine power is available at 85 % MCR for a large slow speed diesel engine, as in this case.

The triple steam pressure system has been selected for this study in order to get as much as possible recovered energy to support CO2 reduction and cover electrical demands associated with the emission technologies.

The principles for the waste heat recovery system can be seen on figure 17 and figure 18.
Fig. 17: Air and exhaust flow diagram for main engine, exhaust boilers, power turbine and scrubber.

The green loop is the EGR exhaust recycling, the red the air intake and the blue the exhaust flow after the main engine.

In order to utilize as much as possible of the exhaust energy, it is proposed to use a triple steam pressure system. A steam system with high pressure (HP), intermediate pressure (IP) and low pressure (LP) steam circuits and consisting of the following components: 1) A feed water system that utilizes energy from the main engines jacket water system and the main engine scavenging air cooler, 2) Heat in the EGR system is used by placing a EGR exhaust boiler in this circuit and 3) IP & LP evaporators and super heaters are placed in the exhaust flow after the main engine.

The EGR exhaust boiler includes HP super heater, HP evaporator / drum and IP evaporator / drum sections.
Fig. 18: Waste heat recovery steam circuit – **Blue** 15 Bar(a) steam, **green** 6.5 Bar(a) steam and **red** 1.5 Bar(a) steam.

The waste heat recovery exhaust boiler system and components proposed by Aalborg Industries are given more in details in the following:

**EGR exhaust boiler.**

The EGR exhaust boiler will be supplied in three units’ high pressure (HP), intermediate pressure (IP) and low pressure (LP) units, designed similar to the horizontal cylindrical AV4 boilers. The IP and LP evaporator units act as steam drum for the heating surface in the conventional exhaust boiler arranged in the casing together with the scrubber.
The EGR exhaust boiler parts have the following dimensions and weights:

**HP unit included Superheater:**

Diameter: 3450 mm  
Length: 7100 mm  
Height: 3900 mm  
Weight incl. water: 92.6 tons

**IP unit included HP Economizer and IP Economizer:**

Diameter: 3450 mm  
Length: 5700 mm  
Height: 3900 mm  
Weight: 29.2 tons

**LP unit:**

Diameter: 3450 mm  
Length: 4800 mm  
Height: 3900 mm  
Weight: 45 tons

The boilers are connected to the EGR system - coupled with exhaust gas ducts.

**Conventional exhaust boiler**

The Conventional exhaust boiler consist of two parts intermediate pressure (IP) and low pressure (LP) part and the installation has to be designed so that the exhaust gas flows upstream in the IP section and downstream in the LP section as well as in the scrubber. After the scrubber a cyclone is placed beneath the scrubber and after the cyclone the exhaust gas has to flow upstream through the reheater section:

**IP exhaust boiler incl. superheater:**

Length: 6000 mm + 2000 mm for retraction of soot blowers  
Width: 3950 mm plus 1200 mm for supports and columns  
Height: 4200 mm  
Weight: 84 tons

**LP exhaust boiler incl. superheater:**

Length: 5250 mm + 2000 mm for retraction of soot blowers  
Width: 3950 mm plus 1200 mm for supports and columns  
Height: 4150 mm  
Weight: 66 tons
A typical conventional waste heat recovery exhaust boiler from Aalborg Industries is shown in figure 19. The low pressure exhaust boiler is arranged above the intermediate pressure exhaust boiler to utilize the main engine exhaust gas enthalpy.

Fig. 19: Waste heat recovery exhaust gas boiler (Aalborg industries).
6.3 Scrubber system
This concept study is based on using Aalborg Industries scrubber technology, which basically can be seen in figure 20.

![System diagram for the scrubber in the casing (Aalborg Industries).](image)

The system will use both on sea water and fresh water with NaOH depending on the situation. The basis is to use sea water for scrubbing at open sea and fresh water with NaOH for scrubbing during manoeuvring and in harbour conditions at up to 20% main engine load. The SOx in the exhaust gas comes in contact with sea water or fresh water with NaOH in the scrubber and it reacts into sulphate which is harmless in sea water. PM will likewise be collected in the scrubbing water. The sea water contains a lot of sulphate (see figure 21), anyway, so a bit more sulphate added will not make a detectable difference. The PM will be discharged in concentrations accepted according to IMO rules.
Fig. 21: Salt in sea water and the composition of salts.

The scrubber must be arranged after the waste heat recovery exhaust boiler in the casing area, as indicated on the following figures 22 and 23.

Fig. 22: Arrangement with recirculation of fresh water with NaOH as reactant (Aalborg Industries).
The scrubber for this ship will be very big and require much space – (read more in section 6.5 concerning space considerations).

The scrubber from Aalborg Industries will look as shown in figure 24.
Aalborg Industries have calculated the scrubber system to have the following data for the exhaust data given by MAN:

**Data for FW operation 20 % MCR**
- Max engine loading during FW operation: 20 % MCR
- Power consumption of water pump: 9 kW
- Plate heat exchanger: 6 MW
- NaOH consumption: 162 kg/h 50 % (w/w) solution
- Re-circulation flow: 249 m$^3$/h
- Water discharge: 2.5 m$^3$/h
- FW storage tank capacity: 20 m$^3$

**Data for SW operation 100 % MCR**
- Power consumption water pump: 367 kW
- SW consumption = SW discharge: 3110 m$^3$/h

Dimensions of scrubber:

- Scrubber:
  - Length: 4950 mm
  - Width: 3650 mm plus 1200 for supports and columns
  - Height: 6600 mm
  - Weight: 21 tons

- Cyclone:
  - Diameter: 3200 mm
  - Length: 5400 mm
  - Weight: 10 tons

- Reheater:
  - Width: 1800 mm
  - Length 4950 mm
  - Height 2000 mm
  - Weight: 20 tons

Aalborg Industries states the following reductions by using scrubber for this case:

- SOx reduction: >90%
- PM reduction: > 60%

These reduction figures will be used in the calculation of the total ship emissions.
6.4 Turbo generator system
The following WHR turbine data, table 7, has been supplemented by MAN Turbo based on MAN engine exhaust data and Aalborg Industries steam data.

<table>
<thead>
<tr>
<th>Load Point</th>
<th>Design 85%</th>
<th>100%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP Steam at Turbine Inlet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure bar(a)</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Flow t/h</td>
<td>14.055</td>
<td>15.500</td>
<td>7.795</td>
</tr>
<tr>
<td>MP Steam at Turbine Inlet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure bar(a)</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>260</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>Flow t/h</td>
<td>12.070</td>
<td>17.530</td>
<td>7.700</td>
</tr>
<tr>
<td>LP Steam at Turbine Inlet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure bar(a)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Flow t/h</td>
<td>9.920</td>
<td>11.170</td>
<td>6.320</td>
</tr>
<tr>
<td>Condensing Steam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure bar(a)</td>
<td>0.08</td>
<td>0.098</td>
<td>0.057</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>41.5</td>
<td>45.4</td>
<td>35.2</td>
</tr>
<tr>
<td>Flow t/h</td>
<td>36.045</td>
<td>44.200</td>
<td>21.815</td>
</tr>
<tr>
<td>Cooling Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Temperature °C</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Outlet Temperature °C</td>
<td>33.0</td>
<td>34.7</td>
<td>29.9</td>
</tr>
<tr>
<td>Flow t/h</td>
<td>2.473</td>
<td>2.473</td>
<td>2.473</td>
</tr>
<tr>
<td>Output at steam turbine coupling kW</td>
<td>6.045</td>
<td>6.650</td>
<td>3.494</td>
</tr>
<tr>
<td>Output at power turbine coupling kW</td>
<td>1.260</td>
<td>1.740</td>
<td>430</td>
</tr>
<tr>
<td>Electrical Output kW_e</td>
<td>7.052</td>
<td>8.099</td>
<td>3.551</td>
</tr>
<tr>
<td>Steam Turbine Layout</td>
<td></td>
<td>20 cylindrical stages</td>
<td></td>
</tr>
<tr>
<td>Steam Turbine Speed rpm</td>
<td></td>
<td>2 twisted stages</td>
<td></td>
</tr>
<tr>
<td>Steam Turbine Speed rpm</td>
<td>8 657</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Medium pressure (MP) in this table is the same as intermediate pressure (IP).
The MAN Turbo power turbine (P/T) & steam turbine (S/T) generator unit composed of the following components:

