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ABSTRACT

In this thesis three new technologies with the potential to significantly reduce the release of air emissions have been evaluated. The rigs considered are semi-submersibles and drillships as they have the capacity to reach ultradeep water sites. One potential method is to implement natural gas engines on MODUs, as natural gas is the cleanest burning fossil fuel. LNG will allow for 20-25% lower CO_2 emissions and 90-95% lower SO_x emissions. In addition, the NO_x emissions will be significantly reduced. The technology exists and is becoming widely accepted in the shipping industry. However, there may be problems during bunkering of LNG to floating rigs, as the temperature of LNG can be down to minus 170 degrees. When the LNG enters the bunkering hose it will freeze and become brittle. The risk of breakage will therefore be significant. An alternative potable tank transfer method may be a solution to this. Also the availability of LNG is currently insufficient as mobile rigs need fuel supply at varying locations. However, LNG will become more available in the future as several new LNG powered ships are under construction or planned for the next decade.

Another measure is to implement new drilling technologies, which have the potential to reduce required rig size and indirectly reduce the air emissions. There are large differences in fuel consumption for the large and the small rigs, as large rigs have higher power requirements. In addition, larger rigs require more power for station keeping which is a major fuel consumer. The RDM-Riserless drilling method from Reelwell and the slim well drilling method both have a great potential to reduce required rig size. In this thesis a semi-submersible with a displacement of 53 000 mT and a drillship with a displacement of 84 000 mT have been used to estimate the weight reduction, due to less mud and riser tension required for the new drilling methods. The new displacements are used to find the typical fuel consumptions and thus the reduced air emissions. The reductions are significant. The RDM-R method allows for the largest reduction of the two drilling methods, with 24% reduction of air emissions for the semi-submersible considered and 33% for the drillship. The slim well drilling method has the potential to reduce the air emissions with approximately 19% for semi-submersible and 31% for the considered drillship. The reductions will vary from rig to rig as the VDL is not linear to the displacement.

The drilling methods have the potential to be combined. The reductions are even larger, especially for the semi-submersible which allows for a reduction of 43%. The drillship considered allows for a reduction of 38% when the drilling methods are combined. Both methods will lower the cost of operation and may therefore be an attractive alternative in the future. The weight reduction is only based on mud and riser weights and one can expect even larger reductions in air emissions as BOP, Xmas tree, mud pumps and associated equipment are to be implemented in the calculations. To use LNG as fuel combined with the drilling methods may be attractive for new builds as LNG is a lower cost fuel than diesel.

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LIST OF ABBREVIATIONS

API :	American Petroleum Institute
BOP:	Blow Out Preventer
BP :	Beyond Petroleum (former name British Petroleum)
CH_4 :	Methane
CNG :	Compressed Natural Gas
CO_2 :	Carbon Dioxide
DDS :	Dual Drill String
DFV :	Dual Float Valve
DNV :	Det Norske Veritas
DP :	Dynamical Position
ID :	Inner Diameter
ISO :	International Organization for Standardization
JIP :	Joint Industry Project
LNG :	Liquefied Natural Gas
MODU :	Mobile Offshore Drilling Unit
nmVOC :	Non-Methane Volatile Organic Compounds
VOC :	Volatile Organic Compounds
NO :	Nitric Oxide
NO_x :	Nitrogen Oxides
NO_2 :	Nitrogen Dioxide
OD :	Outer Diameter
RBOP :	Rotating Blow Out Preventer
RCD :	Rotary Control Device
RDM :	Reelwell Drilling Method
RDM-R :	Reelwell Drilling Method – Riserless
RMR :	Riserless Mud Recovery
ROV :	Remotely operated Vehicle
SECA :	Sulphur Emission Controlled Areas
SO_x :	Sulfur Oxides
SO_2 :	Sulphur Dioxide
TDA :	Top Drive Adapter
VDL:	Variable Deck Load

1. INTRODUCTION

1.1 BACKGROUND

The world is facing climate changes as the temperature increases. Some major effects the world is facing because of global warming are increased sea level as result of ice sheet melting, more extreme weather and loss of species. There is now a need for more environmental equipment worldwide and procedures to stop the temperature increase before the consequences becomes serious. Since the oil and gas companies are major contributors of greenhouse gases, it would be convenient to reduce the environmental footprints from these companies. The release of air emissions due to combustion of diesel can give adverse health effects, in addition contribute to change ecosystems and damage buildings.

New technologies improve rapidly, and several technologies can today be implemented to reduce the air emissions. However, the technologies offered on today's market are not ground breaking and will not be sufficient in the long run. Therefore it is important to not only improve the existing solutions but to find new ground breaking solutions. This will require many years of development and may only be implemented if the costs could be reduced.

A potential could be to implement Liquefied Natural Gas (LNG) for power generation as this is the cleanest burning fossil fuel, in addition a lower cost fuel. This over the last decade has proven to be widely accepted for several ships worldwide. To use this solution on floating Mobile Offshore Drilling Units (MODUs) have not yet been a subject. The technology exists but there may be problems with supply and bunkering of LNG to floating offshore rigs. To develop such a solution may in the future solve the related problems. Problems today may not be a problem in the future when several years of development has taken place.

Two new drilling technologies are currently under development. Both the riserless drilling method from Reelwell and the slim well drilling method have the potential to significantly reduce rig size, as less weight is required for the drilling operations. This indicates that a smaller rig with less power requirements and day rates could be used to drill in ultradeep waters. A smaller rig will indirectly result in lower air emissions. The methods also have the potential to be combined and may reduce required rig size further. To implement new drilling methods are independent of fuel type and therefore the potential to combine the mentioned technologies could be a goal for the future.

1.2 OBJECTIVES

It is believed that there is a great potential of reducing the air emissions from MODUs. In this paper the focus will be on semi-submersibles and drillships, as they have the capacity to reach unexplored ultradeep water sites. To give the reader some understanding, the present situation and the drilling units considered in this paper will be described. A graph displaying how the magnitude of the variable deck load varies with the displacement of the rig will be created. This is to give the reader an overview of the relevant dimensions and in addition it will be useful later in the thesis. How much horsepower the different rigs have and the corresponding diesel consumption will be investigated. This will later in the thesis be used to calculate the potential reductions of air emissions that the new technologies can offer.

Main new technologies will be described and evaluated with respect to air emissions. One obvious potential is represented by the possibility of changing fuel from diesel to LNG on floating MODUs. The other potential has the possibility to reduce rig size and thus the power requirements by implementing new drilling technologies. The two are independent, but have the potential to be combined.

The prime objective of the thesis is reflected in the title:

> *"An evaluation of new technologies with the potential to reduce air emissions from floating Mobile Offshore Drilling Units"*

According to the above the work is split into two independent parts:

- Evaluation of the potential to implement natural gas engines on floating MODUs. This chapter will describe natural gas and the existing natural gas technology in the oil and gas industry. Since natural gas is starting to be widely used as fuel on Norwegian ships, similarities will be made. Together, this information will provide a basis for the discussion that examines whether or not natural gas has the potential to be implemented on floating MODUs.
- Evaluation of the impact of two new drilling technologies. Both riserless drilling and slim well drilling are to be described. Riserless drilling and slim well drilling have both several advantages. Both have the potential to reduced rig size needed to drill in ultradeep waters. The two new drilling methods will be compared to the conventional drilling method. Mud volumes, riser tension and riser weights are calculated to estimate the weight reduction and the corresponding reduction of air emissions.

The potential rig size reduction, air emission reduction and the possibility to implement both drilling methods will also be evaluated.

1.3 STRUCTURE OF THE REPORT

Chapter 1 – “*Introduction*”. The background, objective and structure of report are presented to give an introduction to the thesis.

Chapter 2 – “*Present situation*”. The conventional drilling method and the corresponding air emissions are described. The substances released during diesel combustion and the corresponding consequences are presented.

Chapter 3 – “*Mobile offshore drilling units*”. Briefly describes the main characteristics of semi-submersibles and drillships. The variable deck load is defined and a graph of the variable deck load against the displacement is presented for semi-submersibles and drillships.

Chapter 4 – “*Diesel consumption on drilling rigs*”. The average installed vessel power is presented for semi-submersibles and drillships. The main energy users and the percentages of them are evaluated. A graph of the fuel consumption is presented and explained for semi-submersibles and drillships.

Chapter 5 – “*Alternative fuel - Natural gas*”. In this chapter the possibility to implement LNG on floating MODUs is evaluated. Today’s technology and the availability of the fuel are described.

Chapter 6 – “*New drilling methods*”. Two new drilling methods are described and compared to the conventional drilling method. The potential to combine both drilling methods and the possible reduction of air emissions are evaluated.

Chapter 7 – “*Summary and conclusion*”. A short summary and the conclusions are presented. Combining the two new drilling methods with a LNG powered MODU is briefly evaluated.

2. PRESENT SITUATION

About 600 mobile offshore drilling rigs today are currently in operations worldwide. The technology continues to improve and frontier areas are being explored. Large and costly drilling units are conventionally used to drill in deep water. The size of the structure is required to support the floater with enough buoyancy to handle large and heavy drilling equipment. Fifth and sixth generation Semi-submersibles are usually used for deep and ultradeep water drilling. Drilling rigs today can drill in water depths up to 3 600 m. These drilling rigs have the capacity to drill down to 12 000 m below surface. Smaller and older semi-submersibles are often towed or transported on vessels to drilling location, as they often do not have propulsion systems. However, the larger and newer generations of semi-submersibles are self-propelled. The majority of drillships are self-propelled and can transit to new locations rapidly.

Chain, synthetic fiber rope, and wires or the combination of them can be used to positioning a MODU. Water depth and environmental factors determine which materials or combinations to be used. The synthetic fiber rope is the lightest alternative of the three and is often used in combination with the other materials in ultradeep water. The mooring system mainly depends on the anchor strengths, vessel size and prevailing weather conditions. The spread mooring system can be used in a large variety of applications and is commonly used for MODUs [1]. Mooring lines can also be used in combination with thrusters. This is called thrust assist as the propellers (thrusters) help positioning the rig in harsh weather. Another method to station the rig is to use Dynamical Positioning (DP). Sensors and satellite signals are used to provide information about the rigs position. Thrusters keep the rig inside its allowable envelope. DP has been used on drillships since the 1970s. On semi-submersibles it did not become common to incorporate DP systems until late 1980s. Newer generations of MODUs often use DP systems alone to position the rig in deep and ultradeep waters.

Typically, a rig has several diesel engines which combined gives between 8 000-60 000 horsepower. The thruster power varies but can be in the range of 85% of the installed vessel power. The smaller rigs typically have an average power load between 20-40% of the total installed vessel power. As larger rigs often have more advanced DP systems, the average power load can be up to 70% of total installed vessel power. Therefore, the difference between small and large units can be very large and the emissions may vary significant. The average fuel consumption can vary between 5 mT and 135 mT per day, mainly dependent on rig size, installed power, thruster power, mooring systems and weather. This corresponds to a daily release between 16 mT and 430 mT of carbon dioxides. The methane emissions can be up to 0,11 mT per day, the sulfur oxides can be up to 0,16 mT per day and the non-methane volatile organic compounds can be up to 0,68 mT per day for the larger DP rigs. In, addition significant amounts of nitrogen oxides are released during diesel burning. Theses emissions are rig specific and can be in the range of 60 kg per mT fuel consumed.

A marine riser connects the rig to the Blow Out Preventer (BOP). Most commonly used is the 21" riser. An 18-3/4" wellhead system is conventionally used with an 18-3/4" BOP stack. A large conductor string, often 30", is set prior to the BOP and functions as the foundation for the wellhead. Several decreasing casing sizes are then used to reach drilling target depth. Surface casing, intermediate casing and production casing are most often used. In deep water drilling liners are also commonly used.

