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Report

NOx abatement in marin sector – review of new techniques and their potential

NOx-Fund

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TITLE

NOx abatement in marin sector – review of new technologies and their potential.

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ABSTRACT

New NOx abatement technologies /concepts are and will be tried applied through the NOx-fund support. A pre-technical review of possible new technologies in the marine sector is therefore appropriate and is done herein.

The first part of the report reviews some basics useful to bear in mind when evaluating new technologies, both the pre- and post- NOx abatement.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	NOx abatement	NOx redukjson
GROUP 2	New concepts	Nye konsept
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1 Introduction

The first part of the report explains the basic thermodynamic and physics of NOx formation. This basic theory is useful to consider when evaluating the potential of new technologies. Some known and quite common abatement technologies are further described in detail to illustrate the theory/ mechanisms and the different options available to counteract NOx emissions.

The concepts / technologies described in the first part of this report are well known and put to use, but not all are extensively used in the marine business. Examples are the water based technologies and EGR as described in section 2.2.3. The gas fuel concepts are covered on general basis (section 2.2.5) and further outlined in section 4.8.

The last part (from chapter 4) deals with new abatement concepts including an evaluation of their potential for NOx reduction when applied in a vessel.

2 Basic NOx formation and reduction

Technologies for NOx reduction have to be based on fundamental thermodynamics, physics and chemistry. In this section an overview of the basics for NOx formation in a diesel engine is described with focus on important parameters which influence this formation (thermodynamically and physically) and thereby the NOx content in the raw exhaust gas. This is useful to bear in mind when evaluating the potential of new NOx abatement technologies for marine use, not only the pre- treatment methods but also post- treatment of the exhaust gas. As a an assistance to the evaluation the following background knowledge is given:

- a description of the basic for NOx formation in a diesel engine
- an outline of some common and quite mature technologies for NOx reduction that can be explained and supported from basic theory

2.1 NOx formation in diesel engines

Formation of NOx in a diesel engine is mainly related to high combustion temperatures. When the nitrogen in the air is exposed to sufficiently high temperatures during combustion in an engine, it oxidizes to NO, which later forms NO_2 (as raw exhaust approx. 90% NO and 10 % NO_2). The combination is usually referred to as NOx and represents a recognized serious pollution problem to both people and the environment. To form NOx, a minimum temperature of about 1500-1550 °C is needed.

High combustion temperature is necessary and inevitable for an engine to achieve complete combustion with the desired effect and efficiency. Hence, the formation of NOx is a side-effect of an efficient engine with good combustion. As a result of this, NOx-reducing measures which affect the combustion process can lower the efficiency of the engine.

The degree of NOx formation in a combustion engine is thus largely dependent on the combustion temperature and engine speed (RPM). The engine RPM is often a given parameter, but the temperature during combustion depends on conditions in the cylinder, where the most important are:

- the air/fuel ratio, i.e. ratio between air and fuel (air surplus) during combustion
- the condition of the intake air (temperature, humidity, oxygen content etc)
- heat capacity of the cylinder charge

A particular problem for diesel engines is that the mixing ratio is not directly controllable, but changing all the time around the individual diesel droplets due to the diffusion in the combustion. In addition, the ignition characteristics of the fuel are important parameters, given the inevitable ignition delay which accumulates fuel in the cylinder before combustion takes place. The accumulated fuel results in higher pressure and temperature rise for the following ignition, resulting in higher NOx emissions. This issue is further enhanced by fuel with lower combustion point and on fast running engines. It is a clear relationship between NOx production and the degree of ignition delay in diesel engines and some NOx-reducing measures target this ignition delay to reduce emissions (i.e. pilot injection)

This means that there is both design and operational factors that can affect NO_x formation in diesel engines. Of the design factors, the following are highlighted:

- Process conditions: The choice of compression ratio has a major influence on the pressure in the cylinder before and during combustion.
- Selection of valve timing. Affecting the air filling and thus both the compression pressure and (indirectly) the air excess.
- Turbocharger-settings and charge-air cooling. Similar to the valve timing, but with more effect. Cooling capacity affects the charge-air significantly and hence, the formation of NOx.
- Cylinder-design. The design must be optimized for a complete combustion, even fuel distribution and correct ignition delay. On large diesel engines, the effect of this is limited.
- Injection equipment has a great influence on the combustion for a diesel engine, with a number of parameters which must be carefully optimized. Parameters include fuel pressure ratio as a function of load and speed, rate of injection and spray design.

In addition, a number of operational parameters also have an impact in reducing NOx formation (for a given engine design). The most important of these are:

- Charge air temperature: directly affects the temperature inside the cylinder
- The condition of the charge air, such as oxygen content and humidity, affects the combustion temperature.
- Injection timing: has a decisive influence on the pressure level in the cylinder and thus the combustion temperature, as well as a strong impact on efficiency and carbon build up.
- Modification of the fuel. Emulsification of water (and other additives)

An important point of operating parameters is that they can be easily changed and to some extent adjusted automatically during operation. However, they can also be easily manipulated with regards to control measurements, a problem known for the automotive industry where parameters are "performance adjusted" with increased NOx as a consequence.

2.2 Common technologies for NOx reduction

Common and mature technologies described in the following are also used as examples to illustrate the basic theory of formation and reduction of NOx where the reduction principle can be explained, including reduction potential and limitations.

2.2.1 Design measures *(refr. 1)*

As mentioned, NOx reducing measures with regards to the combustion are usually on the expense of an efficient and clean-burning engine, which makes these measures a compromise. Achieving both is often only possible for older engines which have not previously been optimized, by installing new and expensive technology.

However, upgrading older engines with new technology may not even be possible, as existing vital parts cannot cope with higher stress. The alternative in these cases is to accept that NOx reduction may cause penalty in fuel consumption and soot.

The consequence is limited opportunities for NOx reduction through structural changes of a basic engine. The following will describe these measures.

Optimization of process parameters (Miller-process) *(refr: 1,2)*

Since introduction of TIER I and in particular TIER II the introduction of Miller timing on marine diesel engines has become widespread among engine manufacturers as a means to comply with NOx regulations. A correctly tuned Miller timing reduces the combustion cycle temperature and thereby the NOx formation. Miller timing reduces the effective compression ratio, which consequently reduces the peak compression temperature.

However a too advanced miller timing causes significant ignition delay which tends to increase NOX emission due to a rapid premixed combustion following the ignition delay. This phenomenon is often called "cold-combustion" which points to the compression temperature being too low for acceptable ignition conditions for the fuel.

