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Control

Fuel Consumption and Emission Predictions: Application to a DP-FPSO Concept

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Introduction

From 2000 through 2003 a joint industry project (DP-JIP) was carried out, in which the effects of various dynamic positioning control options were investigated. The impact upon fuel cost and emission is a major factor in the assessment of DP performance. Hence, a method was developed to predict the fuel consumption and emission of a DP-vessel, making combined use of a simulation model for dynamic positioning and a simulation model for energy flows in an operating ship.

In the present paper the method is presented and the results of an application are shown, comparing a passively moored FPSO and a DP-FPSO concept for the Gulf of Mexico.

DP time domain simulations for the DP-FPSO concept in full and ballast loading condition have been carried out to assess the thruster action (delivered thrust) in the range of conditions of a typical Gulf of Mexico climate scatter diagram. The time series of delivered thrust were input to the dynamic simulation of the energy systems, taking into account the thruster characteristics. Fuel consumption and emissions (CO_2, SO_2, NO_x, HC and CO) could be evaluated over a typical year of operation in the Gulf climate. The method allows the designer to account for variation of design and operational parameters as well as off-design conditions, such as partial loading of generators.

The application of the simulation technology is found useful and effective for evaluation of environmental effects of operations with DP vessels, and for the investigation of the economic and environmental benefit of system modifications aimed to save fuel and/or to improve energy efficiency.

DP simulations

Time domain simulation methods for DP vessels have been described in various publications (Ref 1, 2). The software package “DP-Master” comprises a time domain DP simulation with the following elements:

- A mathematical model of the ship, to compute the forces acting on it due to environment
- A mathematical model of the thrusters, to compute the unit’s thrust given the power setting from DP control, and to compute the effective force acting on the vessel taking into account thrust degradation effects.
- A DP control module for position feedback, wind feed forward, optionally wave drift force feed forward and an optimum thrust allocation method.

With these elements it is possible to simulate the dynamic positioning of the vessel and obtain time series of dynamic variables like heading, position and thrust.

For the present application the delivered thrust at each of the thrusters formed the link between the DP simulations and the power system simulations, as will be explained in the Section “Simulation method”.

Energy flow simulation

The structure of the Integrated Energy Systems (GES) software simulation package is based on the bond graph method. The basic concept behind the bond graph is that energy is the fundamental constraint in a physical system and is the one variable that is common to the whole system. Thus, the essential feature of the bond graph approach is the representation of energy interactions between systems and system components by an energy bond. The physical laws of energy preservation are fulfilled in this method.

This method facilitates building a model in multi-physics systems, such as marine engineering systems, by ensuring that the model components are connected through the power flow. This is done by defining an effort variable and a flow variable, which, when multiplied with each other, represent the power flow between the components.
Figure 1 shows the GES model of the diesel with its various gates. The input and output gates describe:

- Fuel and combustion air inflow;
- Torque and rpm output;
- Output of the above specified emission components.

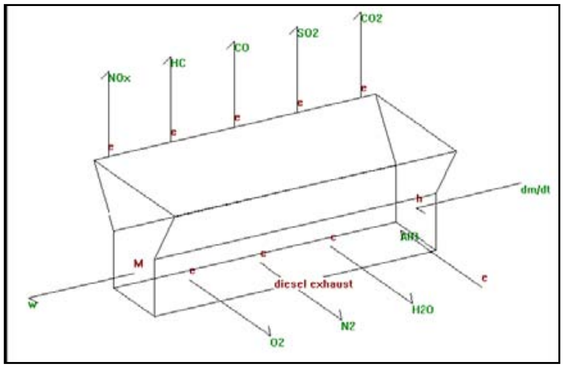

Figure 1: Diesel Engine representation in GES

Due to the open architecture of GES, a special functionality could be included in GES for operational profile analyses. In such operational analyses, a static model of the complete propulsion installation of the ship is simulated.
By using the operational profile of the ship the total energy balance of the installation can be calculated for each operational condition. This method is very useful for comparing different ship configurations. A model of a propulsion and energy system consists of the various components from power generation to energy consumers. GES calculates the energy flows among all those components using the mathematical descriptions of the component models and the operating profile of the vessel. Due to the open architecture of GES, many aspects can easily be included in the simulation, such as initial purchase costs, maintenance and operational costs, size and weight of the installation, fuel consumption and efficiency, availability, exhaust emissions.