Drilling fluids, also known as mud are used to control pressure and to transport drilling cuttings. When the formation pressure increases, higher weighted mud must be added to balance the pressures. The mud therefore stabilises the hole and functions like a barrier to prevent ingress of hydrocarbons into the well. During the tophole drilling operation mud is disposed on the seabed. After BOP is set, the mud is transported from the well up to the drilling rig.

2.1 FOOTPRINTS AND CONSEQUENCES

Offshore drilling operations cause several forms of pollution which impacts the environment, see Figure 1. Drilling mud are discharged to the seabed when drilling the tophole during the open hole operation. Drilling mud contains toxic chemicals which may affect the marine life in a negative manner. Also polluted produced water and runoff water from deck is released to the ocean and may influence the local marine life. There are also the risks of large spills and blowouts which can have significant effects on the environment.

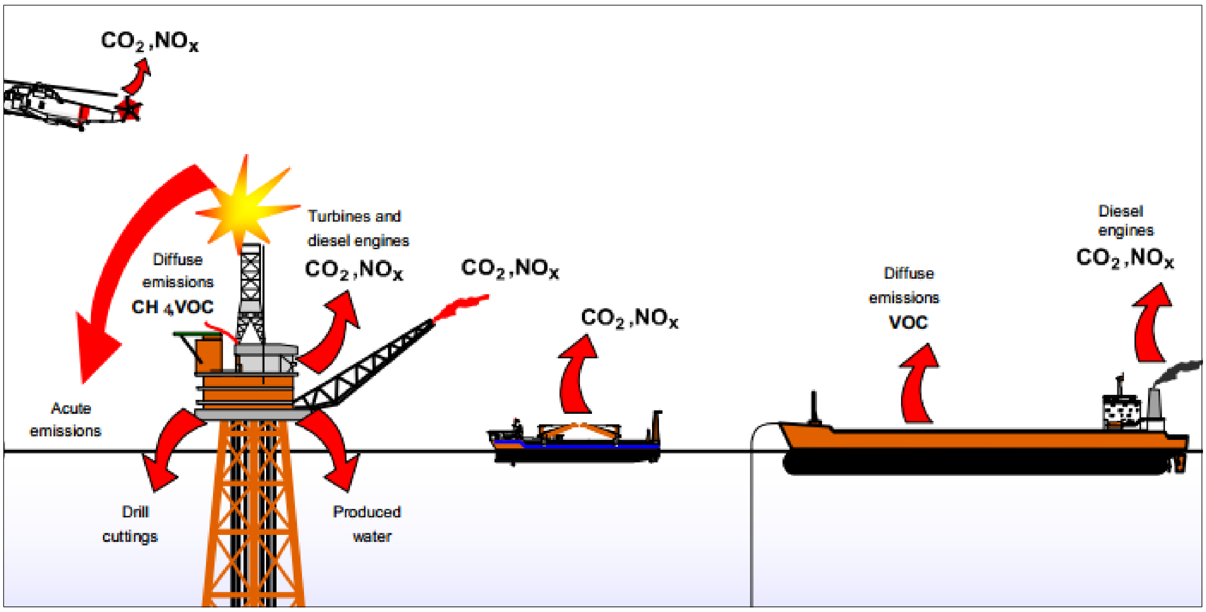

FIGURE 1: EMISSIONS RELATED TO OFFSHORE DRILLING OPERATIONS [3]

Another consequence during drilling operations is the vast air emissions which contributes to global warming, in addition release of toxic substances that can give adverse health effects. Some substances also contribute to damage buildings and change ecosystems. Significant air emissions are released during the combustion of diesel for power generation. Emissions from other activities like venting, fugitive emissions from process equipment, transfer of bulk materials and circulation of drilling fluids are considered negligible compared to the diesel combustion [2].

2.2.1 EMISSIONS TO ATMOSPHERE

Emissions to the atmosphere during drilling largely consist of exhaust gases from diesel combustion. Carbon Dioxides (CO_2) and Nitrogen Oxides (NO_x) are substances which these exhaust gases contain. Together with Non-Methane Volatile Organic Compounds (nmVOC), Sulphur Dioxides (SO_2) and Methane (CH_4) they are released to air during drilling. The volume of emissions is most often calculated on the basis of fuel consumption. An emission factor given by industry standards or field-specific measurements provides sufficient basis to calculate these emissions [3]. Particulate matter is also a form of air emission, which is released during diesel combustion.

CO_2 is the major greenhouse gas which is released from fossil fuels during combustion. Different types of fuels give different quantity of the substances in the exhaust gas. Natural gas is the fuel which gives the lowest emission of CO_2 per energy unit. Roughly estimated, one kilogram of fuel oil will produce 3,15 kilograms of CO_2 when burned [3]. CO_2 and CH_4 are the major greenhouse gases. CH_4 decomposes faster into the atmosphere than CO_2 but due to more efficient trapping of radiation than $CO_{2,}$ methane is considered to impact the climate change over 20 times more than CO_2 over a 100-year period [4].

NO_x is the generic term for NO and $NO_{2,}$ both having a negative effect on the environment. These compounds cause acid rain which damages buildings, metal and stones. Acid rain also causes eutrophication, which results in undesirable algae growth and may lead to changes in ecosystems due to change in composition of species. Pollution of waterways and the soil will impact fishes and other fauna. Another consequence is production of ground-level ozone which gives damage to buildings, crops and health [3].

Most of nmVOC emissions occur during loading and storage of crude oil due to vaporization. Oil from various fields gives large differences in emissions because the oil content varies. These volatile organic compounds can impact human health and environment, as ground-level ozone forms by these substances. nmVOC affects the greenhouse effect indirectly as there are formed ozone and CO_2 when nmVOC reacts with air [3].

Burning of fossil fuel also forms SO_2 which gives adverse health effects, especially with regard to breathing, pulmonary defences and respiratory illnesses. Contamination of streams and lakes, corrosion of buildings and health effects are some consequences sulphates are associated with, and the precursor to sulphate is SO_2 [5].

Particulate matter is a term used for the pollution of liquid droplets and solid particles in the air. The emissions come from different materials and chemicals and with varying sizes. Small particles are of concern as they can cause health effects when inhaled. The particulate matter also affects the environment. Some consequences are increased acidity of lakes, changes in coastal waters and rivers, reduced visibility and damages to corps, stones and other materials [6].

3. MOBILE OFFSHORE DRILLING UNITS

The most common mobile offshore drilling units are semi-submersibles, drillships and jack-ups. These structures can be moved without significant effort. The size of a MODU is primarily influenced by water depth, environment and its intended function. A MODU will need high variable deck load because of different drilling requirements, which together with transit speed requirements largely determines the configuration. Unlike most production vessels, MODUs have the ability to disconnect from the riser and leave location, or slacken the mooring lines during extreme weather conditions to avoid damages. With modifications and replacements MODUs can be used as production units [7]. In this paper only semi-submersibles and drillships will be discussed, as they can explore ultradeep water sites and provide capabilities for future needs.

The proportions of the different drilling units on the global market are collected data from RigLogix [8] and shown in Figure 2. The total worldwide rig fleet is approaching 1500 units. Over 200 units are currently under construction, the majority of them are semi-submersibles, drillships and jack-ups. Most of the existing units are performing drilling, completion and workover operations. There are also several units which are ready stacked, waiting on location, under inspection and modification or are mobilized from one location to another. About 100 rigs are temporarily “shutdown” because of lack of work.

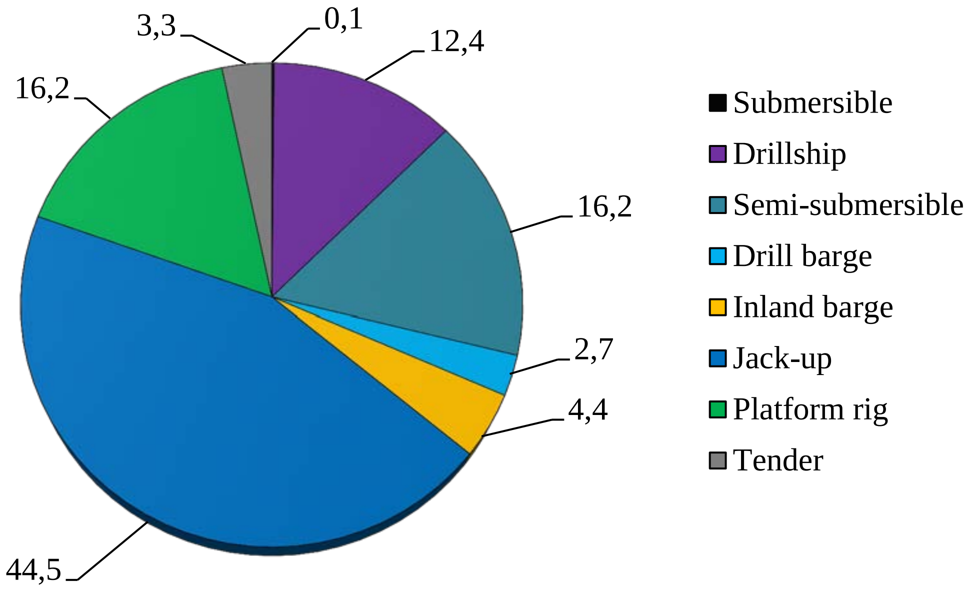

FIGURE 2: DRILLING UNITS SHARE OF THE MARKET

Rigs are often divided into classes based on maximum water depth capabilities. Typically floaters are divided into the following categories [9]:

- Midwater ~ 900 - 1400 m
- Deep, less than ~ 2300 m
- Ultradeep, more than ~ 2300 m

3.1 SEMI-SUBMERSIBLE

The semi-submersible is characterized by the large columns which stabilize the vessel and provide flotation stability along with the submerged pontoons. The hull of a semi-submersible drilling unit is typically made up of horizontal pontoons connected with four to six columns. These structures have advantages as large deck space and good motion characteristics. In harsh weather conditions they can therefore stay longer in drilling mode than a typical drillship [7]. The majority of semi-submersible drilling units was previously towed or transported on vessels but newer generation semi-submersibles have incorporated DP systems and can transit to new location independently.

Semi-submersibles are classified into generations. There are currently six defined generations. The generations are based on building year, technology and capacities like variable deck load and water depth capacity [9]. In Table 1 the different generations are listed, and in Figure 3 examples of the different rig generations are shown.

TABLE 1: GENERATION OF SEMI-SUBMERSIBLES [8,9]

Generation semi-submersible	Typical building period	Typical water depth [m]	Typical displacement [mT]
1st Generation	1962 - 1969	Less than 250	Less than 10 000
2nd Generation	1970 - 1981	300 - 450	16 000 - 24 000
3rd Generation	1982 - 1986	800	25 000 - 30 000
4th Generation	1987 - 1998	1 700	30 000 - 53 000
5th Generation	1999 - 2004	2 000 - 3 050	35 000 - 53 000
6th Generation	2005 - 2014	3 050 - 3 600	40 000 - 60 000

The first generation rigs had significant variety in the structural design. The second generation standardized two pontoon systems, as this gave less resistance during tow. The size of the third generation rigs was larger than its predecessors and had an increased payload and redundancy standards. The fourth generation rigs were even larger and had increased the variable deck load further. This generation standardized the BOP controls and it became more common to incorporate DP systems. Fifth generation rigs were capable of drilling in deep water and ultradeep water, as the technology had improved over the years. The displacement was usually about the same as the previous generation but capabilities for drilling were increased, partially because of dynamic positioning. The sixth generation rigs have even larger drilling capabilities and can manage to drill more complex wells. All of them have DP systems and are therefore more mobile than the previous generations. Often they can reach 8 knots of speed self-propelled [9].