For medium speed engines Miller timing means early closing of the inlet valve, before the inlet stroke has ended. This way the full piston stroke of the engine cannot be utilized for compression, and as a side effect the cylinder charge is reduced given that the turbocharger pressure is not changed.

A reduction of cylinder air charge will normally lead to increased smoke emission. To avoid this negative effect, the charge air pressure is increased to compensate the reduced volumetric efficiency from the Miller timing. At low load the reduced volumetric efficiency will affect the load response potential leading to an extended speed pick-up time. The normal countermeasure has been to introduce a variable Miller timing, where the valve timing can be shifted relative to the crank position, usually in two positions.

Optimization of the Miller cycle requires a number of changes to the engine, where the most important are:

- Advanced turbocharger with higher pressure ratio and improved efficiency
- Intercooler with increased cooling capacity
- Different camshaft with altered valve timing
- Adjustment of compression ratio

It must be added that the changes and upgrades related to Miller timing are extensive and thus not applicable to existing engines in service (retrofit).

NOx reduction effect:

Offers NOx reduction to comply with Tier II and DNV "Clean Class", with about 20-30% NOx reduction. Extreme Miller and two stage turbocharging has been reported to 60 % reduction in combination with EGR.

Conclusion:

- Engine internal and external measures, making it less applicable as retrofit measure
- Can be introduced in steps (with subsequent results in NOx reduction)
- No increase in fuel consumption

- Complicated and expensive
- Main disadvantages are increased formation of soot and PM in part-load and transient operation. This may result in fouling of the engine, increased thermal stress and increased maintenance and costs.
- Not considered as a sufficient option for the long run, when regulations on PM emissions will apply.
- Not very suitable in combination with catalyst solutions (SCR), due to PM. Reduced exhaust temperature after turbo might be a side effect that is negative for SCR.
- Limited applicability where the majority is part-loads, unless the engine has equipment to allow for easy monitoring and adjustment.

Modification of injection equipment *(refr.1, 3)*

As previously stated, the injection equipment is very important for engine performance, including NOx formation. However, the tuning (operational parameter) of the equipment is often just as effective as design changes.

Description:

- Modified injection rate (altered camshaft speed and/or plunger diameter, depending on the output specification)
- Higher pressure level
- Nozzle modifications
- May include transition to Common Rail (CR) injection equipment.
- New adjustment of timing, operating pressure etc.

<u>NOx reduction effect:</u>

Measures intended to alter the injection timing will typically give a reduction of 0.5 to 0.7 grams (NOX)/kWh per crank angle degree, with an estimated maximum of 20% from the initial NOx value *(1, 3).*

Assessment:

- Standard measure for Tier I (equivalent to about 20% NOx reduction for an unregulated engine)
- NOx reduction effect is limited by the increase of soot and PM, as well as it depends on the initial condition (max. 20% NOx-red)
- Transition to CR can provide a net NOx-red up to 10% without increasing PM.
- The measures will lead to higher loads on vital parts of the engine (such as pumps, camshaft), thus making it complicated to implement in older engines.
- Can lead to more frequent maintenance of the nozzles, higher fuel consumption and increased emission of soot and PM.

Modification of combustion space

As described in the previous sections, the injection equipment is a very important parameter for NOx reduction. Changes in injection equipment must often be complemented by modifying the design of the combustion space in order to compensate some of the negative aspects. As an independent measure; changing the design of the combustion space will seldom give results for medium speed engines (low turbulence), but NOx reduction can be achieved on high speed diesel engines.

Description:

- Changes on piston (to varying degrees)
- Nozzle modifications
- Adjustments of injection timing, opening pressure etc.

NOx-reduction effect

Normally 0.5 to 0.7 grams (NOx)/kWh per crank angle degree. Estimated maximum NOx reduction of 15-20% from the initial emission. Part of the standard measures in order to comply with Tier I regulations (*1*)

Assessment:

- NOx-red effect is limited. The measure is mainly to reduce soot emissions as a result of retarded injection times.

- Hardly profitable as independent NOx-red measure

2.2.2 Optimization of operating parameters *(refr. 1)*

Depending on initial parameters, a NOx reducing effect is possible by re-optimization of key operating parameters. This is not a robust or very efficient measure, and it may in fact be used to manipulate results. It has only limited relevance in this context, but will nonetheless be included.

An engine must be assumed to have been optimal adjusted by the supplier. However, a NOx reduction may be possible by adjusting the operating parameters, but most often this will be on the expense of other parameters, such as fuel consumption and soot emissions.

In principle, the following adjustments can provide a certain reduction of NOx, independently or in combination:

- Retard injection. 0.5 to 0.7 grams/kWh NOx reduction per crank angle degree. It is limited by the rising emission of soot *(1).*
- Reducing the charge air temperature. Lowering the temperature of the charge air by 10 degrees will result in 0.6 to 1 g/kWh reduction of NOx (down to a certain limit) *(1).*

It should be noted that a charge air temperature of 45°C is often mentioned as the lower limit of what is reasonable and operationally acceptable on modern diesel engines. Lowering the temperature may result in precipitation of water in the charge air system, which is undesirable. Based on empirical data, the minimum charge air temperature should exceed 50°C when using heavy fuels.

2.2.3 Manipulating intake air

The condition of the intake air has an impact on the combustion temperature and hence also NOx formation. High humidity of the intake air will lower the combustion temperature due to the increased heat capacity of the cylinder charge, as well as less oxygen. NOx reduction technologies based upon this principle are the Humid Air motor (HAM) and the Combustion Air Saturation System (CASS) and Direct Water Injection (DWI).

HAM *(ref 1,4)*

HAM include a new charge air system where the charge air cooler is replaced by a humidifier and necessary devices to regulate the process of the hot charge air taking up moisture (water). The overall goal is to achieve a charge air maximum saturated with water.

NOx-reducing effect is claimed to be up to 50-60% (compared to Tier I)

Assessment:

- The system provides good NOx-red effect, but also increases fuel consumption slightly (+ 2-3%). PM emission will increase, but not soot, which makes the smoke white.
- Can use seawater, which is an advantage.
- Expensive and bulky
- May require additional water and/or oil heating to evaporate sufficient water, which may be a complicating factor
- Provides reduced exhaust heat recovery
- Precipitation of moisture in the engine may affect the engine’s reliability and maintenance requirements.