1 steam turbine with high pressure (HP), medium pressure (MP) and low pressure (LP) steam feed including the following features:
   - multiple stage reaction design,
   - turbine casing of cast design,
   - guide blade carriers of cast or forged design,
   - HP, MP and LP part throttle control by external steam armatures: 1 emergency stop armature and 1 control armature for each steam feed (loose delivery),
   - steam strainer for each steam feed (loose delivery),
   - gland steam system and turbine drainage system,
   - rotor turning device,
   - thermal insulation consisting of glass fiber mats with mineral wool filling.

1 exhaust gas turbine (power turbine) including the following features:
   - variable inlet area geometry (VTA),
   - thermal insulation consisting of glass fiber mats with mineral wool filling.

1 parallel shaft gearbox between steam turbine and generator including high speed curved tooth coupling at the fast and the slow end.

1 parallel shaft gearbox between power turbine and generator including high speed curved tooth coupling and SSS coupling.

1 three-phase 4-pole synchronous generator driven from both sides including the following features:
   - out feed and star point box,
   - brush-less excitation system,
   - automatic voltage regulator,
   - single air/water cooler.

1 combined oil system for lubrication and control for turbine, gear box and generator, comprised of:
   - oil tank integrated in package base frame,
   - single water-cooled oil cooler,
   - 5 bar(g) low pressure system for lubrication with 1 x 100% mechanical driven main pump and 1 x 100% electrical driven auxiliary pump,
   - 2 x 100% lubrication oil filters,
   - 160 bar(g) high pressure system for control with 1 x 100% electrical driven pump,
   - 2 x 100% control oil filters,

1 common base frame for steam turbine, power turbine, generator, gear boxes and oil system including spring elements for integration into vessel structure.
1. Local MAN package control cubicle as a black box system for installation in proximity of the package, comprised of two fields containing:
   - package control system based on Siemens S7-400,
   - package supervisory equipment,
   - package protection equipment,
   - automatic synchronizing equipment,
   - power management system for package.

1. Measuring and control cabling between MAN package and MAN cabinets.

1. Water cooled condenser incl. connecting steam line between turbine and condenser, evacuation unit based on steam ejectors or water ring pumps, discharge/circulation control and 2 x 100% condensate pumps. Cooling water design inlet temperature according ISO ambient conditions.

The power turbine and steam turbine generator unit proposed by MAN Turbo can be seen on figure 25 and 26.

![Diagram of P/T & S/T generator unit (MAN Turbo)](image)

**Fig. 25:** Top view of P/T & S/T generator unit (MAN Turbo).
The shown power turbine and steam turbine generator unit arrangement in figure 26 is a typical turbo generator arrangement. The power turbine, steam turbine, gears and generator are placed on one foundation on deck and the big steam condenser is placed on the deck below.

The P/T & S/T generator unit proposed by MAN Turbo has the following main dimensions and weight:

Length: 10943 mm

Height: 4812 mm excl condenser

Width: 4262 mm

Weight: 115 tons
Power output of the P/T & S/T generator unit.

Based on the steam data given by Aalborg Industries and MAN exhaust data - MAN Turbo has given the following output data for the power turbine (P/T), steam turbine (S/T) and electric output from generator as seen in table 8:

Table 8: Power turbine, steam turbine and generator output data.

<table>
<thead>
<tr>
<th>ME Load</th>
<th>ME Power</th>
<th>P/T Power</th>
<th>S/T Power</th>
<th>Electric Power</th>
<th>Power recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>kW</td>
<td>kW</td>
<td>kW</td>
<td>kW(e)</td>
<td>%</td>
</tr>
<tr>
<td>100</td>
<td>62230</td>
<td>1737</td>
<td>6650</td>
<td>8094</td>
<td>13,0</td>
</tr>
<tr>
<td>95</td>
<td>59110</td>
<td>1568</td>
<td>6448</td>
<td>7735</td>
<td>13,1</td>
</tr>
<tr>
<td>90</td>
<td>56000</td>
<td>1407</td>
<td>6247</td>
<td>7386</td>
<td>13,2</td>
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<tr>
<td>85</td>
<td>52890</td>
<td>1255</td>
<td>6045</td>
<td>7045</td>
<td>13,3</td>
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<td>80</td>
<td>49780</td>
<td>1112</td>
<td>5680</td>
<td>6554</td>
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<td>6042</td>
<td>12,9</td>
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<td>851</td>
<td>4951</td>
<td>5541</td>
<td>12,7</td>
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<td>40450</td>
<td>734</td>
<td>4587</td>
<td>5028</td>
<td>12,4</td>
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<td>60</td>
<td>37340</td>
<td>625</td>
<td>4222</td>
<td>4532</td>
<td>12,1</td>
</tr>
<tr>
<td>55</td>
<td>34220</td>
<td>526</td>
<td>3858</td>
<td>4055</td>
<td>11,8</td>
</tr>
<tr>
<td>50</td>
<td>31110</td>
<td>434</td>
<td>3494</td>
<td>3594</td>
<td>11,6</td>
</tr>
</tbody>
</table>

The generator output is over 13% related to the engine power – which offers good opportunity for full electrical power supply in many conditions even after reduction for the extra power consuming components.
6.5 Space considerations and consequences of installing WHR system and scrubber.

The A-class container ship, as designed in 2002, does not have space for all the energy saving and emission reducing technologies which therefore require design changes. The necessary modifications will be described in the following.

Two additional engine rooms aft of the existing engine rooms have to be added and a total redesign of the casing / accommodation has to be carried out including also redesign and optimization of the existing rooms in general.

Fig. 27: Re-arranged machinery room. Compared to A-class vessels the machinery rooms beside the main engine have been rearranged to make space for the waste heat recovery system. This included rearrangement of auxiliary diesel generator sets further aft.

To make room for the EGR system the cargo hold above the starboard auxiliary engines needs to be included in the machinery room. With this location short exhaust gas piping between main engine and EGR components including EGR exhaust boiler are obtained. 35 TEU container positions are lost due to this re-arrangement. Figures 28 and 29 show the necessary changes.
Fig. 28 & 29: Proposed area for installation of EGR equipment.

Scrubber 1

Scrubber 2

EGR exhaust boiler
(HP incl. superheater, HP and IP Economizers, LP Economizer)
Together with the EGR boiler and EGR scrubber units, NaOH pumps and tanks have to be installed as necessary ancillary equipment.