Two seventh generation semi-submersibles are currently under construction [8]. However, there is no clear distinction from the previous generation. The first, a Frigstad D90^{TM} design, is scheduled for delivery December 2015. It is a DP rig with extended drilling and water depth capacities. It has a fuel efficient design to give lower environmental footprints than its competitors, according to the power generation supplier Siemens Energy [10].

Nowadays most of the first and second generation semi-submersibles are either scrapped, upgraded to newer generations or converted to accommodation vessels and production facilities. Many third generation rigs have been upgraded to increase water depth capabilities, and they make up the majority of the midwater rigs. As few as 13 fourth generation rigs were built because of low oil prices in the late 1980`s and early 1990`s, in addition to the reduced demand for drilling in this time period [9].

FIGURE 3: DIFFERENT GENERATIONS OF SEMI-SUBMERSIBLES [8]

3.2 DRILLSHIP

Drillships are self-propelled and they can therefore transit to new locations rapidly. The large Variable deck load (VDL) and deck space on drillships can accommodate the drilling equipment needed on board. A disadvantage with drillships is the less favourable motion characteristics compared to semi-submersibles [7]. Drillships are therefore more dependent on weather conditions to operate than semi-submersibles, but have the advantage to operate without resupply for three months, which makes them suitable to work in remote locations [9].

In late 1950`s the first drillship was build and about a decade later the basic drillship layout was standardized. In the early history of drillships, mooring was usually used for station keeping. Not before early 1970`s were modern DP drillships made, and they were capable of drilling twice the water depth than semi-submersibles at that time. These drillships generally had a displacement of about 15 000 mT. In late 1990`s, a complete new generation of drillships were made. These fifth generation vessels had a displacement between 45 000 mT and 100 000 mT, making them significantly larger than its predecessors. In addition, almost all of them had DP systems. In the mid 2000`s, greater water depths could be reached and dual activity derricks became standard when the sixth generation drillship were introduced. The seventh generation drillships from 2011 do not have a clear distinction from the earlier generation [9]. Figure 4 shows some drillships from different periods.

FIGURE 4: DRILLSHIPS FROM DIFFERENT PERIODS [8]

3.3 VARIABLE DECK LOAD

Weights are usually considered as fixed or variable. Fixed weights are physically attached to the rig when installed. The substructure which is the structure providing the buoyance must support the functional weights, also called the payload. The Variable Deck Load (VDL) is the maximum variable payload a rig can during operation. The variable payload includes personnel, operating supplies, active mud and bulk mud, drill pipe, casings and riser, BOP and subsea equipment, working loads and drilling loads (hook loads, drilling riser tension, riser guideline loads), liquids, Xmas trees, spare parts, ROV and support equipment [7].

The VDL is a critical factor when moving in to deeper waters. This is mainly because the large rig size that is needed to ensure sufficiently high VDL. Typically, an additional increase of 1 000 mT deck payload requires additional 3 500-4 500 mT buoyancy [7]. This results in a substantial increase of hull size. For the purpose of understanding the relation between the VDL and the displacement, Figure 5 and 6 on next page has been prepared. Note that the drillships have much higher VDL capacity than the semi-submersibles within the same displacement range

The average values of different rig sizes collected from RigLogix [8] were used to make the graphs. The values marked with red in Appendix A have been removed as some values may vary or be wrong. For the semi-submersibles was the smallest and largest VDL value removed for each of the defined displacement ranges found in Appendix D. Only the strongly deviating numbers have been removed for drillships, mainly because few data was available.

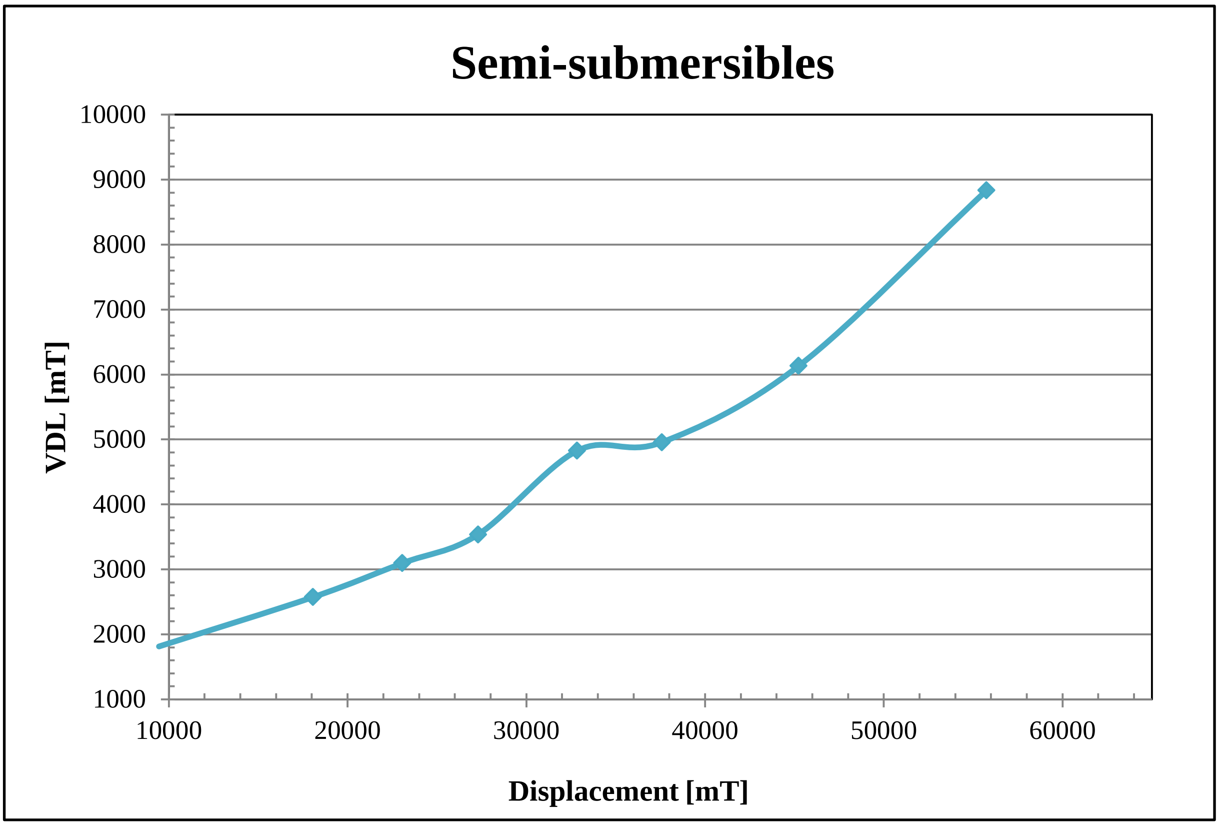

FIGURE 5: AVERAGE VDL CAPACITY FOR DIFFERENT DISPLACEMENT RANGES OF SEMI-SUBMERSIBLES

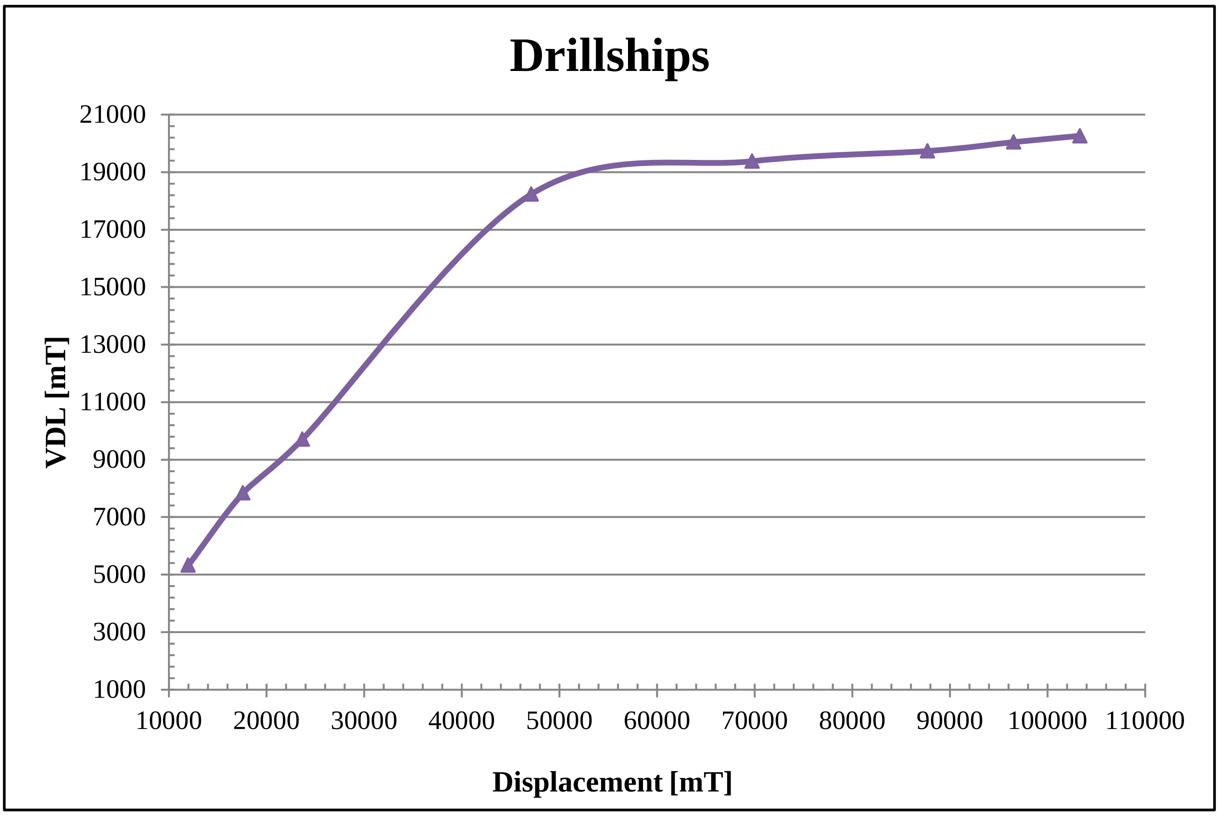

FIGURE 6: AVERAGE VDL CAPACITY FOR DIFFERENT DISPLACEMENT RANGES OF DRILLSHIPS

The graph in Figure 5 has a tendency line which is exponentially shaped. This is as expected as the needed VDL increases with the water depth and pressure exponentially. For instance the riser weight will increase linearly with the length, but as the pressures increases also the wall thickness must increase. However, there is a discontinuity in the curve were the average displacements are between approximately 28 000-38 000 mT. A reason for this can be wrong data, but there are no values that deviate from the normal. Therefor a better explanation could be the rigs mooring systems. DP allows for drilling in deep and ultradeep water. The rigs prior to the discontinuity are typically moored and have midwater depth capabilities. The majority of the rigs post the discontinuity have incorporated DP systems. They also have higher displacements to account for the high VDL needed to drill in deeper waters. Rigs which have a displacement between 30 000-40 000 mT normally has both DP and mooring systems. This is consistent with the typical fourth generation rig, where it became common to incorporate DP systems.

The first part of the curve in Figure 6 is approximately linear. As DP is standard for drillships there is no discontinuity in the curve as for semi-submersibles. However, the curve goes towards a VDL of approximately 20 000 mT after the first linear part of the curve. This may indicate that a VDL of about 20 000 mT is sufficient for current drilling operations. Note that semi-submersibles with ultradeep water depth capabilities have an average VDL of about 8800 mT. This implies that larger drillships probably have more spare capacities than semi-submersibles.