Application

The FPSO concept was based on a design by IZAR (see Figure 2) and has the following overall particulars and dimensions:

Type:	New-build, $0.85*10^6$ bbl
Production:	50,000 bopd,
Water depth:	1500 m
Design base:	GoM: (winter storm and hurricane limit conditions)
Limit production:	Hs=7.3 m , Tp=12.4 s, Vc=0.73 m/s, Vw=33 m/s

	Ballast	Loaded	
Lpp	262.4		[m]
B	46		[m]
T	14	21	[m]
displ	160739.1	244226.4	[t]

Table 1: General dimensions of FPSO

On basis of the hull design, MARIN carried out diffraction theory computations providing the hydrodynamic data for the computation of wave drift forces for the mooring and thruster design. WINDOS calculations for the wind loads and OCIMF values for the current drag coefficients were used to determine the environmental loads for the design conditions.
The moored version of the FPSO has an internal turret with 3*3 chain mooring arrangement, designed by Bluewater Engineering. The thruster layout and power system is designed by GustoMSC and given in Table 2 and Figure 2 respectively.

It has to be noted that these designs are conceptual and just sufficiently refined to be able to realistically carry out this comparison study.

Type	Diameter	X-pos	Y-pos	Max.	Means of thrust	PD	RPM	Z	AeA0
Ka (nozzle 19a)	4.30	-120.00	15.00	950.87	Variable RPM	1.10	127.51	4	0.70
Ka (nozzle 19a)	4.30	-120.00	-15.00	950.87	Variable RPM	1.10	127.51	4	0.70
Ka (nozzle 19a)	4.30	-90.20	0.00	950.87	Variable RPM	1.10	127.51	4	0.70
Ka (nozzle 19a)	4.30	59.20	18.00	950.87	Variable RPM	1.10	127.51	4	0.70
Ka (nozzle 19a)	4.30	59.20	-18.00	950.87	Variable RPM	1.10	127.51	4	0.70
Ka (nozzle 19a)	4.30	95.20	14.00	950.87	Variable RPM	1.10	127.51	4	0.70
Ka (nozzle 19a)	4.30	95.20	-14.00	950.87	Variable RPM	1.10	127.51	4	0.70

Note: X- and Y-position relative to amidships.

Table 2: Thrusters on DP FPSO

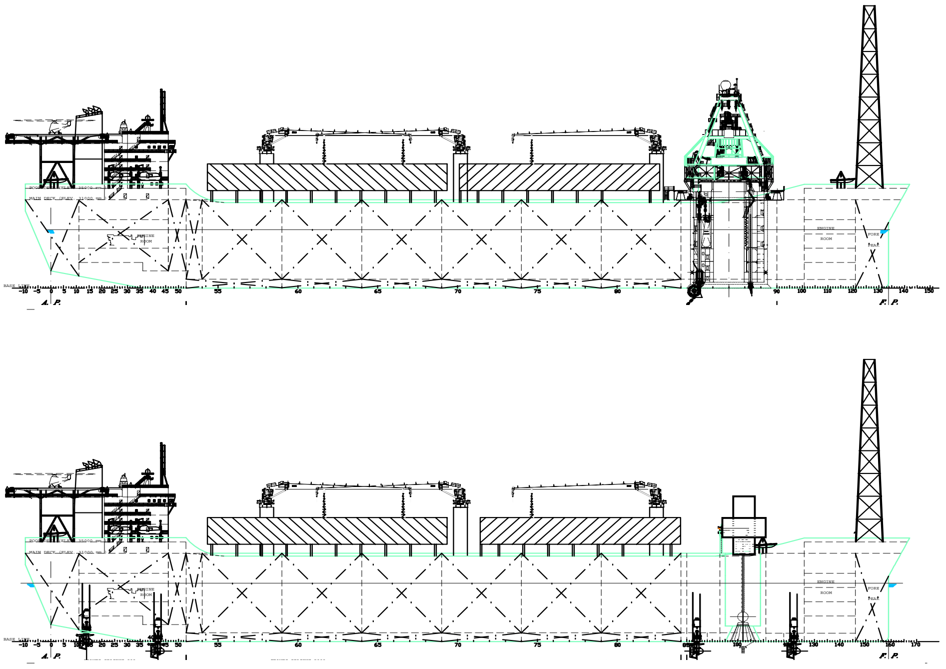

Figure 2: FPSO general arrangement, Moored and DP version

The design conditions for the FPSO concepts (Moored and DP) shown in Table 3 are realistic for the Gulf of Mexico at the time that the investigation was carried out. The recent hurricane history of the summers of 2004 and 2005 may have changed these criteria. However, for the purpose of the study the assumption is valid.