Fig. 30: Typical casing arrangement for a large container ship with WHR exhaust boilers installed. The additional volume necessary for this equipment more than doubles the existing engine casing size.
To insure space for the scrubber system and necessary ancillary machinery for the scrubber system the casing volume must be doubled – see below figure 31.

Fig. 31: Space necessary for scrubber system. Based on dimensions given by Aalborg Industries the casing has to be extended as shown by the red lines.

The installation of the scrubber system and WHR exhaust boiler in casing area has the impact the ship looses 35 TEU positions.
**Total impact on cargo space and light weight.**

The rearrangement of the engine room to secure sufficient space for the extra components related to WHR and emission technologies has further the effect that the ship losses 44 TEU positions for the WHR system, 35 TEU positions for the EGR components below main deck and 35 TEU positions above the main deck aft of accommodation for the scrubber installation. Totally 114 TEU positions are lost compared to the original 8500TEU’s (1,3% capacity reduction).

All these waste heat recovery and emission reducing technologies have apart from volume and space requirement also a weight penalty of about abt. 880 ton including rebuilding of casing and decks in machinery rooms.

**6.6 Effect of WIF and scrubber system on water demand.**

Due to the added consumers of fresh water onboard compared to the basis vessel the GSF concept ship shall have installed a large plant for production of fresh water.

**Fresh water consumers:**

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Consumption/24 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>General purposes</td>
<td>24 t/24 hr</td>
</tr>
<tr>
<td>Water in fuel</td>
<td>126 t/24 hr</td>
</tr>
<tr>
<td>EGR scrubber system</td>
<td>1 t/24 hr</td>
</tr>
<tr>
<td>Main scrubber system</td>
<td>10 t/24 hr</td>
</tr>
</tbody>
</table>

**Total FW consumption** 161 t/24 hr

The most significant consumer is the water in fuel (WIF) system. The fuel is mixed with 50 % water to reduce NOx emissions as described in this report.

The EGR scrubber system is using fresh water in a closed circuit. A small portion is lost during the cleaning process where the sulphur and particulate matter are separated. However the humid exhaust gas is condensed to some extent of which reason the total FW consumption is relatively low.

The main scrubber is using sea water which is diluted overboard when at open sea. In port and within national territorial waters the main scrubber system is using fresh water in a closed circuit. Topping up is necessary to compensate for the volume lost in the cleaning process.
**FW production:**

The basis ship is equipped with a conventional fresh water generator of the vacuum evaporation type with a capacity of 36 t/24 hr.

To cover the increased demand for fresh water in the concept ship a pair of two-stage Fresh water generators is envisaged.

Each has a capacity of up to 75 m³/24 hr. Heat required for the evaporation process will be approximately 1500 kW per unit.

The fresh water is produced by utilizing the heat in the HT cooling water circuit on the ships main engine. The cooling water leaves the engine at about 90°C after having cooled the cylinder jackets. 7690 kW is available in the HT cooling water system and is otherwise transferred to the sea and lost if not utilized onboard for heating purposes.

The fresh water generating plants capacity is on the limit of the required production to fulfill the demand by the consumers. Therefore additional means for producing fresh water will be necessary.

The main engine charge air coolers condense a large amount of water from the combustion air, water that is normally led overboard.

Even at modest engine loads several tons of water is drained from the mist catchers and can easily cover the deficit between production and demand.

\[
\text{Fresh water generators } 2 \times 75 \text{ t/24 hr} = 150 \text{ t/24 hr} \\
\text{Total fresh water consumption} = 161 \text{ t/24 hr} \\
\text{Required amount condensated from main engine T/C Air coolers} = 11 \text{ t/24 hr} \\
The \text{electric power for the pumps used to run these fresh water generators is 38 kW.}
\]

6.7 Pump and cooler optimization

Onboard the ship the following cooling water systems are present:

**Machinery related cooling systems:**
- SW cooling system for central coolers
- LT cooling system (for cooling of auxiliary machinery and HT circuit)
- HT cooling system (For main engine and fresh water generator heating)
Reefer cooling system:
SW cooling system
FW cooling system.

Turbo generator condenser cooling system:
SW cooling system for steam condenser

To obtain an effective and pricewise solution for the cooling water systems it is important to specify:
- pipe dimensions for low pressure drop (maximum 2 m/s)
- sufficient numbers of pumps or frequency converters to obtain flow deviations
- coolers, SW filters and components with low pressure drop
- valve types with low pressure drop
- pumps head close to pressure drop in system to avoid regulating orifice
- motors with high efficiency
- pumps with best efficiency

An important parameter is the number of hours of port stay per year. As a containership often spends 2000-2500 hours in port each year opportunities for installation of port slow-down means become obvious as listed in table 9 including the associated power reductions.

Table 9: Power savings in port by different reducing means

<table>
<thead>
<tr>
<th>Topic</th>
<th>kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omit orifices</td>
<td>413.000</td>
</tr>
<tr>
<td>Coating of pumps</td>
<td>390.000</td>
</tr>
<tr>
<td>High efficiency motors</td>
<td>140.000</td>
</tr>
<tr>
<td>Optimum pump efficiency</td>
<td>84.000</td>
</tr>
<tr>
<td>VSD on SW pumps</td>
<td>485.000</td>
</tr>
<tr>
<td>HT pump at port stay</td>
<td>100.000</td>
</tr>
<tr>
<td>LT system split up at port</td>
<td>113.000</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
<td>~1.725.000</td>
</tr>
</tbody>
</table>

In total, a rough saving on 40% and 1040 tons of CO₂ per year can be obtained.

For details see enclosure 1.
Savings in turbo generator condenser cooling system

Equals means as for machinery related cooling water systems can be utilized for the turbo generator condenser cooling system. Estimated saving is 700.00kWh at 100% flow conditions (the result will be lower if 2x50% pumps are installed and reduced operation of pumps are used, when possible). The main reason for the large saving is the use of frequency control. A load factor on 25% is included as this is when the pumps could be turned off (harbour time), resulting in an annual saving on 525.000kWh.

Summary of all cooling water systems

The total savings per system is summarised in table 10.

Table 10: Electrical power savings from changes in the cooling systems.

<table>
<thead>
<tr>
<th>Name:</th>
<th>Before: kW(e)</th>
<th>After: kW(e)</th>
<th>Saving: kW(e)</th>
<th>Comment:</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW pump</td>
<td>236</td>
<td>159</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>LT pump</td>
<td>194</td>
<td>131</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>HT pump</td>
<td>62</td>
<td>42</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>SW pump (reefers)</td>
<td>70</td>
<td>49</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>FW pump (reefers)</td>
<td>125</td>
<td>88</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Condenser SW pump</td>
<td>143</td>
<td>96</td>
<td>47</td>
<td>Not running in harbour</td>
</tr>
<tr>
<td><strong>Total saving – el-balance:</strong></td>
<td></td>
<td></td>
<td><strong>255</strong></td>
<td></td>
</tr>
</tbody>
</table>

The 255 kW(e) is a saving of abt. 13% of the average electric service load at sea!