4. DIESEL CONSUMPTION ON DRILLING RIGS

The diesel consumption on a drilling rig is mainly dependent on mode of operation and installed vessel power. DP rigs have much higher emissions than rigs with thrust assist. The DP systems are oversized to have redundancy in extreme weather situations. The installed vessel power, main energy users and the fuel consumption will in this chapter be discussed.

4.1 INSTALLED VESSEL POWER

Diesel engines are used to provide power on MODUs. A rig has several engines which combined typically gives an installed vessel power in the range of 8 000-60 000 horsepower (h.p.), see Figure 7. The variation of total h.p. is large for the rigs considered. However, there are some typical differences in h.p. capacities of the displacement ranges for the vessels considered. The figure is based on average values for the displacement ranges defined in Table B-3 in Appendix B. For semi-submersibles one can see that the installed vessel power increases for the rigs with a displacement over 30 000 mT and for the rigs with a displacement over 50 000 mT. There are few data available for drillships, however from Appendix B one can see a tendency. The drillships over 40 000 mT have significantly higher installed power than those with lower displacement. The installed vessel power does not differ much for a drillship with a displacement of about 60 000 mT and a drillships with a displacement of about 100 000 mT, see Figure 7.

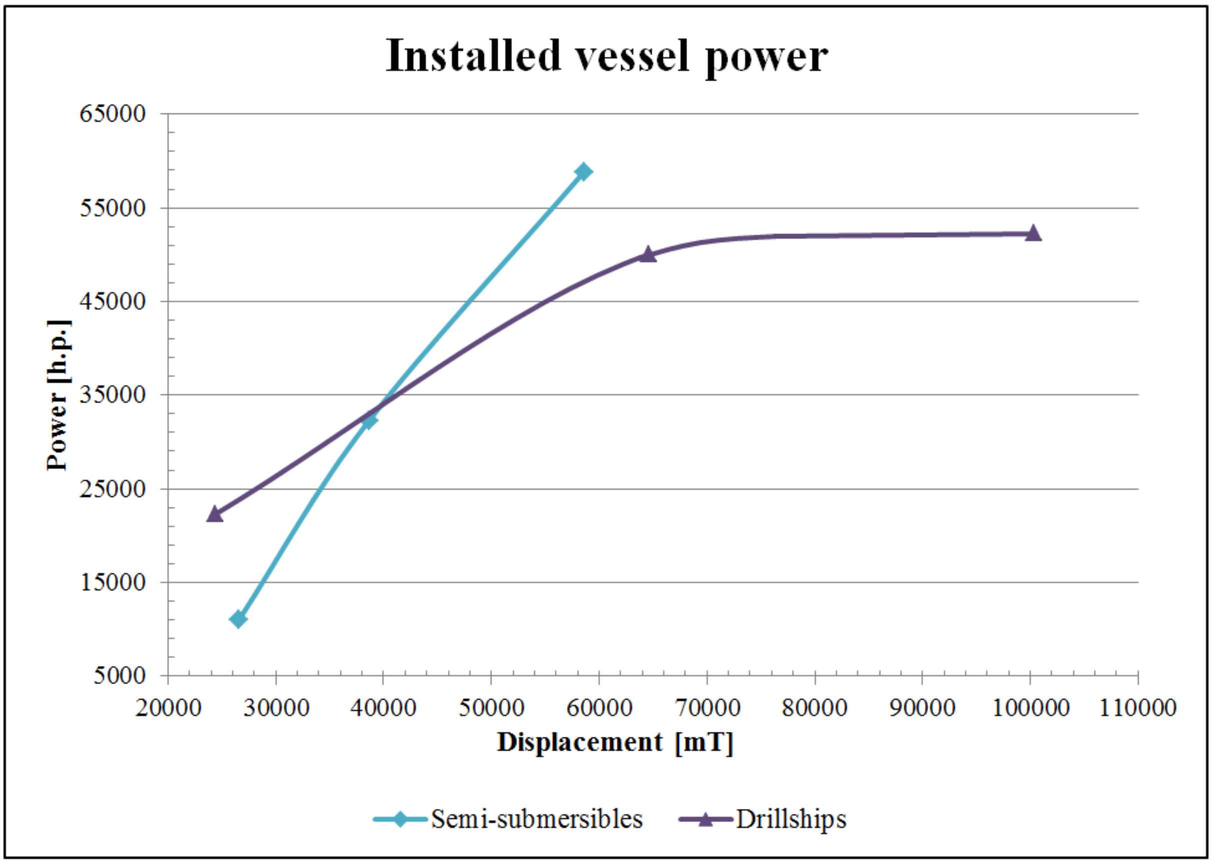

FIGURE 7: AVERAGE INSTALLED VESSEL POWER FOR SEMI-SUBMERSIBLES AND DRILLSHIPS. DATA FROM [8][11][12][13]

From Figure 7 one can see that the installed vessel power is lower for semi-submersibles than drillships with a displacement less than approximately 40 000 mT. This is in consistence with the typical displacement of the fourth generation semi-submersibles, which started to incorporate DP systems. However, many of smaller semi-submersibles used today have DP systems, since the majority of them have been modified. Therefor a better explanation could be that smaller drillships are self-propelled and needs higher installed power, compared to smaller semi-submersibles which are often towed to location.

The majority of drillships have been using DP systems since the early 1970s and therefore the installed vessel power is dependent on rig size and DP system. One can see that the installed vessel power increases linearly up to a displacement of about 65 000 mT. After the change of gradient all drillships are typically equipped with redundant DP systems and the difference in installed power is low, as most of the installed vessel power is implemented for station keeping, see section 4.3.

Newer generations semi-submersibles are often self-propelled and have advanced DP systems. The graph for semi-submersibles has higher gradient than for the drillships. An explanation for this is that semi-submersibles needs higher thruster power because of the unfavorable shape in wind and waves, as opposed to drillships that normally head into revealing weather. For semi-submersibles with even higher displacements it is likely that the graph will change to a lower gradient. This is because more advanced and redundant DP systems have been implemented over the years. This may be sufficient for larger semi-submersibles as well.

4.2 MAIN ENERGY USERS

The main energy consumption goes into positioning, drilling and utilities when a rig is drilling. For positioning is DP systems used, often in combination with mooring. During the drilling operation the mud pumps and the top drive system must be provided with power. The utilities comprise power for electricity, hot water, cooking etc. The Aker H-6e semi-submersible design will be further used as an example to indicate how much of the total power the different users need. The rigs design displacement is 65 300 mT when operating and the total installed power is 56 858 h.p. The available thruster power is 85% of the total installed power [14]. Table 2 shows the normal average power for the Aker H-6e design, estimated by Aker Kværner.

From Appendix B one can see that the ratio of thruster power and installed vessel power is increasing with water depth. The total thruster power can be in the range 85% of the total installed vessel power. The thrusters on new rigs are oversized to have redundancy in extreme weather situations. Form Table 2 one can see that the rigs normal average thrust power is 41% of the total thrust power when drilling without anchors for station keeping. If anchors are implemented the normal average thrust power will be 10% of the total thrust power. However, it must be stated that this rig is designed for extreme conditions and therefore the normal average may be high compared to a rig in mild environments. During transit 75% of the total thruster power will be used. The total power needed for propulsion and utilities will then be 73% of the total installed vessel power.

TABLE 2: ESTIMATED FUEL CONSUMPTION FOR THE AKER H-6E SEMI-SUBMERSIBLE DESIGN [14]

Energy users	Normal average (no anchoring)	Normal average (anchor)	Transit	Comment
Drilling [h.p.]	11399	11399	0	
Utility [h.p.]	8046	8046	5364	
Thrust [h.p.]	19793			41% thrust without anchors
		4828		10% thrust with anchors
			36207	75% thrust average
Power consumed [h.p]	**39238**			69% of total power
		24273		43% of total power
			41571	73% of total power
Fuel consumption [g/h.p. hr]	136,46	136,46	136,46	Average 50-100% load
Fuel consumption [mT/day]	**128,5**	**79,5**	**136,2**	

When the rig is positioned without anchors the total power needed on a normal average basis is 69% of the total installed vessel power. From the total power needed will 29% be used for drilling, 20,5% be used for utilities and 50,5% be used for positioning. The fuel consumption for drilling and utilities are the same when the rig is positioned by anchors. However, less diesel consumption is required for station keeping and therefore the total power needed will be 43% of the total installed vessel power on a normal average basis. From the total power needed will now 47% be used for drilling, 33% be used for utilities and 20% be used for positioning.

4.3 TOTAL FUEL CONSUMPTION

In Table 3 actual diesel consumption from five of North Atlantic Drilling rigs are given. The maximum diesel consumption is the total installed vessel power multiplied with the fuel consumption (136,46 g/h.p. hr). It is assumed that the same fuel consumption in Table 2 applies to the engines on the rigs listed in Table 3.

From Table 3 one can see that the fuel consumption is not as large compared to the normal average of the Aker H-6e design. The Aker H-6e will use approximately 43% of installed vessel power when the rig only uses thrust assist. However, a rig will not be operating 100% of the time during a year. There are situations like not intended shutdowns, waiting on weather, relocations and other factors that will affect the total fuel consumption. Therefore it will further be assumed that the average fuel consumption over a year is about 30% of the maximum fuel consumption for vessels with thrust assist. The semi-submersibles with a displacement equals or above over 50 000 mT are assumed to use 45% of the total installed vessel power. This is because many of them only use DP for positioning and are operating in ultradeep waters. This will also apply for all drillships as they usually are positioned with advanced DP systems. From Table B-2 in Appendix B one can see that West Navigator has low thruster power compared to the other rigs. This can explain the low ratio of fuel consumption.

TABLE 3: FUEL CONSUMPTION IN 2013 [11][15]

Name of rig	Type of rig	Installed power [h.p.]	Thruster power [%]	Thrust assist	Fuel consumption Maximum [mT/yr]	Fuel consumption Actual [mT/yr]	Actual/ possible [%]
West Alpha	Semisub	16200	-	Yes	19365	6319	33
West Venture	Semisub	43000	81	Yes	51402	12385	24
West Hercules	Semisub	50400	73	-	60248	11801	20
West Phoenix	Semisub	50500	71	Yes	60367	13994	23
West Navigator	Drillship	43000	57	No	51402	15596	30

In Figure 8 the calculated fuel consumption for semi-submersibles and drillships are shown. Even though the installed vessel power are higher for semi-submersibles with a displacement over approximately 40 000 mT, the fuel consumption for semi-submersibles will not be higher until a displacement of 50 000 mT is reached, due to the assumptions made.