Set Point	Thrusters	Sea Condition	Hs	Tp	Vw	Vc
20^o	Thr 7 out	100 Yr Survival	12 m	15.7 s	44 m/s	1.10 m/s
10^o	Intact	10 Yr Independent	8 m	12.8 s	33 m/s	1.33 m/s
10^o	Intact	Max operating	7.3 m	12.3 s	33 m/s	0.73 m/s

Table 3: Design Conditions (used on ballasted FPSO)

The power system was designed according to DP class 2 regulations with separated engine rooms and switchboard rooms in such a way that a fire or flood in one room will effectively lead to the loss of only one thruster. The gas turbines which are used for production can be switched over to supply power to the DP system. In the very scarce high sea states (Hs > 7.3 m) the production process will be stopped. In this way the required back-up power is available in case of a power failure in the diesel engines. In lower sea states the diesel engine arrangement has sufficient power backup.

The installation exists of 3 gas turbine generators with 25 MW, 8 diesel generator sets with 4860 kW, 7 AC engines of 5000 kW with gearbox, converter and transformer.

The one-line diagram of the installation is given in Figure 3.

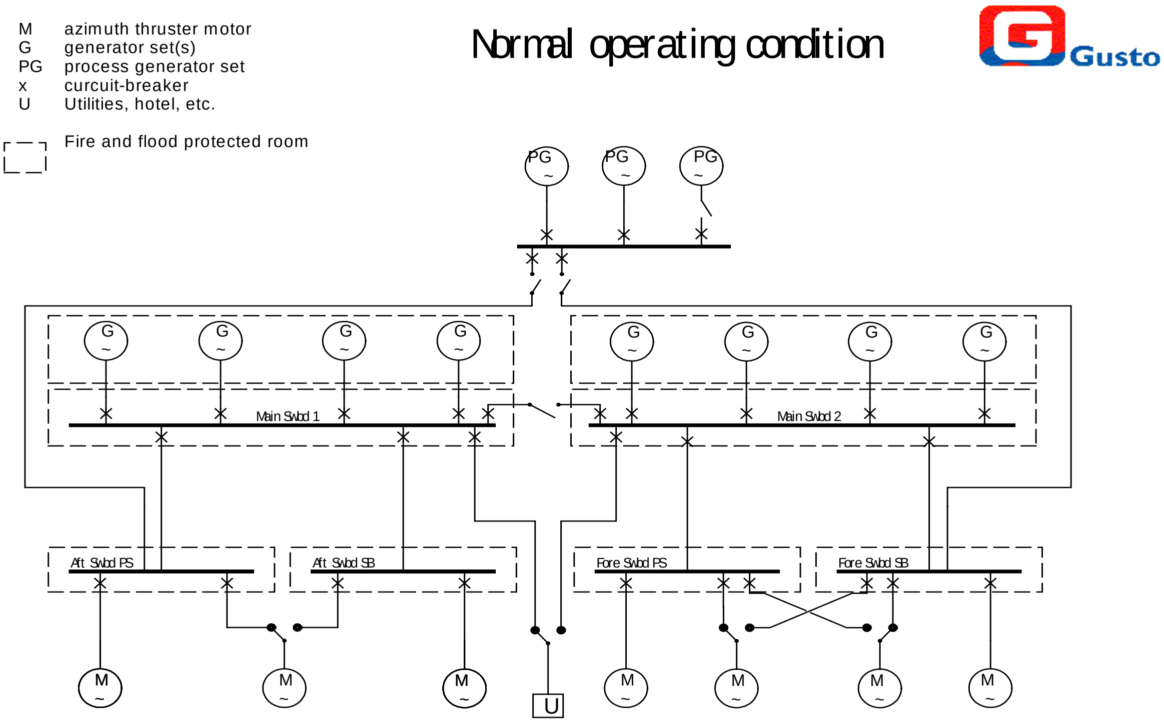

Figure 3: Key-one line diagram for DP FPSO

Simulation method

The following simulations were carried out:

1. DP station keeping simulations
2. Power use and fuel consumption simulations

The fuel consumption analysis considers a typical annual scatter diagram of sea states (Table 4) for the Gulf of Mexico.