The total saving is 2.450.000kWh per year. It can roughly be calculated that 1 tons of HFO produces 3 tons of CO₂ emission, hence the annual saving in CO₂ with the before mentioned means are 1480 tons of CO₂ or 1% of the total CO₂ emission per year for this size of container ship.
6.8 Ballast treatment system
The IMO ballast water treatment rules was planned to be in force already, which however has been delayed (probably due to lack of approved systems). Whenever the rules will come into force is at this moment un-clear, but expectations are heading for a full implementation within few years. How the delay will affects the present implementation schedule is at the moment unclear.

![ IMO ballast water treatment implementation plan.](image)

The ships ballast system consists of 2 ballast pumps each designed for a capacity of 600 m$^3$/h. One ballast stripping ejector with motive water from the general service pumps is installed. It is important that the capacity of the ballast water treatment system is designed for a capacity close to the sum of the motive water consumption + the suction flow.

A DESMI OCEAN GUARD ballast water treatment system is used for this study. The system consists of the following main parts:
- Gravity/"open" filter
- Buffer tank
- UV sterilizer
- Ozone generator
- Ozone reactor

This new ballast water treatment system meets the international maritime organisation’s *International Convention for the control and management of ship’s ballast water and sediments*. It also takes the expected US ballast water regulations into consideration.

This system has low power consumption - only 50kW needed for treatment of a 2x600 m$^3$/h ballast water system.

For further details see enclosure 2.

6.9 LNG for aux. engine in harbour mode
Container ships have long harbour stays per year, APM inform, that the A-class spend about 25% of the time per year in harbour. The average electric loads in harbour of about 2000 kW will generator much emission.
One of the promising technologies to solve this problem is to install auxiliary diesel generators of the dual-fuel type. This type of engine is designed to run both on HFO, diesel or natural gas. It will be possible to reduce emissions if the dual-fuel auxiliary diesel generator runs on gas during port stays. When the ship is at sea, HFO or diesel will be utilized. Natural gas could also be utilized in a dual-fuel boiler during port stay to decrease the emission from the boiler.

The benefits by using LNG operation of an auxiliary diesel generator during port stay are following:

- Sulphur emission very close to zero
- ~90% lower NOx emission
- ~15% lower CO₂ emission (gas leakage deducted, which is lowering the CO₂ saving)
- ~97% lower SOx emission
- ~85% lower particle emission (due to the pilot fuel)
- No visible smoke

The natural gas can be stored in liquefied state as LNG in 40-feet containers each holding roughly 30 m³ of LNG. As the LNG supply chain for harbour hardly exists today a solution could be to supply the LNG in special containers. This solution will simplify the necessary changes for the ship installation. However, handling of the LNG containers in port and storage of LNG onboard needs to be approved by class and authorities prior to the selection of this solution. This is at the moment a “dark horse” which needs to be discussed and developed further.

During port stay the average electrical load is roughly estimated to 2000kW including 25% reefer container consumption.

![Gas consumption on DG](image-url)  

**Fig. 33:** Gas consumption based on diesel generator load.
The CO₂ saving at an average harbour electrical service load of 2000kW is calculated to 180 kg CO₂/h.

**Installation of one dual fuel aux. engine running on LNG at harbour operation will save the harbours for 400 ton CO₂ per year (and requirements for Tier III are fulfilled).**

**Other harbour emission reduction alternatives**

**Selective catalytic reduction (SCR)**

Change of fuel type may not be possible. Then a solution could be to install SCR system in the exhaust stack for the auxiliary engines and run the engines on MDO or MGO. The SCR system can be offered by a number of manufactures around the world. The SCR system consists of a reaction chamber (ceramic honeycomb structure) and a urea dosing system.

The SCR installation will reduce NOx emission by more than 90%.

**Electric power from harbour**

Diesel generator emissions can be zero, if the ships electric power is supplied from ashore. Some harbours have this option, but it is not common yet throughout the world. This solution will require extra electric power equipment to be installed - a “cold ironing” solution – both on the ship and at the harbour side.
6.10 Other means to reduce propulsion power – advanced rudder, hull devices and paint.

There exists on the market a whole series of devices that can reduce hull resistance or increase propulsion efficiencies:

**Hull coatings.**

The present ship has conventional anti-fouling coating. By introducing of silicone type of hull coating (so-called 2nd generation), tests at FORCE have indicated up to a 2 % reduction on the frictional resistance of the hull. This means a total resistance reduction of abt. 1.5 %.

**Advanced rudder.**

By “twisting” rudders, as on the Becker-type, to utilize the swirl in the propeller race, model tests according to FORCE have shown efficiency savings of 2%.

**Advanced propeller.**

There are distinct advanced propeller blade designs available, the Danish Kappel-design, and the Spanish CLT (both claim less induced efficiency loss at the blade tips) and the Japanese NPT-type (New Profile Technology). The claimed savings in efficiency varies much, but 3 % savings is at least possible according to FORCE. For the CLT is even claimed up to 7 %.

Also the so-called Propeller Boss Cap Fin (PBCF) by Japanese Mitsui-OSK comes into this category. 5 % efficiency gain is claimed.

Common for the above is that it is difficult to determine the exact full scale performance based on model tests. Only when these have been installed on some ships in a larger series of ships a fair comparison of the full scale performance can be obtained.

Contra-Rotating propellers have, from a purely hydrodynamic point of view, great expectations and the model tests can better predict the full scale performance being well established. Up to 14-15 % gains in efficiency have been claimed by Japanese manufacturers and some ships have already been built.

Container ships up to 10000 TEU with CRP are reported being on the drawing board in Japan. Due to the mechanical complexity of CRP-systems they have, however, not found wider use.

Contra Rotating Pods have been extensively investigated. There are hydrodynamic gains, but this is overshadowed by electric transmissions losses and that the electric power must come from 4-stroke diesel engines with poorer specific fuel consumption.

In the present study the reductions used for the above are taken to 1.5 % for coatings, 2 % for advanced rudders and 3 % for new propeller designs. The results by including these reductions means can be seen in section 8.2.
6.11 Effect on electric balance
Energy saving and emission technologies components requires a number of pumps, blowers etc. which consume electric power - and this adds to the electrical balance for the ship. Details can be seen in enclosure 3. The added electric power can be summed up to:

<table>
<thead>
<tr>
<th></th>
<th>Basic ship:</th>
<th>Ship with emission technologies:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kW(e)</td>
<td>kW(e)</td>
</tr>
<tr>
<td><strong>Normal service at sea</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>excl. Shaft motor, excl. Reefers:</td>
<td>1820</td>
<td>3377</td>
</tr>
<tr>
<td>excl. Shaft motor, 50% Reefers:</td>
<td>4100</td>
<td>5657</td>
</tr>
<tr>
<td><strong>Average:</strong></td>
<td>2960</td>
<td>4517</td>
</tr>
<tr>
<td><strong>Harbour load</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>excl. Reefers:</td>
<td>890</td>
<td>890</td>
</tr>
<tr>
<td>incl. 50% reefers:</td>
<td>3150</td>
<td>3150</td>
</tr>
<tr>
<td><strong>Average:</strong></td>
<td>2020</td>
<td>2020</td>
</tr>
</tbody>
</table>

The added electric power to support energy saving and emission reduction technologies is calculated to 1557 kW(e) at sea – an increase of 53% (average at sea load basic).

The three most power demanding components are the EGR blowers, scrubber sea water pump and steam condenser sea water cooling pump. They represent a total added electric power of 1272 kW(e) or 81% of the added electric power.
6.12 Economical consequences associated with implementing emission technologies
All these emission and waste heat recovery technology can’t be installed in a ship without extra initial costs.