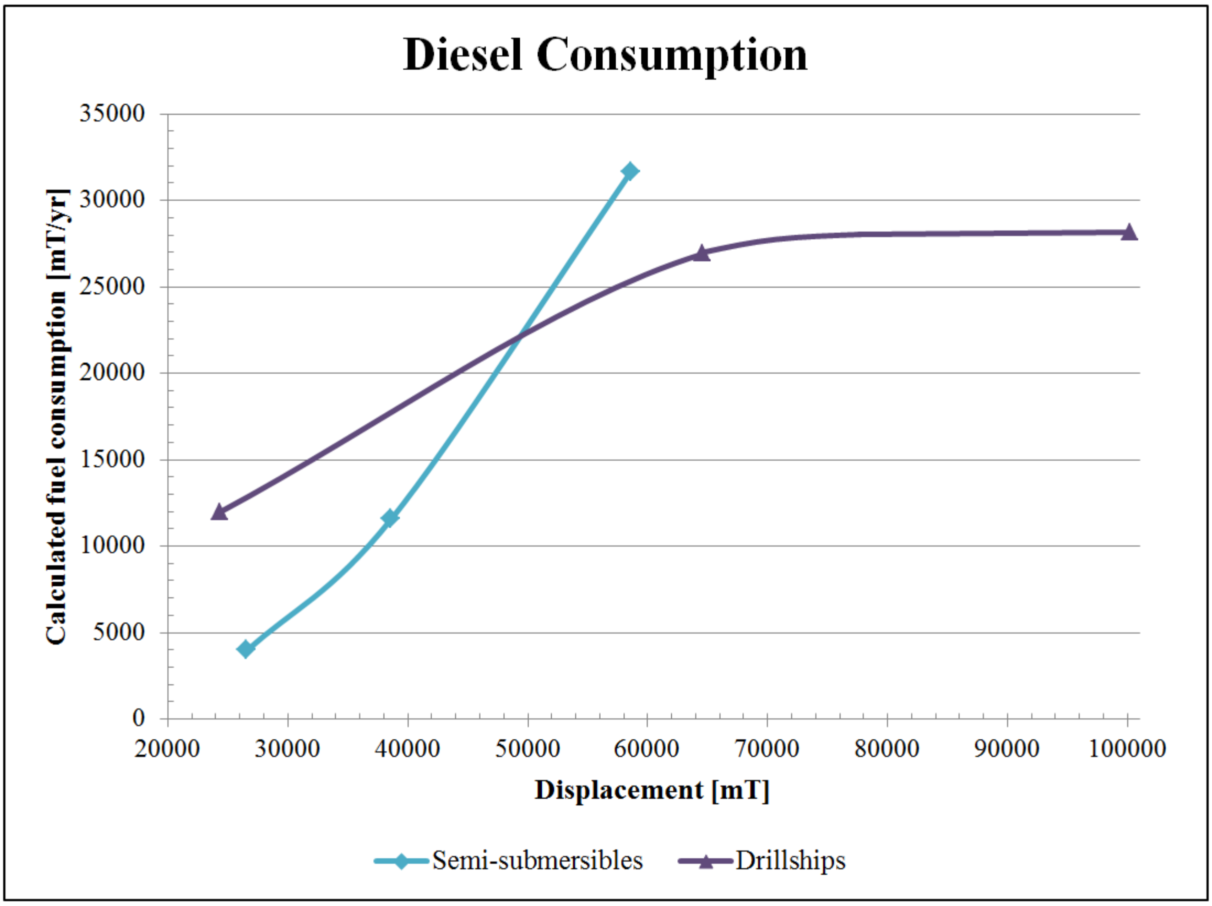

FIGURE 8: CALCULATED FUEL CONSUMPTION FOR SEMI-SUBMERSIBLES AND DRILLSHIPS

5. ALTERNATIVE FUEL – NATURAL GAS

Worldwide there are about 600 mobile offshore drilling rigs which all run on diesel fuel. As described in chapter 4, offshore drilling rigs consume large amounts of diesel fuel per day. The release of greenhouse gases is significant. In addition, large amounts of toxic substances are released during diesel combustion. LNG is a cleaner alternative fuel to diesel and will further be discussed.

As technology improves, more natural gas applications can be adapted. Today, natural gas is mainly used for electrical generation and heating. Worldwide there are several million land vehicles powered by natural gas and the industry is growing. In the shipping industry there is a demand to improve existing technology to be more environmentally friendly, as authorities set stricter regulations for emissions. And in the oil and gas industry field gas is widely used for power supply. This chapter describes natural gas applications and the availability of LNG. Whether MODUs could be appropriate candidates to be powered by natural gas will thereafter be discussed.

5.1 NATURAL GAS - LNG AND CNG

The cleanest burning fossil fuel is natural gas, see Figure 9. It is available as a transportation fuel today. Natural gas consists of around 90% methane, while the remaining percentages consist of propane, ethane and small fractions of other gases. Byproducts of methane, which burns almost completely, are CO_2 and water. Since natural gas is lighter than air it has the advantage of rising and spreading quickly in the event of leakage or spillage. Because of this quick rise and disperse, the surrounding will not be threatened by unwanted events [16]. However, methane is a major greenhouse gas, and if one kg of methane is released the consequences in terms of climate change can be compared to a release of 25 kilogram of CO_2 [17]. Natural gas has a range in quality and may go through expensive treatment before it can be used as a fuel. The CO_2 emissions are 15-25% lower compared to diesel. [18]

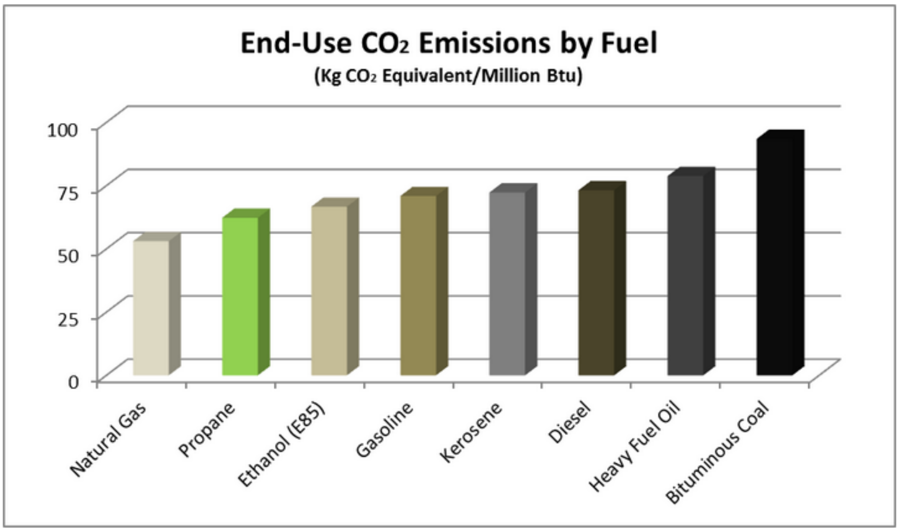

FIGURE 9: CO_2 EMISSIONS FOR DIFFERENT FUELS [17]

Liquefied Natural Gas (LNG) is natural gas which is condensed at low temperatures and stored as a cryogenic liquid. Typical temperatures to condense the gas are between -120°C and -170°C dependent on its composition [19]. The volume of LNG occupies about 1/600 (0,167%) compared to natural gas in its gaseous phase [20]. Although LNG provides substantial environmental benefits there is high cost associated with cryogenic storage. In addition there are high requirements for LNG stations and facilities [19].

Compressed Natural Gas (CNG) is stored in high-pressure tanks, where the pressure is ranging from 200 to 250 bar. To detect a leak, a sulphur-based odorant is added to the compressed gas [19]. Compared to natural gas at standard atmospheric pressure, CNG is compressed to less than 1% of the volume [21]. CNG requires frequent refilling compared to diesel and LNG, and several trips for bunkering are needed.

When natural gas is at atmospheric pressure, it cannot be compared to liquid fuels as it has less energy by volume. Therefore, natural gas must be converted to CNG or LNG to get sufficient vessel range. In Table 4 a comparison of energy densities relative to diesel are listed [20].

TABLE 4: COMPARISON OF ENERGY DENSITIES [20]

Fuel type	Energy [MJ/litre]	Equivalent energy density [%]
Diesel	36	100
LNG	21	58,3
CNG	7,5	20,8

CNG will not be feasible in MODUs as the storage capacity will be insufficient, and field gas will not be present during drilling from mobile units. Therefore LNG will be the natural choice to use as an alternative fuel on floating drilling rigs. In addition LNG has high quality. LNG is not stored under pressure and will therefore not be flammable or explosive in its liquid state [22].

5.2 NATURAL GAS TECHNOLOGY - OIL AND GAS INDUSTRY

There are two types of heavy duty engines that can apply natural gas. The dedicated natural gas engines only use natural gas as fuel and burns the fuel by spark ignition, as opposed to diesel engines which ignite by compression. Two independent fuel systems are incorporated in dual fuel engines. Dual fuel engines can run on both fuels simultaneously or on one fuel alone. Conversion of engines to natural gas can be done by retrofitting existing diesel engines to spark ignition [18]. Both dual fuel and dedicated natural gas engines can utilize field gas, CNG and LNG. A huge advantage with dual fuel engines is that they can run on diesel alone in case of low natural gas supply. It also gives the company the flexibility to select what is best for the operation and fuel costs on a day to day basis [23].

When engines are fuelled with natural gas, the percentages of different gases will directly affect the engines performance in terms of power, emissions, efficiency and engine lifetime. High methane content will result in high quality, while butane usually affects the performance in a negative way. By utilizing a high quality gas or LNG with the correct percentages of substances, some engines will actually provide horsepower which exceeds the engines full rated horsepower [24].

One clear benefit when implementing natural gas engines are the low emissions they produce when compared to diesel engines. A test performed over four years on a Encana landrig in the Jonah field onshore in the United States supports this statement. Not only did their natural gas engines run quieter than their diesel engines, but also reduced VOC emissions by more than 4000 tons and NO_x emissions by 600 tons per year [22]. Another benefit is the low LNG prices. Assuming the price for LNG remain stable at a low rate, return of investment will increase thus making it more profitable.

To operate with natural gas on existing diesel fuelled rigs, one can retrofit some engine types with kits. Some companies specialize in natural gas technology. Caterpillar is a company which is offering dynamic gas blending kits to be used for drilling and well stimulation in dual fuel operations onshore. The kits are relatively easy to install [23]. The diesel replacement is up to 70%. The system will adjust automatically with different gas qualities and can achieve a maximum substitution over the full operation range under various loads and speeds [25]. Another company which design and manufactures alternative fuel systems is Energy Conversions Incorporated. They also have dual fuel solutions for the offshore industry, and in 2000 the company received The American Bureau of Shipping type approval for its EMD dual fuel conversion system. The system can apply for offshore platforms and commercial vessels [26]. Kits are designed to retrofit an engine type or an engine series. If the engine is prepared for retrofit and there are retrofit kits made for that engine type, one can convert the engine to natural gas operation. As kits already are implemented for several onshore drilling rigs and some bottom supported rigs offshore, the MODUs will also be target candidates.

Field gas is standard to use for power generation on offshore production units. Both dedicated and natural gas engines are used for this purpose. To power with natural gas in offshore installations is not new technology. However, using it in offshore applications which do not have access to field gas is a new approach. In Norway the leading company for power generation for mobile offshore applications is Wärtsilä. They have dual fuel solutions and retrofit kits for ship engines. Since Norway is the leading country to use LNG powered ships, there are several bunkering stations along the coast. Therefore Norway could be the nation that leads the way by example. The technology is not ground breaking and could be implemented for new builds, and on existing engines which are prepared for retrofits. The main challenge whit LNG powered MODUs will not be the power generation, but loading and supply of LNG.

5.3 MARINE APPLICATIONS

Ship owners must reconsider to use low sulphur fuels or integrate exhaust gas scrubbers, as new sulphur requirements are to be enforced from January 2015, in the Sulphur Emission Controlled Areas (SECAs), shown in Figure 10. The sulphur content of fuel for the shipping industry has to decrease from 1% to 0,1% in the SECAs. Therefore there is an increasing interest for LNG fuelled ships as they meet the new sulphur requirements [27].

FIGURE 10: EXISTING AND FUTURE POSSIBLE SULPHUR EMISSION CONTROLLED AREAS [28]

In June 2013 an ISO draft standard was published to provide overall requirements to design and operation related to LNG bunkering. According to DNV the CO_2 emissions are reduced with 20-25% and the SO_x emissions with 90-95% when using LNG as ship fuel. The NO_x emissions are also significantly reduced [29]. There were 42 LNG-powered ships in operation and 39 confirmed new builds worldwide in the end of October 2013 [28]. Norway is a leader in LNG technology for the shipping industry and was the first country to fuel a ship with LNG in 2000. Fjord 1, Eidesvik Offshore and Nor Lines AS are leading operators of LNG powered vessels in Norway.