CASS *(refr: 4)*

This system for saturation of combustion air includes changes in the charge air system with water injectors downstream compressor and modified charge-air heating system (rather than cooler) with demister. A fresh water supply system with tank, filter, pump, control system etc. is also needed.

NOx-reducing effect is claimed to be up to 50% (compared to Tier I).

Assessment:

- Provides good NOx-red effect, but also increases fuel consumption slightly (+ 2 - 3%) and PM (but little soot, - white smoke!)
- Less expensive and bulky than HAM
- A fresh water consumption of about two times of the fuel oil consumption is a disadvantage)
- Provides reduced exhaust heat recovery
- Precipitation of moisture in the engine can affect the engine's reliability and maintenance requirements

Direct water injection (DWI) *(refr: 4)*

Fresh water is injected directly into the combustion chamber through a separate injector from a pressurized common rail type of water supply alongside the cylinder bank.
The amount of water and timing of injection is electronically controlled.

NOx-reducing effect is claimed to be up to 50% (compared to Tier I)

Assessment:

- Technology most applicable for bigger engines
- Typical amount of water is 0.4-0.7 times the amount of fuel (volume basis).
- The fuel sulphur content has to be considered when applying DWI and a limit of 1.5% is typical.
- Adds complexity to the engine

Exhaust Gas Recirculation (EGR) *(refr.1,5)*

EGR is commonly used in the automotive industry both for Otto- and diesel engines. Up to quite recently EGR has been sufficient to fulfill the automotive NOx requirements. As a consequence of tougher regulations for heavy duty diesel engines (trucks and buses), EGR has been replaced by SCR.

There are different concepts for EGR:

External high pressure EGR:
Part of the exhaust gas from the exhaust receiver is diverted to the air receiver where it is mixed with air. The exhaust is cooled before it enters the air receiver. The pressure pulses in the exhaust system combined with inlet throttling in the air receiver are utilized to obtain the EGR exhaust flow needed (active pressure control).

External low pressure EGR:
Part of the exhaust gas from the turbo charger outlet is diverted to the compressor inlet. The exhaust is cooled before it enters the air receiver. The differential pressure is low and to obtain the EGR circulation it is necessary to lower the inlet air pressure by means of a venturi or nozzle.
The volume flow is higher than for high pressure EGR and accordingly a bit more space is needed.

Internal EGR:
By means of advanced control of the exhaust and inlet valves it is possible to “return” exhaust from the exhaust receiver to the cylinder. Some exhaust is then trapped during the next combustion cycle and an EGR effect is obtained.

Fuel quality is crucial when using EGR because the particle content causes fouling of components, especially for external EGR with piping and coolers.

Diesel exhaust contains N2, O2, CO2 and water (>99%). When mixing in EGR the amount of O2 decreases while N2 increases in the charge. The amount of CO2 also reduces the charge specific heat. The EGR affects the combustion temperature, (i.e. a lower flame temperature) leading to reduced NOx production.

When the EGR share increases it can be seen from analysis of the combustion process that ROHR (rate of heat release) becomes less intense and last for a longer period. This reduced intensity implies a lower combustion temperature and lower NOx. However, the longer period of combustion reduces the thermodynamic efficiency.

Lower ROHR intensity reflects the availability of O2 in the charge and EGR contributes to a lower O2 content in the combustion air. The reaction on molecular basis require more time. If there is no additional charge air the total amount O2 is reduced and there will be a combined effect with an increased smoke production as a result. This could be improved by optimization or re-matching of the turbocharger. This is not always possible where EGR is based on retrofit.

This negative effect of EGR (more smoke, higher fuel consumption) has to be balanced against an achievable NOx reduction over the operating area for the engine.

Effect of EGR:

Tests have shown that it is possible to achieve down to 2 g/kWh NOx, but the consequence is 3-4 % higher SFOC. An EGR rate of approx. 15% gives approx. 40% NOx reduction and 1-2 % increase in SFOC *(5).*

Low quality HFO as fuel implies more PM (particulate matter) and aggressive SO2 in the exhaust. EGR in such a setting is not a practical solution. Low sulphur HFO fuel can be used in combination with EGR. However for marine engines on marine fuel it is recommended to clean the EGR gas before it enters the combustion chamber.

EGR on marine applications:

It is possible to obtain significant NOx reduction by EGR. From the Tier 1 level it is possible to reduce NOx by 40% with a pay-off of < 2g/kWh in increased fuel consumption without changing or re-matching the turbocharger *(5).*

EGR has potential as a retrofit on exiting marine engines. To avoid contamination of the engine charge air system and extra maintenance, EGR should be combined with particle filtration.

It is also important that the EGR system supplier and the engine manufacturer (if not the same) are coordinated to ensure that the system as a whole is optimized with respect not only to NOx reduction but also smoke and SFOC. It is important to be aware that too ambitious NOx reduction can cause serious negative effects.

As retrofit it is often reasonable to choose an EGR concept also from the aspect of complexity and necessary modifications to be done on the engine. External low pressure EGR is in this respect the easiest solution. A relatively small pressure difference (approx 25mbar) is needed to obtain EGR circulation, incl. the pressure drop across the particle trap. A control system is also needed to control the EGR flow according to engine load.

For the external high pressure concept there is a need for more comprehensive modifications including also the turbo-charging, the high load EGR control and special measures when shutting off the EGR flow. At higher loads when the charge air pressure is higher than the exhaust receiver pressure an additional blower may be needed to secure EGR gas flow.

The main challenge is the particle matter (PM) and soot from the EGR flow. If the EGR flow is not filtered properly the engine will over time be contaminated with an associated negative effect on performance.. The need for maintenance will also increase.

2.2.4 Treatment of the exhaust gas

Exhaust gas treatment (post treatment) has to be based on chemistry and thermodynamics where NO/NO2 is to be reduced to N2 and water. The NOx emission from engine combustion contains NO and NO2, created during the high temperature combustion. The amount is dependent of temperature level and retention time at that temperature. The share of NO and NO2 is close to 90% and 10% respectively. For lean burn gas engines the share is closer to 70% and 30%.

NO2 is soluble in water and forms HNO2 and some HNO3. NO is a relatively stable gas not soluble in water, but a transformation to NO2 is seen when NO is exposed to the atmosphere/sun. From this a NOx reduction of approx. 10% could easily be achieved by bringing the exhaust in contact with water as in a seawater or freshwater exhaust gas scrubber, while the rest (90% as NO) is not affected. A technology including NO to NO2 transformation and downstream scrubbing of NO2 may favourably be combined with SOx scrubbing.