Table 11: The budget prices reported for these technologies are as follows:

<table>
<thead>
<tr>
<th>Costs - initial:</th>
<th>x 1000 Euro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary Prices</td>
<td></td>
</tr>
<tr>
<td>WHR &amp; EGR exhaust boiler:</td>
<td>1200</td>
</tr>
<tr>
<td>WIF system:</td>
<td>125</td>
</tr>
<tr>
<td>EGR system:</td>
<td>2800</td>
</tr>
<tr>
<td>Scrubber after WHR exhaust boiler:</td>
<td>2450</td>
</tr>
<tr>
<td>Turbo, power &amp; steam generator set:</td>
<td>3800</td>
</tr>
<tr>
<td>FW generator (support of scrubbers and WIF).</td>
<td>250</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>10625</strong></td>
</tr>
</tbody>
</table>

Changes to the ship is not included in the above costs, as changes this extensive, should be included in a total new ship design in order to have the most optimal design and price.

All above prices are preliminary component prices and only given as guides of price level!

Running costs:
Apart from more maintenance due to more systems onboard, there will be a direct cost due to NaOH consumption by the EGR system.

NaOH pump capacity at 50% ME power: 114 l/h on a 50% NaOH/H₂O solution, at a cost of $331 per hour! Price per liter (50%) $2.9 according to MAN! Depending on the ships load profile this can be calculated to a yearly cost of abt. $2.2 mill. $.
6.13 Result on emissions using developed technologies.
Using the above waste heat recovery technologies and emission reduction techniques together with the average electrical balance figures will in the following show possible emission reductions.

Basic container ship emission

The basic container ship emissions without waste heat recovery system, EGR, WIF and scrubber systems, can be calculated to the following based of SFOC figures and emission figures (Tier 1 engine).

The power required to obtain the 26.5 knots service ship speed by the original container ship design, the main engine must deliver 56000 kW and the shaft motor 6000 kW (equal to an electric power of 6771 kW(e)), in total 62000 kW.

In average the electric balance shows a load of 2960 kW(e) at sea.

The total oil consumption basis ship for the 26.5 knots is thus:

\[
\text{(56000 x 165.3 + (6771+2960/0.95) x 191.0)*24/1000000 tons/ 24 hours = 267.5 tons/24 hours}
\]

Table12: Basic container ship emissions

<table>
<thead>
<tr>
<th>Emissions:</th>
<th>CO₂</th>
<th>NOx</th>
<th>SOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ton/24h</td>
<td>Ton/24h</td>
<td>Ton/24h</td>
<td>Ton/24h</td>
</tr>
<tr>
<td>ME:</td>
<td>737</td>
<td>22,8</td>
<td>14,0</td>
<td>2,6</td>
</tr>
<tr>
<td>AE:</td>
<td>141</td>
<td>2,6</td>
<td>2,6</td>
<td>0,4</td>
</tr>
<tr>
<td>Total:</td>
<td>878</td>
<td>25,4</td>
<td>16,6</td>
<td>3,0</td>
</tr>
</tbody>
</table>

GSF container ship emissions

The MAN selected engine, 12K90ME9, has an rpm of 94 giving the possibility to change the propeller diameter to 9.2 meter - which will increases the propeller efficiency. The engine lay-out can be defined with a MCR rating of 62230 kW at 94 rpm. The better propeller efficiency reduces necessary added power from the shaft motor to 4000kW (equal to an electrical power of 4514 kW(e)) to achieve the required ship speed of 26.5 knots.

The WHR system offers a power output from the P/T & S/T generator set of 7386 kW(e) at 90% MCR according to data from MAN Turbo based on MAN engine data and AI steam output using a three pressure level steam system - at ISO conditions.

The specific oil consumption of the main engine is 171.1 g/kWh (increased due to WIF and EGR) and the auxiliary engines 191.0 g/kWh respectively - at ISO conditions.
Electric balance shows in average a load of 4517 kW(e) at sea – increased from the basic container ship with 1557 kW(e) extra power consumption (WHR, WIF, EGR, Scrubbers, P/T & S/T generator, extra FW generators etc). The average electrical load includes 25% reefers as a realistically condition.

The total ship average electric load at sea can be covered by the WHR generated electric power and extra power can be given as support to propulsion i.e. 7386 kW – 4517 kW = 2869 kW(e) for propulsion. The aux. engine load changes to (4514 + (4517-7386)/0,95) = 1494 kW(e).

The total oil consumption GSF container ship for the **26.5knots** is thus:

\[(56000 \times 171,1 + 1494\times191,0) \times 24/1000000 \text{ tons/ 24 hours} = 236.8 \text{ tons/24 hours}\]

Based on the figures given by MAN and Aalborg industries, the emission result can be seen in table 13.

**Table 13: GSF container ship emissions**

<table>
<thead>
<tr>
<th>Emissions:</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ton/24h</td>
<td>Ton/24h</td>
<td>Ton/24h</td>
<td>Ton/24h</td>
</tr>
<tr>
<td>ME:</td>
<td>761</td>
<td>4,6</td>
<td>1,0</td>
<td>0,5</td>
</tr>
<tr>
<td>AE:</td>
<td>21</td>
<td>0,4</td>
<td>0,4</td>
<td>0,1</td>
</tr>
<tr>
<td>Total:</td>
<td>782</td>
<td>5,0</td>
<td>1,4</td>
<td>0,6</td>
</tr>
</tbody>
</table>

**Emission reduction**

The achieved emission reduction can be calculated as the difference between basic and GSF container ship figures – see table 14.

**Table 14: Comparing GSF container ship with basic ship gives a total emission reduction.**

<table>
<thead>
<tr>
<th>Emissions:</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>SOₓ</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ton/24h</td>
<td>Ton/24h</td>
<td>Ton/24h</td>
<td>Ton/24h</td>
</tr>
<tr>
<td>Reduction:</td>
<td>96</td>
<td>20,4</td>
<td>15,2</td>
<td>2,4</td>
</tr>
<tr>
<td>%:</td>
<td>10,9</td>
<td>80,3</td>
<td>91,5</td>
<td>80</td>
</tr>
</tbody>
</table>

Comparing the two ships, with and without WHR, WIF, EGR, Scrubber, shows a fuel saving of 30.7 ton per 24 hours - a saving equal to 12268$ per day (based on a HFO fuel cost of 400$ per ton).

Further savings can be achieved if the hull paint, advanced rudder and new propeller design is taken into account – for this see section 8.2.
7.0 Emerging Technologies

7.1 Air Lubrication and/or micro bubbles
Savings by air lubrication, either as micro-bubbles along the hull or air-cavities under ship hulls, are promising!

But it is so far too early to say anything definitive about the possible savings for a large ship as an 8500 TEU container ship!

8.0 Operations

8.1 Lines optimization
There is no indication that the techniques for developing ship hull lines has been developed since the A-class was built when considering optimizing for one particular draught and one particular speed.

Normally ship hulls are optimized for one particular draught, i.e. the design draught, at which draught the Builder has his contractual obligations for the particular speed performance of the ship at a fixed propeller shaft output.

Ships in service, however, operate at various draughts, trim and speed.

By analyzing actual operating draughts for typical container ships and the variation in requirements for operating service speeds it has been shown by systematic model test of various hull forms forward, i.e. bulbous bows that on the average of the various draughts up to 3 % on power can be saved at the maximum operating service speed. At lower speed this saving can even be increased, up to 7-10 %.