Scatter diagram GoM Occurrence in 10**-5
Tp

Hs	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
12																			
11																			
10																			
9													25						
8												9	16						
7												9							
6											16	16							
5										16	415	25							
4									171	921	449				9	49			
3							16	897	9017	1022	113	32	17	16	49	57			
2						163	5829	12110	3806	343	155	82	25	57	123	252	17	65	
1				9	2251	14562	15511	6564	5631	1353	431	178	164	343	195	456	198	320	
0			73	1647	4072	2293	2127	1512	1352	1214	546	164	171	196	66	90	236	25	

Table 4: Scatter diagram for the Gulf of Mexico

A representative selection of conditions from this scatter diagram has been made for the simulations. As shown in Figures 4 and 5 the lower sea conditions (0-4 m significant wave height) comprise about 95 % of all occurrences, while a hurricane may incidentally result in a high sea state. A range of 8 sea states for simulation (see Table 5) was therefore sufficient to cover the climate. Statistical evaluation resulted in the 'average fuel consumption over 1 year operation' whereby it was assumed that full and ballast conditions are distributed evenly.

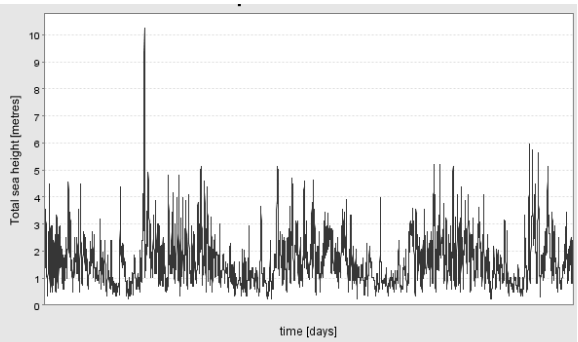

Figure 4: 4 Year history of significant wave height in Gulf of Mexico at 28 N and 90 W

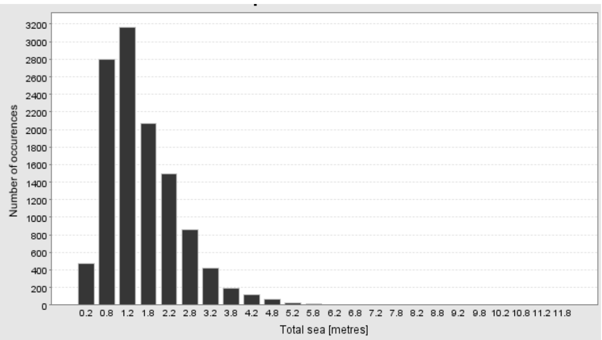

Figure 5: Occurrence distribution of 4 year history of significant wave height in Gulf of Mexico at 28 N and 90 W

DP simulations

The simulations provided the power requirement at the propeller shaft of the thrusters for a 3 hr realization of the sea states listed in Table 5.
The time series of the shaft power requirements were used as input for the GES electrical system simulations.

ENVIRONMENT						
Waves			Current		Wind	
Hs [m]	Tp [s]	Dir_{wa} [deg]	V_c [m/s]	Dir_c [deg]	V_{wi} [m/s]	Dir_{wi} [deg]
1	5	180	0.4	90	6	160
1.8	6	180	0.4	90	9	160
2.5	7	180	0.4	90	11	160
3.5	8	180	0.4	90	13	160
4.5	9	180	0.4	90	14.5	160
5.5	10	180	0.4	90	15.5	160
6.5	10.5	180	0.6	135	18	160
7.5	11.5	180	0.8	150	20.5	160

Table 5: Environmental conditions selection to represent Gulf of Mexico climate

GES simulations

The energy flow simulation program GES needs mathematical modeling of the complete energy system, including power generators, switches, transformers, and consumers. The thrusters of the DP system are variable consumers whereas auxiliary ship systems and production are considered to be constant. The installation has been modeled as shown in Figure 6
On basis of information available for similar vessels the auxiliary power consumers have been identified and their average power consumption is given in Table 6. The power consumption of production is a realistic estimate for an FPSO with the given production rate (see Table 1) and the max. DP power consumption follows from the design calculations in the conditions of Table 3.