A conversion of NO to NO2 is known from particulate filter technology where vanadium oxide in the filter converts NO to NO2. For filter applications such conversion is negative as the emission acidity is increased.

Selective catalytic reduction (SCR) *(refr 6,7)*

Selective catalytic reduction (SCR) is an example where a full transformation of NO and NO2 to N2 and H2O is possible by utilizing ammonium (NH3) as a reactant. On a catalytic surface (i.e. platinum, titanium-oxide at relatively high temperature (>270^{O}C) it is then possible to obtain the speed and degree of conversion needed for practical use. The catalytic compound could either be platinum or titanium oxide as in ceramic catalyst. For soot oxidation some vanadium-pentoxide is added.

Technologies using a hydrocarbon as reactant instead of ammonium require other catalyst material or combination of materials. Tests have shown that the chemical reaction takes place with sufficient speed and degrees of conversion, but there are still challenges connected to efficiency versus amount of hydrocarbon needed and the sensitivity to small amounts of sulphur in the engine fuel. More documentation on these matters is needed.

<u>NOx reduction effect:</u>
For base load power plant a SCR plant can achieve more than 95% reduction of NOx. For a ship application efficiency will vary dependent of the vessel operating profile where the overall efficiency can vary from below 70% to 90% *(6).* At ideal conditions efficiency above 90% has been measured *(7).*

Assessment:

- SCR exhaust treatment can comply with the coming Tier III requirements.
- SCR also reduces the volatile part of the particulate matter quite efficiently.
- Ammonia slip must be regulated. As an example Sweden has set the slip limit to 10ppm. This can be achieved by adding an oxidizing catalyst element.

2.2.5 The gas engines *(refr: 8)*

Lean burn concept:

This concept comprises the Lean Burn Spark Ignited engine (SI) and the Lean Burn Micro Pilot Ignited (DF) engine. The engines are based on the Otto cycle with lean “cold” combustion (high air excess) and thereby low NOx emissions. The gas fuel is supplied to each cylinder at pressure slightly above the charge air pressure through a gas admission valve.

These engines were from the origin developed for power plants and high specific power. They are adapted for use in marine propulsion both as gas-electric and lately also for with variable speed for direct mechanical drive. Both concepts are available with safety features that make the marine installation easier. Especially the double wall gas piping all the way to the combustion chamber is a necessity for classifying the engine room as intrinsically safe.

<u>The Lean Burn SI engine</u> is often named as the “gas only” engine (LBSI). The main charge in the combustion chamber, a lean mixture of air and gas, is ignited by burning jets from a pre-chamber which in turn is ignited by a spark plug. The pre-chamber creates a quite powerful ignition and significant turbulence generator helping to speed up combustion. For marine use these are now available in the range from below 100 kW to 420 kW pr. cylinder.

In marine operation NOx emission < 2 g/kWh is achievable. For base load power production 0.5 g/kWh is achieved, but then suffering some loss of thermal efficiency *(8).*

The dominating use is so far in multi-engine ferries where bunkering facilities and time for bunkering can be effectively arranged. Other types of vessels with the LBSI engine propulsion are known to be on order. A diesel powered generator set in combination with power take in (PTI) system is then an alternative for back-up propulsion power.

The fuel consumption of this engine concept is better than the diesel engine counterpart due to faster combustion and less parasitic loss such as the fuel injection pump. The load pickup is in the same range as the diesel engine. The main challenges of this concept are the sensitivity to engine knock (related to fuel quality, MN and bore size) and unburned methane (methane slip).

The dual fuel DF engine has the ability to alter between gas and 100% diesel. In gas mode the small micro pilot diesel jets are ignited by the compression heat (as a in a diesel engine) which in turn ignites the lean mixture in the combustion chamber. The amount of pilot diesel varies with engine load and is at full load typically between 1-1.5% of total energy input pr. cycle. In diesel mode it operates as a standard diesel engine with diesel injection through a second nozzle included in the same injector (combined injector for pilot and main diesel). The change-over between the fuels can be done while the engine is running. The DF engine can be used for single unit propulsion without extra back-up arrangement.

The Low pressure DF (LPDF) marine engine is available in the range from 180 kW to 950 kW pr. cylinder, and the concept show NOx reduction close to 90% compared to the diesel engine operation. In marine operation NOx emission < 2 g/kWh is achievable. The PM and sulphur is removed to a minimum, depending of the pilot fuel amount and quality. The unburned hydrocarbon for this engine is almost 100% methane (methane slip), and higher than for the diesel engine. Methane is difficult to oxidize in a catalyst (needs 650-700^{O}C) *(8).*

Fuel consumption at high load (above 50% load) is in the same range or better than in diesel operation. The main challenges of this concept are sensitivity to engine knock (fuel quality MN and bore size), slow load pickup and unburned methane (methane slip). For this concept there is a limited possibility for improvement of these challenges due to the need for compression heat to ignite the pilot fuel.

It is of interest to gather better documentation on the hydrocarbon emissions for typical marine operation profiles.

High Pressure Dual Fuel concept (HPDF):

In the High Pressure Dual Fuel (HPDF) concept the gas is injected and burned according to the diesel cycle. This means that this concept maintain the diesel engine performance, and is applicable for all type of diesel engines, from the smallest heavy duty truck engines to the large slow speed diesel engines. Three different products of this concept are on the market: Wärtsilä with their Gas Diesel engine (GD) mainly in offshore applications, Westport with high pressure direct injection (HPDI) for heavy duty vehicles and MAN B&W with their gas injection (GI) for large two stroke engines.

The gas phase fuel is injected at high pressure (250-350 bar) and burns in principle as the diesel jets in a diesel process. Small pre-injected diesel pilot jets provide ignition. The HPDF engine advantages are the insensitivity to gas quality (no knocking problem) and the specific power similar to the diesel engine. At comparable efficiency the NOx emission is about 30-40 % lower than diesel operation *(8).* The HPDF technology is relatively easy to adapt to existing engines for conversion. The disadvantage is the high pressure gas compressor that adds cost, complexity and consumes energy. However, the necessary pressure increase from LNG can be done more elegant by means of a high pressure piston pump prior to evaporation.

The HPDF concept is applicable especially for large engines (bores > 500mm) where the premix combustion faces limitations such as engine knock. The 2-stroke engine is also a HPDF candidate due to large bore and low rpm which make the Otto cycle process almost impossible.