As this involves operational considerations by individual Owners the above is disregarded when comparing performance i.e. at one draught.

8.2 Ship speed, including de-rating of main engine
For the case of design speed being 26.5 knots an 11% CO₂ reduction in the general emission from this type of ship can be obtained by the aforementioned methods without taking new propeller design, advantage hull coating and advanced rudder design into account.

Using these possibilities the CO₂ reduction can be reduced by a total of 18% (see table 15 on the next page). The goal of a 30% CO₂ reduction requires inevitable a reduction in ship speed, by solely considering design initiatives.
Table 15: Design comparison.

<table>
<thead>
<tr>
<th></th>
<th>A-class as built</th>
<th>New Engine, Larger Propeller Diameter+ WHRS, + WIF&amp;EGR</th>
<th>New Engine, Larger Propeller Diameter+ WHRS, + WIF&amp;EGR, + new propeller blade design (3%), hull coating (1.5%) and advanced rudder (2%).</th>
<th>New Engine, Larger Propeller Diameter+ WHRS, + WIF&amp;EGR, + new propeller blade design (3%), hull coating (1.5%) and advanced rudder (2%). Lower speed I.</th>
<th>New Engine, Smaller Propeller Diameter+ WHRS, + WIF&amp;EGR, + new propeller blade design (3%), hull coating (1.5%) and advanced rudder (2%). Lower speed II.</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHRS</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>WIF &amp; EGR</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Speed</td>
<td>knots</td>
<td>26,5</td>
<td>26,5</td>
<td>24,1</td>
<td>22,08</td>
</tr>
<tr>
<td>Main Engine</td>
<td></td>
<td>12K90ME9</td>
<td>12K90ME9</td>
<td>8590 ME-C8</td>
<td>8580 ME-C9</td>
</tr>
<tr>
<td>Derated MCR</td>
<td>kW</td>
<td>63000</td>
<td>62618</td>
<td>58282</td>
<td>40945</td>
</tr>
<tr>
<td>Derated RPM</td>
<td>RPM</td>
<td>100</td>
<td>94</td>
<td>94</td>
<td>78</td>
</tr>
<tr>
<td>NCR</td>
<td>kW</td>
<td>56000</td>
<td>56356</td>
<td>52454</td>
<td>36851</td>
</tr>
<tr>
<td>WHRS electric output, gas turbine</td>
<td>kW(e)</td>
<td>0</td>
<td>1348</td>
<td>1255</td>
<td>881</td>
</tr>
<tr>
<td>WHRS electric output, steam turbine</td>
<td>kW(e)</td>
<td>0</td>
<td>6119</td>
<td>5696</td>
<td>4001</td>
</tr>
<tr>
<td>Normal at sea auxiliary power ER and Accommodation</td>
<td>kW(e)</td>
<td>1820</td>
<td>1874</td>
<td>1810</td>
<td>1557</td>
</tr>
<tr>
<td>Environmental additional loads (WIF, EGR etc.)</td>
<td>kW(e)</td>
<td>0</td>
<td>1542</td>
<td>1438</td>
<td>1025</td>
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<tr>
<td>Shaft motor output to propeller shaft</td>
<td>kW</td>
<td>6000</td>
<td>3848</td>
<td>3516</td>
<td>2185</td>
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<tr>
<td>Reefer load</td>
<td>kW(e)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Diameter propeller</td>
<td>m</td>
<td>8,9</td>
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<td>9,2</td>
</tr>
<tr>
<td>no blades</td>
<td></td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>SFOC ME (DO)</td>
<td>g/kWh</td>
<td>165,3</td>
<td>171,10</td>
<td>170,00</td>
<td>170,40</td>
</tr>
<tr>
<td>SFOC DG's (DO)</td>
<td>g/kWh</td>
<td>191</td>
<td>191</td>
<td>191</td>
<td>191</td>
</tr>
<tr>
<td>HFO consumption</td>
<td>tons/day</td>
<td>236,05</td>
<td>245,89</td>
<td>227,39</td>
<td>160,13</td>
</tr>
<tr>
<td>Total HFO consumption</td>
<td>tons/day</td>
<td>278,36</td>
<td>245,89</td>
<td>227,39</td>
<td>160,13</td>
</tr>
<tr>
<td>&quot;No Ships&quot;</td>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Total FO/day for the ship fleet</td>
<td>tons/day</td>
<td>2783,6</td>
<td>248,9,4</td>
<td>227,3,9</td>
<td>1761,14</td>
</tr>
<tr>
<td>Relative consumption</td>
<td></td>
<td>0,894</td>
<td>0,817</td>
<td>0,633</td>
<td>0,523</td>
</tr>
<tr>
<td>% reduction</td>
<td></td>
<td>10,6</td>
<td>18,3</td>
<td>36,7</td>
<td>47,7</td>
</tr>
</tbody>
</table>

Note: Fuel consumption figures corrected to HFO consumption (fuel heat value 40200 kJ/kg) and no reefer load!
Assuming, that the total transportation capacity in a transportation string, is kept constant and the basic ship fleet of 10 ships having a design speed of 26.5 knots, then 11 ships yields 24.1 knots and 12 ships yields 22.1 knots in design service speed – results can be seen in table 15 in details and table 16 for summary.

Table 16: Ship design optimization – ship speed, engine size and number of ships

<table>
<thead>
<tr>
<th>Ship speed: Knots</th>
<th>Number of ships:</th>
<th>Main Engine:</th>
<th>Main engine CMCR kW / rpm</th>
<th>Design point basic Fuel / CO2 reduction %</th>
<th>Load profile basic Fuel / CO2 reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>26,5</td>
<td>10</td>
<td>MAN 12K90ME9</td>
<td>58280 kW – 94 rpm</td>
<td>18,3</td>
<td>11 - 14</td>
</tr>
<tr>
<td>24,1</td>
<td>11</td>
<td>MAN 8S90ME-C8</td>
<td>40945 kW – 78 rpm</td>
<td>36,7</td>
<td>26 - 30</td>
</tr>
<tr>
<td>22,1</td>
<td>12</td>
<td>MAN 8S80ME-C9</td>
<td>31430 kW – 76 rpm</td>
<td>47,7</td>
<td>32 - 37</td>
</tr>
</tbody>
</table>

Basis: New Main Engine, Larger propeller diameter, WHRS, WIF & EGR, Propeller blade design (3%), hull coating (1,5%) and advanced rudder (2%).

Total fuel and CO2 emissions can be reduced by 37% and 48 % respectively. The big fuel and CO2 saving is here firstly related to the fact, that ship resistance is physically ruled by a 3 to 4 Order relation between power and ship speed.

Taking the ship load profile into the equation will reduce the fuel and CO2 saving to abt 28% for 11 ships and abt 34% for 12 ships. Read more about the ship load profile effect on fuel and CO2 savings in section 8.3.

8.3 Fuel consumption and CO2 emission based on load profile.
The technology elements used for the GSF container ship are new engine (derated), EGR, WIF, WHR (3 steam pressure levels), P/T and S/T generator unit, new propeller blade design (3 %), hull coating (1.5%) and advanced rudder (2%). This configuration, as given in table 15, shows 18% fuel and CO2 reduction at the ship speed design point (26,5 knots), but what fuel and CO2 saving can be expected if the ships load profile is taken as basic?