Service:	kW	Production:	kW
Ballast	50	Production Systems:	50,000
Control & communication	140	DP system:	
Lighting/Accommodation	360	Variable load	1,000 to 31,000
Navigation	5		
Services	1,000		
Ventilation & A/C	1,100		

Table 6: Load list for FPSO

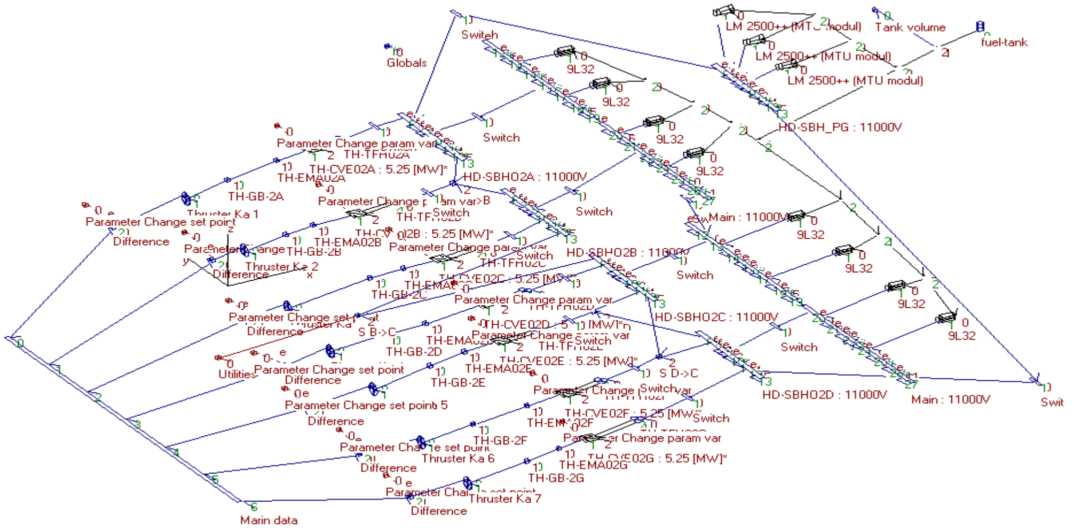

Figure 6: GES model of Energy System and Thrusters

The simulations assume that the number of generators which are in operation is sufficient to take the peak demand in the sea state, while one extra generator is kept on stand-by. For thus defined generator configuration the simulation in a given sea condition is carried out.
The Functional block *"Main data"* reads the delivered trust data time series. In the program GES the 7 thrusters are modeled in the same way as in DP Master, with Ka4-70 propellers and nozzles 19A. The propellers are connected to the gearbox with a reduction of 6.25. The synchronous electric engine is 5000 kW at 750 rpm. These are realistic estimates as there are no detail design values available.
The maximum values of the components have been determined for a maximum thrust of 950 kN.
In the simulation program GES the main voltage setting has been checked against the *Voltage Design Guide* (VDG), which computes maximum expected nominal current and maximum short circuit current and compares that to system allowances. The initially assumed value of 11000 V generator AC output satisfies the power requirements.

Fuel consumption and emission prediction

The emissions and fuel use of the DP FPSO are given in the Table 7a below. Separate calculations are carried out for the ship systems (assuming DP system out, which represents the moored FPSO) in Table 7b.
The fuel properties are HFO with a caloric combustion value of 40000 kJ/kg, 82% carbon, 13% hydrogen and 4% sulphur. The diesel generators are comparable to Wärtsilä 12V32E, with 4860 kW power, but with efficiency curves which are typical for that class of engines. Nominal specific fuel consumption rate is 192.12 g/kWh.

The fuel consumption from the generator sets on the DP version of the FPSO is about 6900 tons per year, corresponding to 1.7 million Euro. About 6400 ton, costing 1.6 million, thereof is due to the auxiliary ship system consumers (assuming average consumption of 2.5 MW). The fuel cost is computed against 250 Euro per ton HFO.