Gas fuel storage

Gas fuelled vessels are realized thanks to LNG onboard storage. The total volume of LNG with tank system is nearly twice as much as for MGO (on energy basis) but in practice a larger space is needed due to the bulky form of the storage pressure vessel. Storage capacity and bunkering facilities are still considered to be a limitation for this development. Even with today's bunkering infrastructure, LNG is applicable for quite many types of vessels. However, new LNG tank systems and more bunkering facilities will boost LNG as marine fuel.

3 New concepts

3.1 Introduction

The NOx-fund has during the years in operation supported different NOx abatement technologies, some well known, some commercialized and more or less ready for marine use. It is anticipated that new applications will be presented for support, based on new technologies and concepts not so well proven. This is already seen occasionally. A pre-technical review of possible new technologies for marine use is therefore appropriate and is done by evaluating against criteria's such as:

- stage of development, degree of innovation
- potential for NOx abatement (efficiency)
- effect on fuel consumption
- cost and complexity for marine implementation
- size and weight
- consumables for operation
- maintenance need
- safety aspects

Most of the NOx reduction concepts published as “new” are based on “old” well known principles but in a new setting. It could also be combinations of technologies, all meant for post treatment of the exhaust.

3.2 High pressure SCR *(refr: 9, 10, 11)*

The high pressure SCR means that the catalyst is moved upstream on the pressure side of the turbocharger but still using urea as reagent. This SCR solution has been known for quite some time, but so far only run more or less as prototypes. The NOx reduction efficiency is the same range as for standard SCR applications (>90%) and should not introduce any fuel penalty *(10,11).*

The main advantage is less sensitivity to sulfur in the fuel as the temperature is kept at a higher level for most operating conditions. A SCR unit before the turbocharger will for a slow speed engine (as an example) see an exhaust temperature of 350 - 400^{O}C, enough to secure efficient operation of the SCR unit without a quick damage of the catalytic surface. A unit after the turbocharger will not have the same conditions as the temperature is at least 100^{O}C lower.

It is also possible to reduce the size of the catalyst because of the higher exhaust gas density, and possible to operate with a wider load range due to higher temperature level.

The challenging part is to fit a system into an engine turbo charging system on a ship and to handle transient operation of the engine. As thermal mass is added to the exhaust system ahead of the turbocharger the turbine response time is affected.

It is also of importance that the catalyst stones are robust and properly arranged/fixed to withstand the loads they are exposed to. An increases thermal mas upstream the turbocharger because of an SCR unit will affect the engine operability (transient loading).

The use of this SCR concept is mainly for larger engine installations to be run on HFO. Systems have been tested both in the laboratory and onboard.

Comments on SCR :

The commercial NH_3 catalyst for diesel engines is typically:
- $TiO_2–WO_3–V_2O_5$ or
- Fe/Cu zeolits.

New catalyst can be:
- Perovskits as:
    - $LaCoO_3$, $LaCo_{1-x}Cu_xO_{3-\delta}$, ; $La1-xAxMn1-yByO3$;
    - $La_{0.5}Ce_xSr_{0.5}xMnO_{3;}LaFe_{0.57}Co_{0.38}Pd_{0.05}O_3$..
- Zeolits as:
    - Fe-beta, Cu-FER, Cu-MOR, and Fe-ZSM-5 with different Si/Al ratios
- Oxides as: - Ag /Al2O3

3.3 Diesel DeNOx (SCR with fuel oil instead of urea) *(refr: 12,13,14)*

The heavy duty vehicle industry has looked for a catalyst where no extra reagent has to be carried, ie. using diesel fuel instead of urea, and with a NOx abatement efficiency that copes with the stricter emission regulations. Such catalysts have for some time been marketed as commercial (all US origin). From the information available the catalysts seem to be based on a zeolite copper ion structure coated with cerium oxide. It is known that these catalysts combined with a HC injection could convert NOx quite effectively at higher temperatures (>300^{O}C) *(12).* These catalyst systems are likely to be combined with an upstream NO2 “generator” (converting some NO to NO2) and a particle filter. As a standalone unit the efficiency would be reduced.

Extensive research and testing using diesel in NOx catalysts has been done. Manufacturers such as Caterpillar as Mercedes Benz have done testing but so far not very successfully. The main challenge is that even small amounts of sulphur in the fuel poisons the catalyst material quite quickly *(6).*This could be one reason why the concept has not seen any commercial boost in the heavy duty vehicle industry.

With respect to use in marine applications a better documentation is needed on:

- effect of sulphur in fuel
- temperature dependency (hydrothermal stability)
- amount of diesel versus NOx reduction efficiency
- sensitivity to O2 / lambda
- transient behavior
- control and safety

If the fuel injected and evaporated in the exhaust gas comes out of control (i.e. not fully utilized in the catalyst) it could, if ignited, causes a serious fire in a vessel exhaust system. Clearly a safety aspect should be considered for such SCR systems.

3.3 Multi abatement systems *(refr: 15, 16)*

Lately inventions of 3-in-1 emission abatement systems have be marketed. One of these are the CSNOX system where Ecospec Global Technology Ltd. declares a significant reduction on SO4 (above 90%), NOx (above 60%) and CO2 (above 70%) in one single system *(15).*

A full detail basic explanation, chemically and physically, of the system working principle(s) is lacking. It is argued that that the seawater in the scrubbing process goes through an ultra-low frequency wave electrolysis and then becomes “highly reactive” in removing SO4, NOx and CO2.

Late 2011 the CIMAC Marine fuel working group was shown a demonstration of the system hooked up to a 300kW diesel engine. The demonstration and the questioning/ discussions during the demo were not convincing to the group, neither the system performance *(16).*

There are still serious questions to be answered and properly documented to justify the system performance (i.e. efficiency on NOx versus energy consumption) and in general the potential for marine use.

Hopefully some results from real operation and thus some more answers will be available as a system is to be installed onboard a ship.

3.4 Catalytic filter *(refr: 17,18,19)*

New advanced material technology has enhanced the possibilities to make catalysts for a variety of chemical processes and applications for environmental purposes.