Fjord 1 is the largest ferry company in Norway. In 2000 they started operating MF Glutra, the world's first LNG powered ferry. MF Glutra is almost 100 m long and has two cryogenic tanks that each can store 27,2 m^3 LNG, see Figure 11. Before the LNG can supply the four lean burn natural gas engines the fuel must be vaporized. Every five to six days the tanks must be refuelled. The LNG is delivered by trucks [30].

FIGURE 11: WORLD'S FIRST AND LARGEST LNG POWERED FERRIES, GLUTRA AND MF BOKNAFJORD [28]

Since 2011 the world’s largest LNG ferry, MF Boknafjord, has operated in Rogaland County in Norway by Fjord 1, see Figure 11. The 129.9 m long ferry needs a high speed to provide the required shuttle frequency. Therefore, MF Boknafjord has high power, the latest propulsion technology and the most advanced gas engines [31]. Fjord 1 also operates MF Tresfjord in Sør-Trøndelag. This is the only ferry which has been converted from diesel-electric operation to gas-electric operation. Fjord 1 has a total of 12 gas-powered ferries in operation along the coast of Norway.

Eidesvik Offshore operates ships within supply, seismic and subsea segments, and is the world’s largest operator of LNG fuelled platform supply vessels. They have a total of 5 LNG powered ships. Together with Kleven Maritime they designed and built the world’s first LNG powered supply vessel, the Viking Energy, which has operated in the North Sea since 2003, see Figure 12. Four Wärtsilä 32DF dual fuel engines were fitted in the vessel. The engines switch between fuels automatically, without losing power. Even though dual fuel engines can run on diesel fuel alone, the normal operating mode is with gas [32]. Another interesting ship Eidesvik operates is the Viking Lady supply vessel. The vessel is one of the world’s most environmentally friendly ships, as it uses a fuel cell together with LNG dual fuel engines to produce power [33].

FIGURE 12: VIKING ENERGY FROM EIDESVIK AND “ENVIRONSHIP CONCEPT” FROM NOR LINES [34][35]

The logistics and shipping company, Nor Lines AS, is a major operator for cargo transportation in northern Europe. Two LNG fuelled cargo vessels are contracted by Nor Lines, and currently one of the ordered ships is under testing in eastern China's Jiangsu province. The design used for both ships is Rolls Royce Marine`s “Environship Concept” that won the “Next Generation Ship Award” at NorShipping 2011, see Figure 12. The ship design together with natural gas engines and Rolls Royce`s Promas propulsion system will increase the fuel efficiency and improve the overall vessel performance. The ships engines are Rolls Royce Bergen B-Series lean burn gas engines that do not need pilot injection of diesel, as the engine has spark ignition. The vessel has a range of about 3,400 nautical miles with its LNG fuel tank capacity of 400 m^3 [35].

5.4 AVAILABILITY OF LNG

To have availability of fuel is an important factor for ship owners if they are considering using low sulphur fuel like LNG. More LNG terminals or storage facilities must be built to meet increasing demand of LNG as marine fuel. More bunkering stations are also needed, so that LNG is an available fuel for ships along their routes. Bunkering LNG can be done in three ways; ship-to-ship, truck-to-ship and bunkering directly from the terminal via pipeline. The different methods depend on fuel tank capacity and location.

In Norway there are 6 production facilities for LNG. Tjeldbergodden was the first facility to be established in 1998. Later Snurrevarden, Kollsnes 1, Kollsnes 2, Melkøya and Risavika have been established, the latest one in 2011. Melkøya produces 4.3 million mT of LNG every year, and is the only plant in Norway that is not a small-scale-plant. Norway has the advantage of having developed a system for LNG bunkering. The bunkering process is normally done with trucks using flexible hoses [27]. Typically is also LNG bunkered via a fixed installation on jetty or pier from a relatively small LNG tank. There are currently five operating LNG bunkering facilities in Norway with permanent LNG storage tanks: Snurrevarden, Halhjem, Coast Centre Base Ågotnes, Risavika and Florø. Several bunkering terminals between or distance from the mention facilities can receive LNG by trucks. The truck transports the small scale LNG and supplies the fuel to vessels [36].

Figure 13 shows established LNG bunkering facilities, plants and terminals in northern Europe before 2011, and new infrastructures that are likely to have been established before 2020.

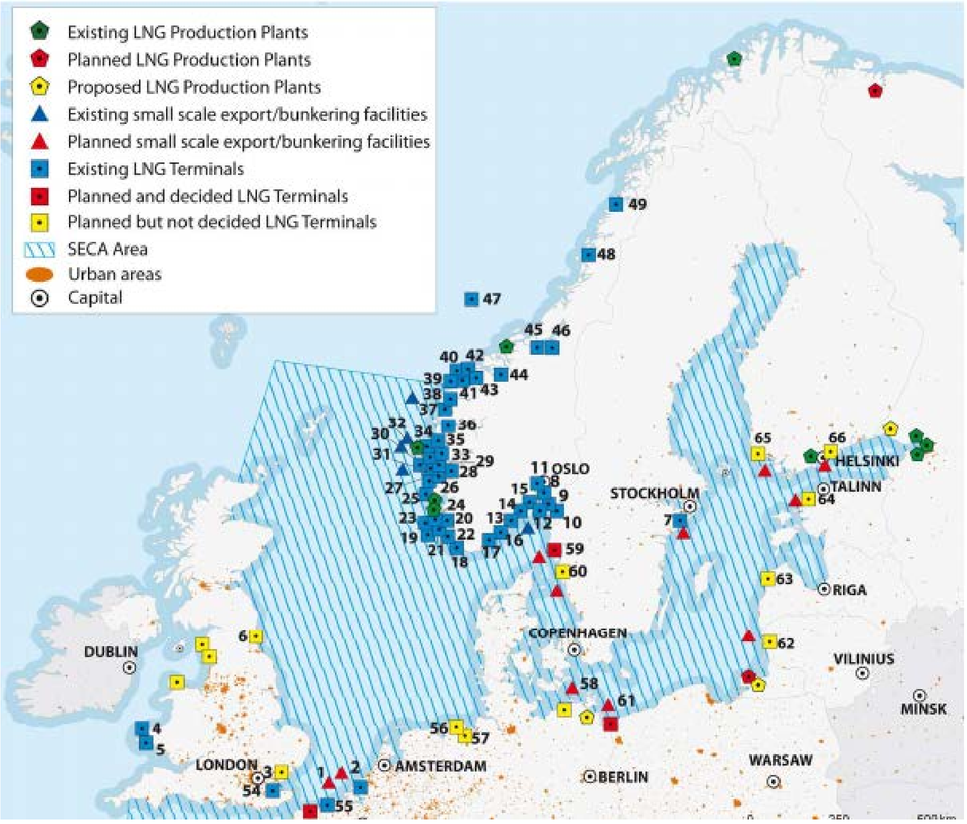

FIGURE 13: EXISTING (2011) AND PLANED LNG FACILITIES IN NORTHERN EUROPE [27]

A major LNG distributor in Norway is Gasnor. They deliver small scale LNG to ships with tank trucks and tankers. Another major facility operator is Skangass, which supplies LNG along the coast of Norway. They have a distribution network with terminals, vessels and tank trucks. In the north of Norway do Barents Naturgass AS distribute small scale LNG from the Melkøya export terminal. Currently are they setting up several new intermediate LNG storage tanks [36]. Skangass recently got approval to build a LNG bunkering station in Risavika, outside Stavanger. With the new approval from Norwegian Directorate for Civil Protection, have ferries in Norway for the first time opportunity to bunker LNG without clearing the ferry for passengers. The LNG demand grows fast, and 139 bunkering stations for LNG are planned to be developed in Europe before 2025 [37].

Globally there are few LNG bunkering ports compared to diesel, but the bunkering ports are located close to the main shipping trade routes. Large capacity bunkering ports are not needed to fuel supply vessels and MODUs. Small-scale LNG bunkering facilities and terminals must be implemented worldwide before MODUs can implement LNG as main source of fuel. LNG must be available in different locations, not only around current drilling location. However, as Norway is the leading country for small scale LNG distribution, long term contracts on the Norwegian continental shelf could facilitate introduction of LNG. Norway has the potential to implement dedicated LNG powered rigs to only operate on the Norwegian continental shelf.

The global LNG bunker demand for ships in 2020 is estimated to be as shown in Figure 14 below. It is estimated that there will be around 1 000 LNG powered ships in 2020, which probably will demand between 0,2-0,3% of the of the total production from 2010 [38]. This results in several new LNG bunker stations, and thus it will be easier to implement LNG powered MODUs in the future.

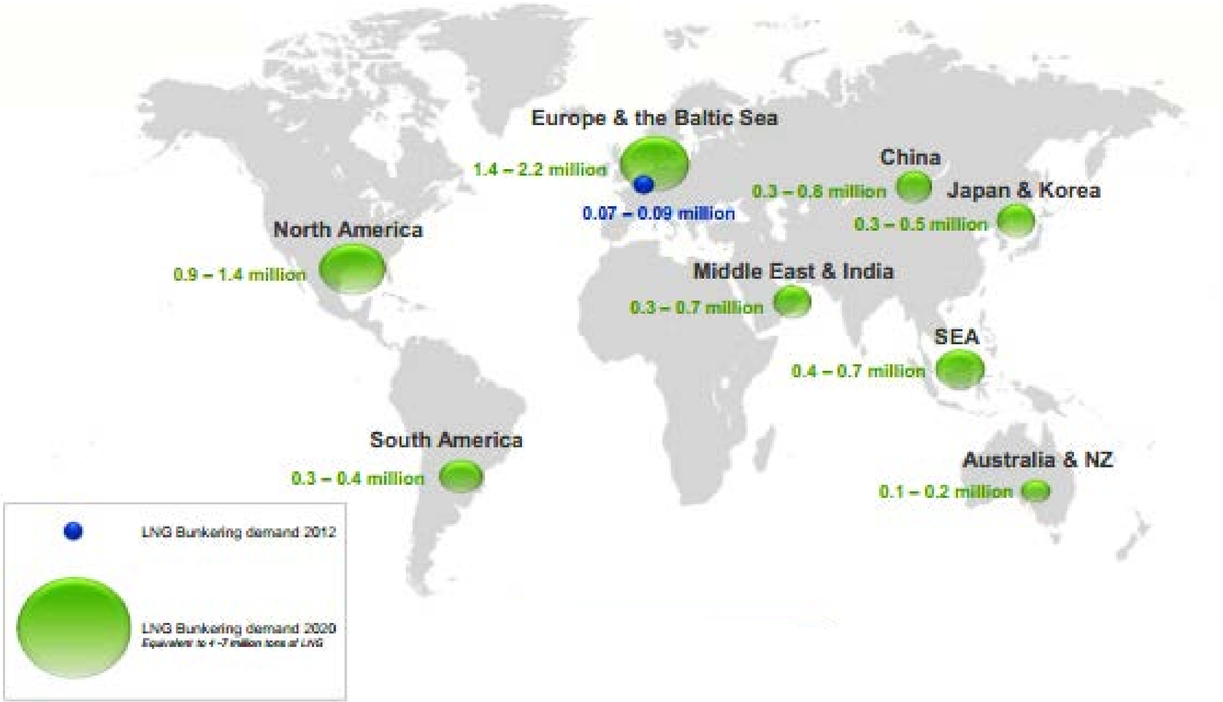

FIGURE 14: LNG BUNKERING DEMAND IN 2012 AND 2020 [38]

5.5 DISCUSSION - LNG FOR MODUS

There are some challenges to overcome before natural gas engines will be widely used for MODUs. First of all, the technology is new for this approach and operators may be sceptical to invest in technology that is unfamiliar. There is a lack of knowledge about how these engines will perform over many years. In addition, previously natural gas engines are associated with power loss compared to diesel and gasoline engines. Some concerns is that safety protocols and bunkering processes have not been established for floating drilling rigs with LNG, but it is convenient that it already exists for ships. Another concern is that the fuel must be globally available before it could be a viable fuel option for MODUs.