Fuel and emissions Review table	HFO t/year	CO2 t/year	SO2 t/year	NOx t/year	HC t/year	CO t/year
Loaded	7016.3	20868.1	561.3	659.2	32.7	79.4
Ballast	6845.1	20357.0	547.6	646.5	32.1	78.3
Annual Avg.	6930.7	20612.5	554.4	652.8	32.4	78.8

Table 7a: Fuel and emission from diesel electric system (DP FPSO)

Fuel consumption Ship Systems	HFO [t/year]	CO2 [t/year]	SO2 [t/year]	NOx [t/year]	HC [t/year]	CO [t/year]
2.5 MW Continuous	6428.4	18485.1	497.4	598.2	29.8	73.5

Table 7b: Basic ship system consumptions and emissions (moored FPSO)

The power generation for the production plant is generated with gas turbines. The simulations used HFO equivalent fuel, but normally these systems work on light fuel or even on the co-produced gas. The emission values in Table 7c have been transferred to MDO equivalent. For simplicity in this exercise, the MDO is assumed to have the same caloric combustion value as the used HFO, but 86% carbon, 13% hydrogen and 1% sulphur. The chosen caloric combustion value makes the results slightly conservative because of somewhat increased fuel consumption.

Review Process Plant						
Gas Turbines 2*25MW	MDO equiv. [t/year]	CO2 [t/year]	SO2 [t/year]	NOx [t/year]	HC [t/year]	CO [t/year]
30MW load	24737.2	77994.7	1484.0	1040.7	60.2	65.5

Table 7c: Fuel and emission from Production Gas Power plant

Table 7: Fuel and emission results in one year of operation in Gulf of Mexico

Discussion of results

The results show that the loaded FPSO generally takes a bit more power to keep on station with DP. Under the assumption of being in a loading cycle with regular cargo take-off, the FPSO drafts are evenly distributed in the range between ballast and full. So, the annual average represents the fuel consumption and emissions from the FPSO in operation. The DP system requires about 7% extra fuel compared to the moored FPSO concept (total for the ship), while it is 1.5% if the power for production is also considered.

Two aspects, related to the assumptions under which the comparison has been made play a role:

- The selection of a GoM climate, which is generally mild and thus requires relatively little DP effort.
- The limitation of the number of diesel generators imposed by the scenario that in high seas the production can be stopped and gas turbine power will be available as back-up.

The assumptions of a GoM climate and the limitation on diesel generators are linked to each other, because the really severe storms in the GoM are related to hurricane passage, in which the vessel has to be stand-by for disconnection anyway.

However, such a concept in a North Sea climate would probably have a higher sea state limit for stopping production –if at all- and would more frequently encounter storms. The system would be laid out for a higher design sea state with more generators and thrusters leading to a somewhat higher percentage of power consumption from the DP system.

The diesel engines produce relatively much CO, HC and nitrous oxides (NO_x). One may question whether this is caused by the partial loading of the generators. The required back-up power (DP class 2) and the fact that most of the time the DP power variations are well below the maximum in the 3 hr period cause partial loading of the generators. An example of this effect is given in Table 8. It represents dynamic positioning in a 7.5 m sea state with 8 respectively 6 generator units running and shows that the setup with 8 generator units consumes 4% more fuel, emits 4% more CO_2 and SO_2 but less than 2.5% extra NO_x, HC and CO. So, partial loading is fuel-inefficient but does not lead to proportionally larger emissions of NO_x, HC and CO.

Case	Comparison of same DP condition with 8 resp 6 generator units running						
No. of generators	Ship draft	HFO [kg/3hr]	CO2 [kg/3hr]	SO2 [kg/3hr]	Nox [kg/3hr]	HC [kg/3hr]	CO [kg/3hr]
8 units	Full	5541.8	16538.1	443.3	421.5	19.1	40.9
6 units	Full	5323.3	15884.0	425.9	418.3	18.6	39.9

Table 8: Engine emission and fuel consumption comparison for one hour operation in 7.5 m sea state.

Conclusions

The overall results lead to the following conclusions:

- *The combination of time domain DP simulations with energy flow simulations package GES is a feasible method to evaluate emissions and fuel consumption of DP vessels and allows to optimize the use of generators and consumers.*

For the application on a FPSO concept in the Gulf of Mexico the following conclusions could be made:

- *The ship emissions stem for the greater part from the gas turbine power generation for the process plant.*
- *The average emissions increase due to applying the DP system is 2% for* CO_2 *and about 3% for* SO_2 *,* NO_x *, HC and CO.*
- *The diesel engine emissions of CO, HC and nitrous oxides (*NO_x*) per kg fuel use is relatively high compared to gas turbine. For the* SO_2 *emissions, the amount of sulphur in the fuel is the overall determining factor.*

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