“Catalytic filter” in the terms of NOx abatement can be a source of confusion as the same terminology is often used when dealing with PM removal. For NOx removal “catalytic filter” is seen used in different settings such as:

The NOx Absorber Catalyst:

The NO from lean combustion is absorbed on a catalyst surface releasing CO2. As the catalyst has a finite capacity it has to be regenerated in a rich exhaust atmosphere, either by running the engine at low lambda or by a secondary combustion in the exhaust (burning extra fuel). During this regeneration the catalyst releases NOx which is reduced to N2 on a secondary catalyst surface. The NOx conversion is reported to be a technology mainly developed for automotive use. It has not been an unconditional success and is not taken into extensive use. Reasons can be the great sensitivity to sulphur and the overall complexity for control/management of the process, including the frequent regeneration needed.

The potential for use in marine applications is assumed to be low.

The Honeywell NOx Catalytic filter *(17):*

There is not much available information about it. It is based on pre-processing for converting NO to NO2 and thereafter absorbing NO2 by means of an alkali on a catalyst surface. It is still a question about the need for regeneration of the catalyst.

NOx Catalytic filter (using PM as reactant) *(18, 19):*

The concept is meant to utilize the particulate mass from the exhaust gas in the catalyst, as a reactant in the process.

Proper documentation of performance is to be recommended before implementation in a vessel, most preferable from extensive tests on a marine engine at realistic operating conditions. Possible PM clogging and need for maintenance actions accordingly should also be addressed properly.

Systems are installed in a Coastal Express vessel, but up to now with low or insufficient efficiency and taken out of operation. Proper documentation of applicability for installing this system on the Coastal Express vessels for NOx abatement is lacking.

A concept that requires a certain PM mass to operate is in general questionable. Minimizing the harmful PM produced from diesel engine combustion is normally a target in engine development. In operation low PM emissions indicates a healthy combustion and thereby a minimized fuel consumption.

For catalytic filters, as for other new technologies, to be installed on commercial basis in a vessel it is of importance to require proper documentation (3. party) of system performance. It is preferable that test results should be generated on the same type of exhaust, scale/flow and operating conditions as could be expected in marine use.

3.5 Pre- emulated fuel ("white" diesel) *(refr: 20)*

Adding water in fuel to reduce NOx is not a new idea and packages for on-line mixing fuel/water to obtain a stable and homogenous emulsion have been on the market for quite some time. The NOx reduction potential and limitations are the same as described below on "white diesel".

The "white" diesel is produced from MGO by adding water and activator (emulsifying agent to keep it stable). The NOx reduction is nearly proportional to the content of water over the whole load range (i.e. 10% water ≈ 10% NOx reduction). The smoke and CO is also reduced with "white" diesel. Specific fuel consumption however increases *(20).*

Too much water affects the ignition and overall combustion in a negative way, somewhat dependant of type of engine, speed etc. Above 20% water the negative effect is clearly noticeable *(20).* Possible long term effects on injection pumps and nozzles should be investigated.

3.6 Fuels *(refr. 21)*

Additives:

Fuel additives are already numerous and more are likely to show up. Most of the additives claim to act as improvers of the fuel economy by reduced fuel consumption, but some also claim to reduce emissions. A theoretical proof of why the additive should work is most often lacking. Neither the explanations given are particularly convincing. “Cleaner” combustion is a commonly used term in the marketing of these products.

MARINTEK has over the years tested several fuel additives in the engine laboratory. None of these have shown any significant reduction of NOx *(21).* Some micro effect on fuel consumption has been measured, but then normally with a NOx penalty. A closer look into the combustion often shows an earlier point of ignition. Thus the additive has influenced on the fuel ignition properties.

It is strongly recommended that all the effects of fuel additives are well documented before the product is taken into use, preferably by realistic 3rd party tests at realistic conditions with respect to type of fuel, type of engine and operation profile.

The same concerns are also valid for “smart” hardware components with a declared effect on performance if attached to the engine fuel or charge air system.

Other fuels *(refr: 22)*

Below a short summary is given of experience from tests done over the years in MARINTEK's engine laboratory:

GTL (fuel oil made from gas, gas-to-liquid):

- equal combustion properties as MGO (higher cetane number, reduced ignition delay)
- NOx reduction 10-15 % (mainly because of reduced ignition delay and premix combustion).
- high price

LPG (as diesel process with diesel pilot ignition):

- < 10% NOx reduction
- high injection pressure to keep up efficiency
- injection pumps not available (LPG's limited lubrication ability)
- safety in engine room (explosion limit, high pressure and density > than air)

LPG (as premix lean burn combustion)

- significant NOx reduction (70 - 80%)
- low specific power pr. cylinder (knocking problem)
- low efficiency (CR ratio low, knocking problem)
- not applicable for marine engines (large engine bore)
- HC slip possible to oxidize
- safety in engine room (explosion limit, density > than air)

DME:

- same NOx level as using automotive diesel fuel (more potential in combination with EGR because of less PM)
- the motive is rather CO2 (i.e. made from bio)
- to be stored pressurized
- limited availability

Methanol:

- severe ignition delay
- net NOx reduction ≈ 0 (even when using significant amount of ignition improver)
- safety aspects as marine fuel (high flammability, corrosive and toxic liquid)
- key component in making biodiesel
- pure methanol more applicable as automotive fuel (Otto-process engines)

3.7 2-stage turbocharging and variable valve timing *(refr. 23, 24)*

By combining 2-stage turbocharging, Miller timing, valve overlap and injection timing it is possible to obtain a 70% NOx reduction without fuel penalty at high loads. Without any NOx reduction a 10 % reduced SFOC can be obtained. In a practical case on a vessel with less complicated engine control a trade-off between NOx and SFOC could be 55 % and 5 % respectively *(23).*

To fully utilize 2-stage turbocharging a careful adjustment is required of the engine setting from low to high load involving changes in valve timing and injection timing as function of load/speed. A variable valve timing system makes this possible.

The concept with 2-stage turbocharging and advanced valve control makes it possible to run with quite extreme Miller timing which reduces compression temperature, and consequently lowers the combustion temperature. Reduced valve overlap increases internal EGR which effectively reduces flame temperature and NOx formation.

A too high Miller factor will lower the compression temperature to a level where the ignition is delayed and with "significant Cold Combustion". Cold combustion is caused by a long ignition delay and with an increasing premixed combustion (diesel fuel is injected and vaporized to a large extent before ignition occurs). Severe Cold Combustion might increase NOx emission significantly to the starting point or in some cases even higher, particularly at low load. Reduced valve overlap will increase the amount of trapped residual exhaust in the cylinder (internal EGR). Increasing level of EGR gives less oxygen available to the combustion and will increase smoke and particulate matter *(24).*

3.8 Gas engines *(refr. 25, 26)*

Even if the lean burn LBSI and LPDF concepts have been available for a while they are relatively new for marine use. The number of gas driven vessels in Norwegian waters are at the moment around 30 and more are on order. So far the majority of gas driven vessels are ferries and offshore service vessels. The motivation is cleaner operation and reduced NOx tax and fuel cost.