The energy density of LNG is about 58% compared to diesel. However the LNG density is about 50% lower than the density for diesel. So, the difference in fuel weight would not differ more than approximately 5-10%. The VDL must be considered when implementing LNG, as heavy equipment is required to store and cool the fuel. This may result in a reduced VDL, which again can influence the rigs overall capability.

Implementing natural gas engines in new build vessels may be the best option, as the warranty in retrofits may vary because it is installed aftermarket. But the greatest potential would be to retrofit engines, as several hundred existing MODUs are in operation worldwide. The natural gas technology exists and with growing demand the solutions may become even better.

Availability and costs

The main challenge with mobile drilling rigs is that they do not have field gas or LNG supply nearby. Norway is the leading country for small scale LNG supply, as several LNG bunkering facilities are located around the coast. Worldwide there are not many LNG bunkering stations compared to conventional fuel stations, but new infrastructures are planned for the shipping industry. During the next decade LNG will be considerably more available in the global market. There is a need for logistic collaboration to make LNG a viable option and to make it an available fuel. Supply vessels to deliver LNG do not exist, but the technology exists as some supply vessels already use LNG for self-consumption.

Several countries, including Norway, have high emission taxes that can be reduced by using a cleaner fuel. A huge advantage with LNG is not only the reduction of CO_2 emissions, but also the low release of dangerous substances like SO_x and NO_x. By using a fuel like natural gas future emission requirements will most likely be met. In addition, there are large savings compared to conventional fuels, as LNG is less expensive. Switching form diesel to LNG will with today’s prices lower the fuel costs with approximately 40-50% [39]. When LNG becomes more available and several new distributors enter the market, probably the price will go further down. However, there is a risk of rising prices when the demand of LNG increases. Therefore, dual fuel operation could be the best solution, as the engines can run on diesel alone in case of high LNG prices or low LNG supply.

Safety

The temperature in LNG tanks is very low. The tanks have very efficient insulation and are constructed as double-wall. Despite this, the temperature and pressure will rise if the vapour is not drawn off. But if LNG is kept at constant pressure the temperature will also stay nearly constant [40]. There must be backup systems that can handle LNG in a safe manner and intensive monitoring and control must be implemented. Explosion of an LNG tank is a highly unlikely event that only could occur if there is system failure [41].

A disadvantage with LNG compared to diesel is that the personnel could only detect a leak if it is large enough to create frost formation or a visible cloud of condensation, as the gas is odourless. Natural gas is lighter than air, and will therefore disperse quickly in the case of a leak. However, the gas can be trapped under or inside the rig structure and cause a major threat of ignition and explosion. Several methane gas detectors can be a proper solution for this problem.

Bunkering

According to Kjell Sandaker in Eidesvik AS they do not see any operational problems while bunkering LNG on their ships at the same time as the engines consume gas from that same tank. However, in the current ship regulations it is required to shutoff the LNG facility during the bunkering process, which dictates that a rig must run on diesel during LNG bunkering. Once again, the dual fuel operation appears to be the best option. Bunkering LNG to floating MODUs can represent problems as LNG usually is bunkered through a spring conduit, which is an armoured flexible hose, according to Kjell Sandaker. When LNG enters the hose will it freeze and become brittle and therefore the risk of breakage is significantly high because of the relative motion between the ship and the rig [42].

Since bunkering of LNG through a hose will most likely presents problems other solutions must be considered. In Figure 15 existing bunkering methods and an alternative method are shown.

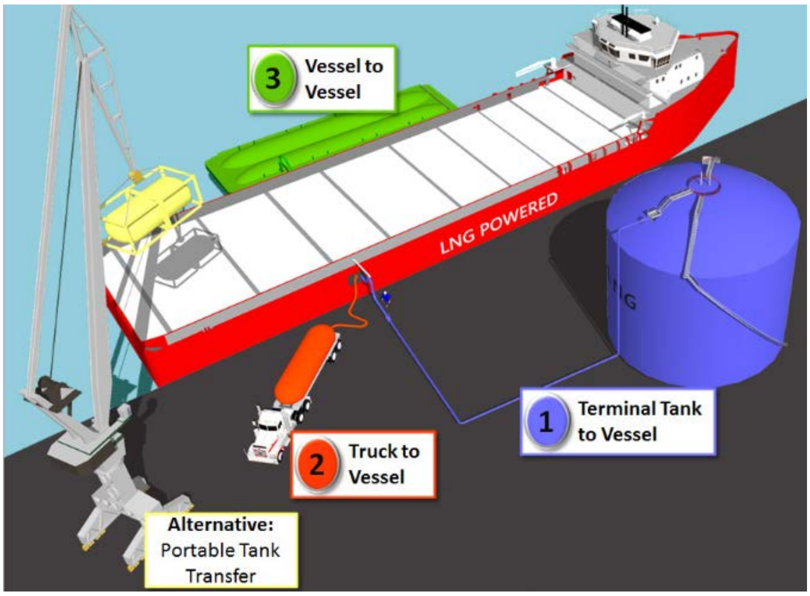

FIGURE 15: EXISTING BUNKERING METHODS AND AN ALTERNATIVE PORTABLE TANK METHOD [43]

An alternative method some ship operators are considering is the “Portable Tank Transfer”, i.e. portable LNG tanks to be used as vessel fuel tanks. In this concept, the ships vessel tanks would be replaced when empty, by preloaded tanks, see Figure 15. The tanks are modular and should be lifted on board to the LNG powered ship from dock. The tanks are easy to move by trucks, in addition considered as cargo and will thus have simpler requirements [43]. Another advantage is that the risk of spills and leaks are reduced as the bunkering process is already “finished”. This method could also be a solution when bunkering LNG to floating MODUs. However, by employing this method offshore the risk of long waiting on weather time will be high in the unfavourable seasons.

5.6 CONCLUSION AND RECOMMENDATION

The main reason for implementing LNG on MODUs is due to the reduced air emissions, as natural gas is the cleanest burning fossil fuel. Typically a new generation drilling rig will release between 183 mT and 430 mT of CO_2 per day. LNG fuel has the potential to reduce the CO_2 emissions with 20-25%. This will correspond to a reduction between 36 mT and 108 mT of fuel per day, for newer generation drilling rigs. Both SO_x and NO_x emissions will be significantly reduced with a natural gas operation.

Natural gas technology is not new, but implementing this technology on floating MODUs is a new approach. Existing diesel engines can be retrofitted to natural gas operation, as long as the engines are prepared for retrofit. However, a disadvantage is that the equipment needed to store and cool the LNG may lower the available VDL and influence the rigs overall capability. Therefore new builds may be the best solution but retrofits of existing rigs have the greatest potential. There are two types of engines which in theory could be implemented on MODUs; the dedicated natural gas engines which only consume natural gas, or the dual fuel engine which can switch between natural gas and diesel operation. The dual fuel engine is probably the best solution, as it has the availability to operate on diesel in case of low LNG supply or increasing LNG prices.

Using LNG as ship fuel has been widely accepted during the last years. Several new LNG fuelled ships are currently under construction as new sulphur regulations are to be implemented from 2015. LNG bunkering stations will during the next decade be more available in the global market. The demand for LNG is estimated to be 0,2-0,3% of the total production from 2010, based on the assumption that there will be 1000 LNG powered ships in 2020. As no existing supply vessels are delivering LNG, is it important with logistic collaboration between companies.

Bunkering of LNG through a hose will present problems due to large movements between the rig and the ship. When LNG enters the hose will it freeze and become brittle and the risk of breakage will be significantly high. The “Portable Tank Transfer”, where a preloaded modular tank is replaced with the empty tank on deck, may be an alternative method. However, this method can require long waiting on weather time due to the harsh offshore weather.

The LNG technology improves rapidly and the safety protocols for different industries are starting to be well established. When LNG becomes globally available it is likely that dual fuel operations with LNG will be a viable solution for power generation on floating MODUs. A safe bunkering method for floating MODUs must be established to make it become a reality.

6. NEW DRILLING METHODS

As explained in chapter 4, the air emissions largely depend on rig size. In this chapter two new drilling methods with the potential to reduce rig size will be described. This will indirectly result in reduced air emissions as the power requirements are lower for smaller rigs. Oil and gas companies are constantly improving their technology to extract resources from frontier areas. When the water depth increases, also the cost will increase. Drilling in deep water represents problems because of increasing pressures and heavier equipment. In this chapter riserless drilling methods and the slim well drilling method will be described.

In section 6.3 the riserless and the slim well drilling method will be evaluated compared to the conventional drilling method. Mud volumes, riser tension capacities and weights will be compared to the conventional drilling method. The potential to combine both methods will also be evaluated. This will be used to estimate the potential reductions of air emissions.

6.1 RISERLESS DRILLING

Riserless drilling systems are based on schemes from late 1960s. The purpose back then was to make drill pipe re-entry easier and to reduce wear on BOP. However, back then the technology was not available to make it a reality, and problems could be solved by increasing size of riser as the water depths were shallow [44]. Riserless drilling is an attractive alternative since drilling companies are exploring deeper waters. This is mainly because of the reduced VDL that is needed for riserless drilling. Because deep water drilling requires large and heavy risers, the vessel needs to have large deck load capacities. Large volumes of heavy mud are also required for the drilling operations.

A tophole drilling operation is conventionally performed without a riser. The mud is then disposed directly on to the seabed. However, the tophole drilling method from AGR is a special approach as the mud is returned through a separated return line up to the rig. After BOP is deployed a marine riser is used to bring mud up to surface. There are two possible methods for collecting the mud from seabed to surface without riser. One possible method is to use a separated return line. This is the basic concept of riserless drilling, as riserless drilling is normally associated with the pumping of return mud back to the rig. Another method which currently is under development by Reelwell is to use a second pipe inside the drill sting.

6.1.1 TOPHOLE (RMR) - EXISTING

The tophole Riserless Mud Recovery (RMR) system from the Norwegian company AGR Subsea AS has for the last decade been widely accepted. This dual gradient system is used for tophole drilling in shallow water before installation of riser and BOP. The system consists of a subsea pump which returns drill cuttings and mud back to the drilling rig for treatment and recirculation [45]. Since the operation is done prior to the BOP deployment the method does not replace the riser or reduce the VDL requirements to a large extent. However, this method is a enabler for slim well drilling, presented in section 6.2, which have the possibility to significantly reduce required VDL.