Calculations based on the ships running profile, as given in section 5.2, can be seen in enclosure 4.

The calculated savings in fuel consumption and CO2 with and without energy saving and emission reduction technologies as described in this report – and ship load profile show:

HFO reduction per year: 5346 tons and in %: 11,43% cost saving: 2,1 mill. US$

CO2 reduction per year: 17678 tons
So depending on the load profile, number of running hours at sea and in harbour, the reduction figure will differ from the design point calculations result. Fuel and CO₂ reductions based on ship load profile data will always be lower than reduction calculations alone on ship design speed and is expected to give more realistic figures.

Further calculations based on ship load profiles with more pronounced high load profile - will raise this fuel and CO₂ reduction percentage to 13 – 14 %.

### 9.0 Summery and Conclusions

The goal for Green Ship of the Future project – achieve emission reduction of 90% on NOx, 90% on SOx and 30% on CO₂ for the concept ship studies.

MAN EGR and WIF technologies can achieve an 80% NOx reduction - sufficient to fulfill Tier III and ECA requirements.

MAN EGR scrubber and Aalborg scrubber technologies together can achieve a 91,5% SOx reduction and an 80% reduction on particular matter. But for high sulphur content fuels the scrubber systems will require much NaOH for the scrubbing process.

The WHR system has been found to be a beneficial contribution to reducing the CO₂ emissions from ships as well as lowering the fuel cost. The WHR system can deliver emission free electric power to run the necessary ancillary machinery components for the NOx, SOx and PM reducing technologies. The WHR system shown will for a main engine power of 62 MW recover more than 8 MW(e) power – 13% efficiency gain!

Design calculation adding advanced propeller design, rudder and hull paint system – and further derating of main engine - makes it possible to raise the fuel and CO₂ savings to about 18% at the design point.

Fuel and CO₂ reduction calculated based on ship design speed alone only gives one part of the answer, the ships load profile must be used to calculate the yearly fuel and CO₂ reduction. Using the ships load profile as basic shows that the 18% reduction found at design point drops to 11,4% fuel and CO₂ reduction. Other owners of container ship with a more pronounced high loaded load profile will find, that it is possible, to raise fuel and CO₂ reduction to about 14%.

Another effect on the container ship is increased space requirements in engine room and casing for these added technologies. The investigation shows that the basic container ship will lose 114 TEU positions and it’s light weight will increase with abt. 900 ton. But if all these technologies were defined as part of a new ship building program, it should be possible, to optimize both loss of container positions and light weight change.
In order to achieve the goal concerning CO₂ reduction of 30%, the marine industry still need new developments if this should be met with unchanged ship design speed!

Investigation concerning lowering the ship speed shows, that with unchanged transport capacity, a change of ship design speed from the 26,5 knots to 24,1 knots would lower the CO₂ emission by abt. 37% (30%) or a change to 22,08 knots shows a CO₂ reduction of 48%(39%) - but it also means 1 or 2 ships more to maintain the same transportation efficiency. The percentages' in brackets are based on ship load profile!

Other possibilities for fuel and emission reductions shown in this report are i.e. optimization of pump and cooling systems, the use of LNG fuel for dual fuel aux. engine in harbour, extensive use of frequency controlled pumps etc. – Components that will lower the emissions both at sea and in harbour conditions. Extra 1 to 2% CO₂ reduction on the ships total emission is possible by these technologies.

Last remarks:

Tier III and ECA requirements can be fulfilled.

Large CO₂ reduction require ship design speed reduction
Enclosures

Enclosure 1: Pump and cooler optimization – details.

Onboard the ship the following cooling water systems are present:

Machinery related cooling systems:
SW cooling system for central coolers
LT cooling system (for cooling of auxiliary machinery and HT circuit)
HT cooling system (For main engine and fresh water generator heating)

Reefer cooling system:
SW cooling system
FW cooling system.

Turbo generator condenser cooling system:
SW cooling system for steam condenser

The basic for an effective and pricewise cooling water optimization takes outset in the basic design specifications. At this stage it is important to specify:

- pipe dimensions for low pressure drop (maximum 2 m/s)
- sufficient numbers of pumps or frequency converters to obtain flow deviations
- coolers, SW filters and components with low pressure drop
- valve types with low pressure drop
- pumps head close to pressure drop in system to avoid regulating orifice
- motors with high efficiency
- pumps with best efficiency

Another important parameter is the number of annual hours of port stay. As a containership is approaching 2000-2500 hours in port each year, this offers the opportunities for installation of system slow-down means.

In the following the savings are listed. Each saving is calculated in relation to the forgoing saving. This means, that if “saving 1” decreases the power from 100kW to 90kW, “saving 2” is calculated from 90kW to e.g. 85kW.
The outset has been a standard containership, where the cooling water pumps are running 100% all the time.

A small remark should be that on top of the savings during operation, also a saving during installation will probably be obtained as the pump capacities and the electrical installations can be dimensioned smaller.
SAVINGS FOR MACHINERY RELATED COOLING WATER SYSTEMS

No orifice for flow adjustment
Flow adjustments to be carried out by adjustment of impeller diameter and not orifices.

Coating of pump impellers and pump houses
Coating of pump impellers and pump houses has been discussed for several years and testing on smaller pumps have been carried out throughout the world. The coating should prevent the decrease in efficiency as the pump gets older, but also the initial efficiency should be improved. However, the long term decrease in efficiency is the main target for the coating.

![Graph: Inspired by Elfor-report]

Fig. 35: Pictures from Jakob Albertsen A/S.

At a containership Odense Steel Shipyard and A.P. Møller – Mærsk has installed one coated SW cooling water pump to test the coating. The pump was tested prior to and after coating which shows potential of roughly 10% better efficiency. However, it is expected that the actual saving will be rather depending on pump size and design/construction of pump.
Below is the test result from the mentioned coated pump test.

Fig. 36: Test results for a coated SW pump installed at a containership.
**High efficient electrical motors**
Specify electrical motors with high efficiency as the initial cost is only marginal higher than for standard motors but efficiency is roughly 4% better.

**Choose the pump with the highest efficiency**
Choose the pump with the optimum working point. Saving will of course depend on maker and what pumps are compared, but 4% is roughly estimated as a possible saving.

![Pump curves](image)

**Fig. 37: Pump curves.**

**Frequency controlling of SW pumps**
When utilizing frequency controlling of the SW pumps it is possible to monitor and adjust the SW flow continuously. The basis control parameters are the LT temperature set-point and a maximum SW-temperature on 49°C.
If running the system continuously with low flow the risk for fouling in the SW piping and central coolers increases significantly. To avoid this automatic or manual back-flushing should be performed on regular basis.
The estimated saving depends rather much on the trade pattern, but is estimated to 35%.

**Partition of the LT cooling water system**
The LT cooling water system is to be divided into subsystems allowing the cooling water flow to be decreased during port stay.
Port stay HT pump

In order to decrease the HT flow during port stay a pump with 10% capacity of the HT pump is installed in order to circulate water during port stay. The pump is in series with the main engine FW heater.
Balancing of the cooling water systems
The entire cooling water system is balanced by calculation and tested onboard in order to ensure a flow to each component close to the required design flow to each component. This means that no excessive flow is circulated in the system. Without balancing the system the circulated cooling water flow could be higher than necessary resulting in waste of energy.