NOx emission below 1.0 g/kWh is possible to achieve for the SI or the DF concept. For power plants operation (base load) these engines can be tuned to ½ TA-luft NOx level (0.7 g/kWh). Thermal efficiency is then reduced approx. 1% compared to operating at 1.5 g/kWh NOx. In a vessel this extreme value is too ambitious, but NOx emission in the range of 1.5 - 2 g/kWh is measured (IMO E2) *(26).*

The LBSI concept still has great potential for improvement in reduction in fuel consumption at a reasonably low NOx emission level around 1.5 g/kWh. This could be achieved by employing extreme Miller as described in section 3.7. Another advantage with this technology is the possibility to increase the tolerance to engine knock. The methane slip can further be reduced to a minimum but not completely removed.

The LPDF concept is a compromise between the otto and diesel cycle and thus somewhat limited in improvements. The main challenges are low tolerance to engine knock, slower load pickup and methane slip, especially at low load. Low NOx level around 1.5 g/kWh is achievable.

The HPDF concept is so far not in operation for ship propulsion. As described in section 2.2.5 this concept maintains all the diesel engine advantages for all kind of piston engines and is thus an interesting concept for ship prolusion. The concept has methane slip, is not sensitive to variation of gas qualities and it is suitable for conversion of existing ships. The NOx level is lower than in diesel operation but not in the level of IMO Tier III. Exhaust cleaning for NOx reduction is required to meet those limits. SCR or EGR are good alternatives due to the clean exhaust when burning gas.

The first gas engine installations were gas-electric only. The latest developments have been to adapt the gas engine to mechanical drive which is now available. Work is also done to improve the dynamic response and to make a gas fuel system which allow for use of intrinsically safe engine room. In general for all the three gas engine concepts are the challenge to reduce cost of LNG on board storage and bunkering system.

It is also of great importance to increase the number LNG suppliers and bunkering facilities.

3.9 Fuel saving concepts

There is at the moment quite some focus on fuel saving in marine business, driven by the high fuel prices, and solutions for this are discussed. In connection with this it is found appropriate (from a sustainability aspect) to mention two commercial available concepts for fuel saving. Even if fuel saving also implies less NOx the net effect is not evaluated as it depends on the specific application.

Advanced diesel-electric *(refr: 27, 28)*

Recently electric propulsion that allows for operating the gensets at variable speed has been launched. The generator can be run over the entire prime mover speed range independent of the synchronous speed. The power control system handles all the onboard gensets so that the engines operate at or close to optimal fuel efficiency versus the total onboard power demand. Especially for multiengine vessels with a great deal of low/part load operation, such a system allows for operating more efficient with an overall reduced fuel consumption and indirectly lower NOx emissions for the same amount of work done by the vessel (a modern medium speed genset engine using MGO as fuel, emits approx. 55 kg NOx pr. ton fuel, IMO E2 cycle).

The concept has the potential for improving the operating conditions for SCR and thereby overall efficiency, by keeping more steady state and probably an average higher exhaust gas temperature.

The potential in real operations will soon be documented as new offshore vessels are to be delivered with such a diesel-electric system. The effect on CO2 (fuel savings) and on NOx can then be verified.

Battery – hybrid *(refr: 29, 30)*

The first commercial battery powered seagoing vessels (ferries) was contracted late in 2011. There are also a few smaller tugboats with hybrid power. The ferries contracted are small, 150 passengers and 23 cars, for short crossings around the Clyde and Hebrides in Scotland. The propulsion is hybrid and include 2 separate battery rooms with to small diesel gensets and a battery bank in each. The gensets can either be used for battery charging or direct for propulsion. In general the batteries are to be charged overnight while the vessel is moored. The batteries to be used are lithium ion, the Nickel

- Manganese – Cobalt type (NMC), with a capacity of 700kWh each and delivered by Imtech Marine. Another supplier of such is Corvus Energy.

By following the link *refr. 30* a lot can be learned about the lithium ion technology i.e. about type of batteries available and their applicability/ strengths/weakness. The lithium polymer system based on NMC is pr. data the most promising for application in hybrid propulsion, combined with one or more gensets (either diesel or gas driven) as hybrid concept. There are different options of power management during crossover, but with the common ability for overnight battery charge.

When looking for applicability, displacement vessels such as ferries could be a candidate as the extra weight is probably not so critical. But even for ferries the applicability of electrical propulsion has to be carefully evaluated with respect to the circumstances for a specific crossing, terms operation for that crossing (distance, speed and schedule), the cost, emission trade off and the overall sustainability. The feasibility is also to a great extent dependent of the infrastructure cost onshore for the electrical supply and facilities needed.

Hybrid solutions have a potential for the type vessel (ie. offshore vessels) where a substantial part of operation is at low to medium load. It opens for a possibility to run the engines more fuel efficient and store energy for use when the need for power is small.

The R&D on battery technology is quite extensive (especially driven by the car makers) and improvements are likely to be seen. The main challenge is still the power to weight ratio. As a rule of thumb you get about 1 kWh pr. 10 kg battery from the latest battery technology.

4 Summary and comments

The technologies revealed herein vary quite significantly both technically and with respect to maturity. To give a common universal recommendation or advice is therefore not appropriate.

However, the post treatment technologies such as HC-SCR, CSNOX and Catalytic Filter have to be better documented for marine use i.e. from tests at realistic conditions. Matters such as need of consumables, need for maintenance and time between component replacement have to be properly documented.

A basic fundamental theoretical outline (chemically and physically) that explains the working principle should also be a required premise.

The same as above is valid for fuel additives and the different remedies to install on the engine for fuel and NOx reduction.

Principally the high pressure SCR is more or less like standard SCR but with more tolerance on exhaust temperature versus fuel sulphur content. The experience from use is so far limited. The expected applicability is for the bigger slow speed engines and HFO as fuel.

Some special application demo project on electric or hybrid propulsion can be anticipated. The battery technology still has to be further developed (the power-to-weight ratio) before any significant marine use can be justified.

The diesel-electric concept as described briefly in section 4.5 is an example of fuel saving potential, especially for vessels with substantial variation in operating conditions. The offshore vessels are the main target. From the motivation of NOx reduction the effect is not substantial and the legitimacy for support is debatable. If such concepts show the anticipated operational benefits and the sustainable fuel savings as promised it should anyway be rentable without an external support.