In total, the savings can be summed as stated in table 17.

<table>
<thead>
<tr>
<th>Table 17</th>
<th>Topic</th>
<th>kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Omit orifices</td>
<td>413.000</td>
</tr>
<tr>
<td></td>
<td>Coating of pumps</td>
<td>390.000</td>
</tr>
<tr>
<td></td>
<td>High efficiency motors</td>
<td>140.000</td>
</tr>
<tr>
<td></td>
<td>Optimum pump efficiency</td>
<td>84.000</td>
</tr>
<tr>
<td></td>
<td>VSD on SW pumps</td>
<td>485.000</td>
</tr>
<tr>
<td></td>
<td>HT pump at port stay</td>
<td>100.000</td>
</tr>
<tr>
<td></td>
<td>LT system split up at port</td>
<td>113.000</td>
</tr>
<tr>
<td></td>
<td><strong>Summary</strong></td>
<td>~1.725.000</td>
</tr>
</tbody>
</table>

In total, a rough saving on 40% and 1040 tons of CO₂ per year is obtained.

On the next page the calculation sheet is shown.
Fig. 40: Pump power calculations using the possible savings.
SAVINGS IN REEFER COOLING SYSTEM

Equal means as in savings for machinery related cooling water systems; however as the pumps are smaller only 6% benefit from coating has been included.

With 100% pumps installed and running all the time the saving is 27% which equals 460.000 kWh per year. However, a load factor for the system is included giving a total roughly estimated saving on 200.000kWh per year.

![Table](image)

**Fig. 41:** Savings in reefer cooling system.

SAVINGS IN TURBO GENERATOR CONDENSER COOLING SYSTEM

Equals means as for machinery related cooling water systems have been utilized. Estimated saving is 700.000kWh compared to 100% flow (the result will be lower if 2x50% pumps are installed and utilized). The main reason for the large saving is the use of frequency controlling. A load factor on 25% is included as this is the time the pumps could be turned off all-ready, resulting in an annual saving on 525.000kWh.

**SUM-UP, all cooling water systems**

The total saving has been summed-up to 2.450.000kWh per year. It can roughly be calculated that 1 tons of HFO produces 3 tons of CO₂ emission, hence the annual saving in CO₂ with the before mentioned means is 1480 tons of CO₂.
Enclosure 2: Ballast water treatment - details.

The ship to be equipped with a DESMI OCEAN GUARD ballast water treatment system in order to keep the energy consumption down. The system consists of the following main parts:

- Gravity/"open" filter
- Buffer tank
- UV sterilizer
- Ozone generator
- Ozone reactor

Fig. 43: Diagram from DESMI OCEAN GUARD.
An increase in the annual running hours is to be expected due to the ballast water treatment system as e.g. free gravity flow is of limited use. As optimum controlling of the maximum flow to the system is important too, the ballast pumps have been fitted with frequency converters.

Today the point of operation is controlled by a regulating valve, meaning that a part of the energy consumed by the pump is not utilized in a beneficial way. Utilizing a frequency converter will decrease the power consumption quite a lot, but due to the low amount of running hours normally on container ships it has not been beneficial to install.

This new ballast water treatment system meets the international maritime organisation’s *International Convention for the control and management of ship’s ballast water and sediments*. It also takes the expected US ballast water regulations into consideration.

This system has low power consumption - only 50kW needed for treatment of a 2x600 m³/h ballast water system.

*Fig.44: Ballast pump operation curve.*
Enclosure 3: Electric add-on power due to the emission technologies.

Add-on electrical power for the installation of WHR, WIF, EGR, FW generators, ballast treatment.

<table>
<thead>
<tr>
<th>Name</th>
<th>kW(e)</th>
<th>kW(e)</th>
<th>Info from:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pr. unit</td>
<td>total</td>
<td></td>
</tr>
</tbody>
</table>

**WHR exhaust boiler system:**
- IP circ. Pumps: 19 AI
- LP circ. Pumps: 9 AI
- LP feed water pumps: 1 AI
- IP feed water pumps: 6 AI
- HP feed water pumps: 11 AI

**WIF system:**
- Extra Fuel pumps power: 15 MAN

**EGR system:**
- Blower: 380 760 MAN
  - Blower load depend on engine load.
- Sea water pumps: 10 20 MAN
- Scrubber pumps: 7,5 15 MAN
- Water cleaning / polishing unit: 7,5 15 MAN
- NaOH pumps: 0,1 0,2 MAN
- NaOH heating: 2 4 MAN
- Actuators / sensors: 0,5 1 MAN

**Scrubber after WHR exhaust boiler:**
- SW / FW pumps: 367 AI
  - SW scrubbing - pump capacity 3110 m3/h

**Turbo, power & steam generator set:**
- LO pumps: 11 MAN Turbo
- Condenser cooling SW pumps: 145 MAN Turbo
- Vacuum pumps: 15 MAN Turbo
- Actuators / sensors: 5 MAN Turbo

**FW generator (support of scrubbers and WIF):**
- SW/FW pumps: 38 Alfa Laval
- Ballast water treatment: 50 Based on 2 x 600 m3/h
- SW pumps: 0 OSS
- Extra ventilation: 50

**Total add-on power:** 1557.2

The three largest power consumers are marked in square boxes.
Enclosure 5: Fuel consumption and CO2 emission calculation based on load profile.

Table 18: Reference ship fuel consumption based on load profile

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>Power kW</th>
<th>SFOC g/kWh</th>
<th>SM load kW(e)</th>
<th>Electric load kW(e)</th>
<th>Auxiliary load kW(e)</th>
<th>SFOC g/kWh</th>
<th>Fuel t/24h</th>
<th>Time at sea %</th>
<th>Time at sea hours</th>
<th>Time Harbour %</th>
<th>Time Harbour hours</th>
<th>Fuel tons/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>62280</td>
<td>167.7</td>
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<tr>
<td>90</td>
<td>56000</td>
<td>165.3</td>
<td>6000</td>
<td>2960</td>
<td>9432</td>
<td>191.6</td>
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<td>3880</td>
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<td>80</td>
<td>49784</td>
<td>163.6</td>
<td>3000</td>
<td>2960</td>
<td>6274</td>
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<td>70</td>
<td>43561</td>
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<td>60</td>
<td>37338</td>
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<td>3116</td>
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<td>147.4</td>
<td>25</td>
<td>1643</td>
<td></td>
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<td>10060</td>
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<td>25</td>
<td>15558</td>
<td>176.1</td>
<td>0</td>
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</tr>
<tr>
<td>Total per year:</td>
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Table 19: Green technology optimized ship fuel consumption based on load profile

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>Power kW</th>
<th>SFOC g/kWh</th>
<th>SM load kW(e)</th>
<th>Electric load kW(e)</th>
<th>Auxiliary load kW(e)</th>
<th>SFOC g/kWh</th>
<th>Fuel t/24h</th>
<th>Time at sea %</th>
<th>Time at sea hours</th>
<th>Time Harbour %</th>
<th>Time Harbour hours</th>
<th>Fuel tons/year</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>58280</td>
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<td></td>
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Achieved savings in fuel consumption and CO2 at unchanged service speed of 26.5 knots with and without energy reduction and emission reduction technologies as described in this report:

HFO reduction per year: 5346 tons and in %: 11.43%

CO2 reduction per year: 17678 tons