In general new technologies to be supported have to show:

- A minimum of objective documentation of performance
- Working principle backed-up by a proper theoretical explanation

In some cases a NOx Fund support can be justified for revealing a system potential in real operating conditions on a vessel. Such support should be on reasonable economical terms with a significant part of the risk placed on the system responsible. A test/development arena on a vessel in commercial business is not always desirable.

A benchmark summary against criteria's as listed in section 4.1 is given below.

High pressure SCR:

- *Stage of development, degree of innovation:* Systems are in development and being tested
- *Potential for NOx abatement (efficiency):* NOx reduction as standard SCR
- *Effect on fuel consumption:* None
- *Cost and complexity for marine implementation:* Adds some complexity to engine exhaust system and engine control.
- *Size and weight*: Reduced compared to standard SCR
- *Consumables for operation:* Reduced urea consumption
- *Maintenance need:* More experience from long term operation needed
- *Safety aspects:* As standard SCR, but some challenges with respect to engine control of transient load

Diesel DeNOx (SCR with fuel oil instead of urea)

- *Stage of development, degree of innovation:* Systems tested for the heavy duty truck industry
- *Potential for NOx abatement (efficiency):* To be documented as a function of fuel input
- *Effect on fuel consumption:* Increases on vessel.
- *Cost and complexity for marine implementation:* To be documented for catalyst. Less complex reagent system.
- *Size and weight*: Reduced weight compared to standard SCR because of no urea tank
- *Consumables for operation:* Fuel oil.
- *Maintenance need:* More documentation needed
- *Safety aspects:* Ad hazard risk if system failure and vaporized diesel enters exhaust system

Multi abatement systems

- *Stage of development, degree of innovation:* Some testing has been performed
- *Potential for NOx abatement (efficiency):* Lack of documentation from real operating conditions.
- *Effect on fuel consumption:* To be documented.
- *Cost and complexity for marine implementation:* Adds complexity
- *Size and weight*: More data needed
- *Consumables for operation:* None. Energy use to be documented
- *Maintenance need:* More documentation
- *Safety aspects:* NA

Catalytic filter

- *Stage of development, degree of innovation:* Extensive development is going on, especially on the catalyst material technology. The main driving force has so far been the automotive industry.
- *Potential for NOx abatement (efficiency):* More documentation needed.
- *Effect on fuel consumption:* None
- *Cost and complexity for marine implementation:* Ideally such systems should be easy to install.
- *Size and weight*: No reactant need reduce weight compared to standard SCR
- *Consumables for operation:* None
- *Maintenance need:* More documentation
- *Safety aspects:* NA

Pre- emulated fuel ("white" diesel)

- *Stage of development, degree of innovation:* Commercially available.
- *Potential for NOx abatement (efficiency):* Almost proportional with water content. 20% reduction is possible, but with fuel penalty.
- *Effect on fuel consumption:* Increases
- *Cost and complexity for marine implementation:* Small
- *Size and weight:* No additional weight/size
- *Consumables for operation:* None
- *Maintenance need:* More documentation

- *Safety aspects:* NA

Fuels

Additives:

- *Stage of development, degree of innovation:* Several products commercial available.
- *Potential for NOx abatement (efficiency):* None effect without effecting fuel consumption

Other fuels (except LNG):

- *Stage of development, degree of innovation:* Commercial available
- *Applicability as marine fuel:* For different reasons evaluated as not applicable for marine use (at least not within the next 10-15 years).

2-stage turbocharging and variable valve timing

- *Stage of development, degree of innovation:* Close to commercially available.
- *Potential for NOx abatement (efficiency):* up to 50% NOx reduction
- *Effect on fuel consumption:* None
- *Cost and complexity for marine implementation:* Add some more complexity to engine
- *Size and weight:* No additional weight/size
- *Consumables for operation:* None
- *Maintenance need:* More documentation
- *Safety aspects:* NA

Gas engines LBSI and LPDF

- *Stage of development, degree of innovation:* Commercially available for a wide range engine power. Bigger gas engines are also under development for marine use.
- *Potential for NOx abatement (efficiency):* 80% - 90%NOx reduction. Methane emission increases, especially at low load operation. To be improved.
- *Effect on fuel consumption:* potential of improvement
- *Cost and complexity for marine implementation:* Add more cost and complexity to fuel storage.

- *Size and weight: A*dditional weight/size because of the LNG fuel storage
- *Consumables for operation:* None
- *Maintenance need:* Marginal more than in diesel operation
- *Safety aspects:* As for diesel. International safety rules/regulation under development.

Gas engines HPDF

- *Stage of development, degree of innovation:* Commercially available for to stroke engines. Under consideration for four stroke engines
- *Potential for NOx abatement (efficiency):* 20%-40% NOx reduction without after treatment. No methane
- *Effect on fuel consumption:* potential of improvement at low load
- *Cost and complexity for marine implementation:* Add more cost and complexity to fuel handling and storage.
- *Size and weight: A*dditional weight/size because of the LNG fuel storage
- *Consumables for operation:* None
- *Maintenance need:* Similar to diesel operation
- *Safety aspects:* As for diesel. International safety rules/regulation under development.

Fuel saving concepts

Advanced diesel-electric

- *Stage of development, degree of innovation:* Commercially available.
- *Potential for NOx abatement (efficiency):* As function of overall fuel reduction.
- *Effect on fuel consumption:* Reduced. Sustainable concept for certain type of vessels/operation.
- *Cost and complexity for marine implementation:* Add more cost and complexity
- *Size and weight:* Marginal extra
- *Consumables for operation:* None
- *Maintenance need:* No extra maintenance should be needed, but has to be documented
- *Safety aspects:* NA.

Battery – hybrid:

- *Stage of development, degree of innovation:* Commercial available. Severe research and development on battery technology, especially driven by the automotive industry.
- *Potential for NOx abatement (efficiency):* High (a function of share of battery operation).
- *Effect on fuel consumption:* Reduced (dependent of share of battery operation)
- *Cost and complexity for marine implementation:* Add more cost and complexity on vessel. Add cost onshore for el-power supply.
- *Size and weight:* Significant extra from battery package
- *Consumables for operation:* None
- *Maintenance need:* Has to be documented
- *Safety aspects:* Can be solved (somewhat dependent of type of battery technology used).

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