The key elements in the RMR system is shown in Figure 16, where [46];

1. Suction module
2. Subsea pump module
3. Umbilical & umbilical winch
4. Office & tool container
5. Power and control container
6. Mud return line

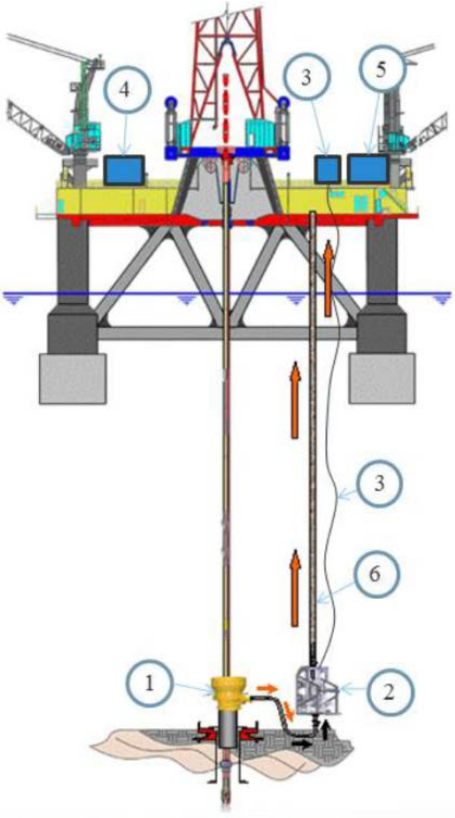

FIGURE 16: SCHEMATIC OF RISERLESS MUD RECOVERY SYSTEM [46]

A suction module is mounted on the wellhead. It collects the return fluids from the well and houses the mud level control system. The suction module provides connections to the suction hose, which directs the mud and cuttings towards the subsea pump module. A flexible hose connects the suction module to the pump module. The pump module pumps the drilling mud and cuttings to the drilling rig through the mud return line. In addition, it functions as a support frame for the pumps and motors. An umbilical winch provides control connections and power supply between the pump module and the power and control container, see Figure 16. The control system monitors pressures and pumps, and ensure a stable mud level inside the wellhead [47].

The RMR system has been used to drill over 200 wells. AGR has experiences from all over the world with the RMR system. This dual gradient drilling system has successfully been used to set 13 5/8" surface casing down to 2 350 m by eliminating the 20" casing [48]. This is an enabler for slim well drilling and thus the reduced VDL requirements and corresponding reduction of air emissions.

Deep Water RMR

In order to develop a deep water version of tophole RMR a Joint Industry Project (JIP) was formed by AGR, BP America, Shell and the Norwegian Research Council`s DEMO 2000 program. This resulted in an earlier DEMO2000 JIP with the same jointed steel mud return line philosophy and increased pumping power. A field trial of the system was in 2004 conducted in the North Sea winter weather. The deep water RMR utilizes two subsea pump modules, one near seabed and the other near mid-water depth. In the late summer of 2008 a large-scale field trial was conducted on a well in the South China Sea, supported by the JIP participants together with Petronas as partner in the well. From a third generation deep water semi-submersible the drilling operation was successfully conducted in 1 419 m water depth. The deep water RMR system offered several advantages for the South China Sea well which are presented in section 6.1.3 [49].

6.1.2 BOP PHASE - FUTURE

In this section the basic concept of riserless drilling and the riserless drilling method from Reelwell are to be described. Both methods have the potential to significant reduce required VDL in ultradeep water as no riser and less mud are needed for the drilling operation. In section 6.3 the Reelwell drilling method will be compared to the conventional drilling method. This will later be used to estimate the reduced air emissions.

6.1.2.1 SEPARATED RETURN LINE

From the basic concept of riserless drilling the mud that conventionally is returned inside a marine riser is returned trough a separated return line. This riserless drilling system consists of a bare drill sting, a rotating blow out preventer (RBOP) and a subsea pump. The RBOP will direct the return mud to the subsea pump and force the mud up to the surface through the return line, see Figure 17. In theory different system configurations can be used with more than one return line dependent on flow rate. Return line(s) can either be separated or tied together with choke and kill lines [44].

The subsea pump is a key component of the drilling system, as it is designed to maintain a constant flow rate or constant inlet pressure. This is important for kick detection and for maintaining well control. Control lines allows for flow rate or inlet pressure adjustments from surface. As the riserless drilling method enables dual gradient drilling where heavy mud are applied below surface, a kick cannot be directly circulated out through the kill line or choke line. It has to go through the subsea pump before it is directed to kill line or choke line. The pressure is therefore maintained at the wellhead and the formation is will not break down [44].

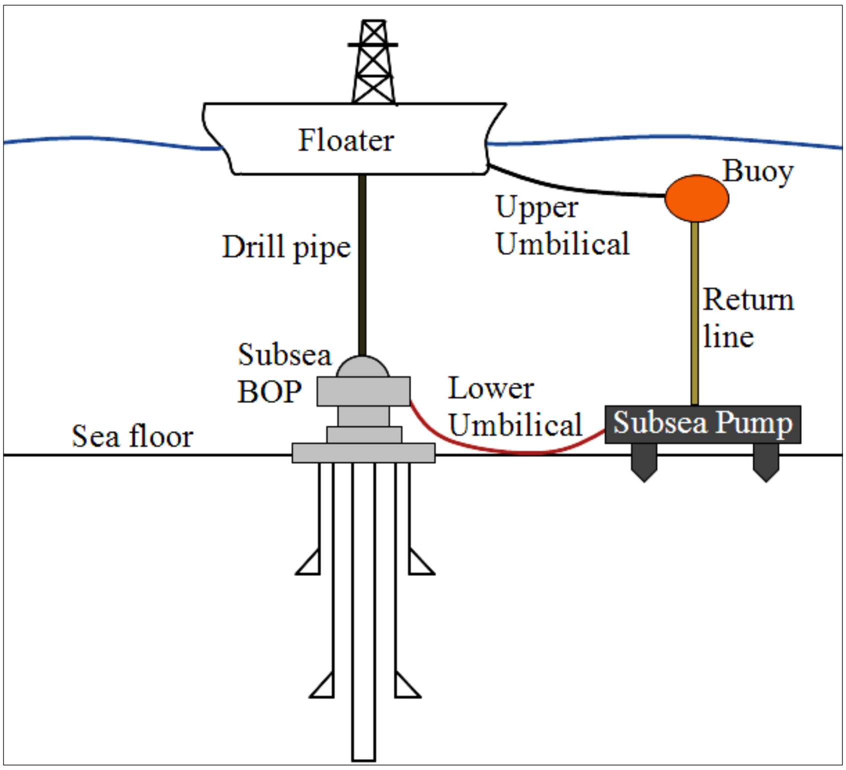

FIGURE 17: BASIC CONCEPT OF RISERLESS DRILLING SYSTEM

6.1.2.2 PIPE INSIDE DRILL STRING (RDM-R)

Reelwell Drilling Method-Riserless (RDM-R) was developed in 2010 by the Norwegian company Reelwell. One of the key elements in the system is the Dual Drill String (DDS). In the centre of the drill string is an inner string. Between the outer and inner pipe is drill fluid pumped down to the bottom of the well, see Figure 18. The RBOP encloses the well volume and force the return fluid back to surface through the inner string, see Figure 19 [50]. Since drill fluids and rock cuttings are transported through the string annulus up to surface a clean hole is ensured. The inner pipe is hung off from the internal shoulder of the outer pipe tool joints. For special applications electrical insulation between pipes are provided by the hanger. If selected, facilitating data transmissions can be done through the inner sting [51].

An essential tool for RDM is the RBOP, also called the Rotary Control Device (RCD), which is installed on the top of the BOP stack. The RBOP must be installed during the whole drilling period as it keeps the pressure in well bore and drill string annulus. A device called Flow Cross Over divert the fluid into the inner string. A Dual Float Valve (DFV) is integrated to prevent backflow and inflow to drill pipe when circulation is stopped, making it a key element in RDM [51]. The DFV is located at the bottom end of the drill string while a Top Drive Adapter (TDA) is located at the top. The TDA is containing a dual swivel system which returns and supplies drilling fluids [50].

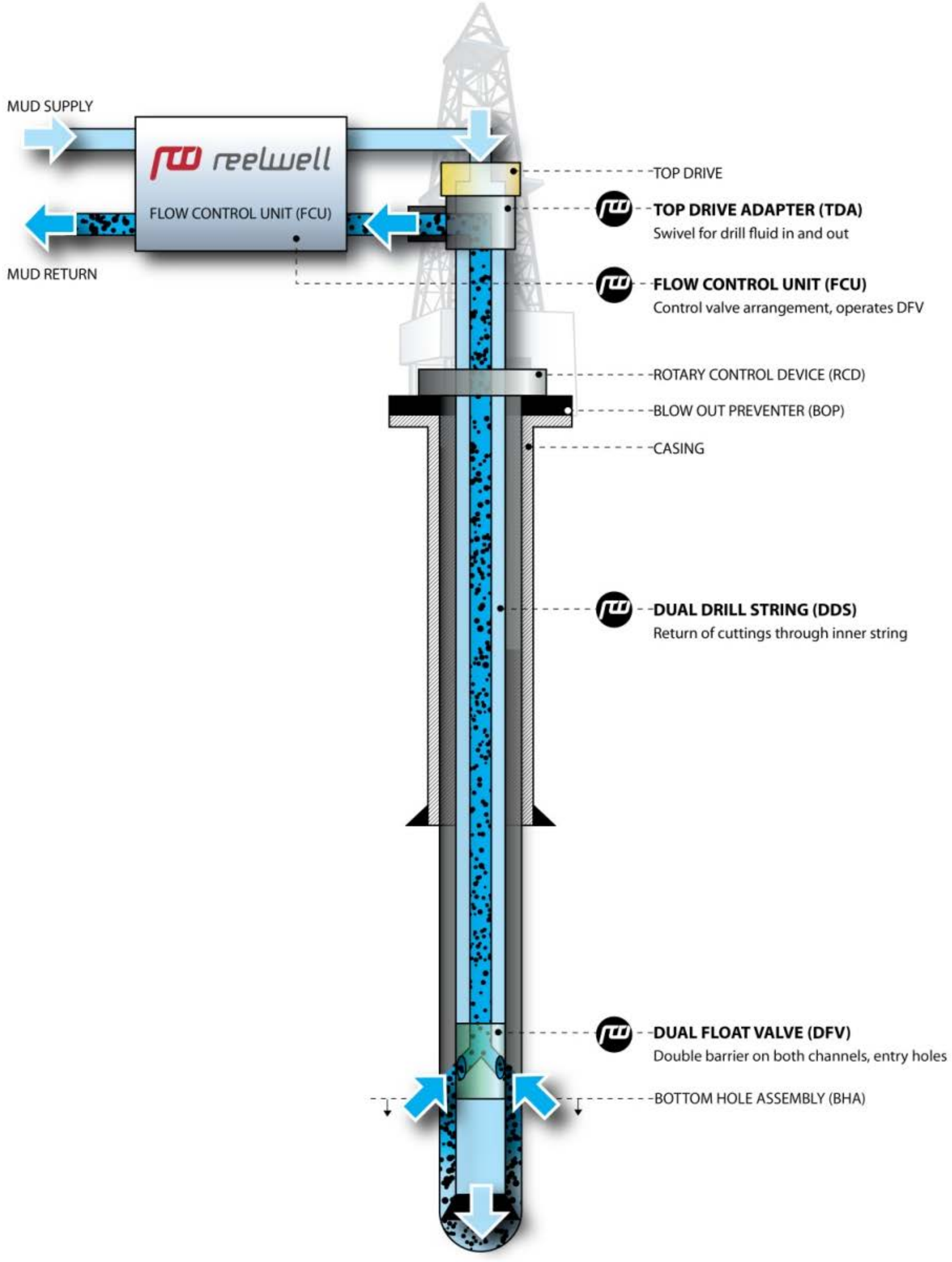

FIGURE 18: SCHEMATIC OVERVIEW OF THE RDM TECHNOLOGY [52]

In Figure 18 the basic principles of the Reelwell drilling method are shown. From the figure one can see that drilling fluid is pumped into the TDA and further routed through the DDS annulus. When entering the DFV the flow is crossed over into a standard bottom hole assembly [50]. In Figure 19 the principal differences between the RDM-R method and the conventional method with marine riser on a floater are shown.

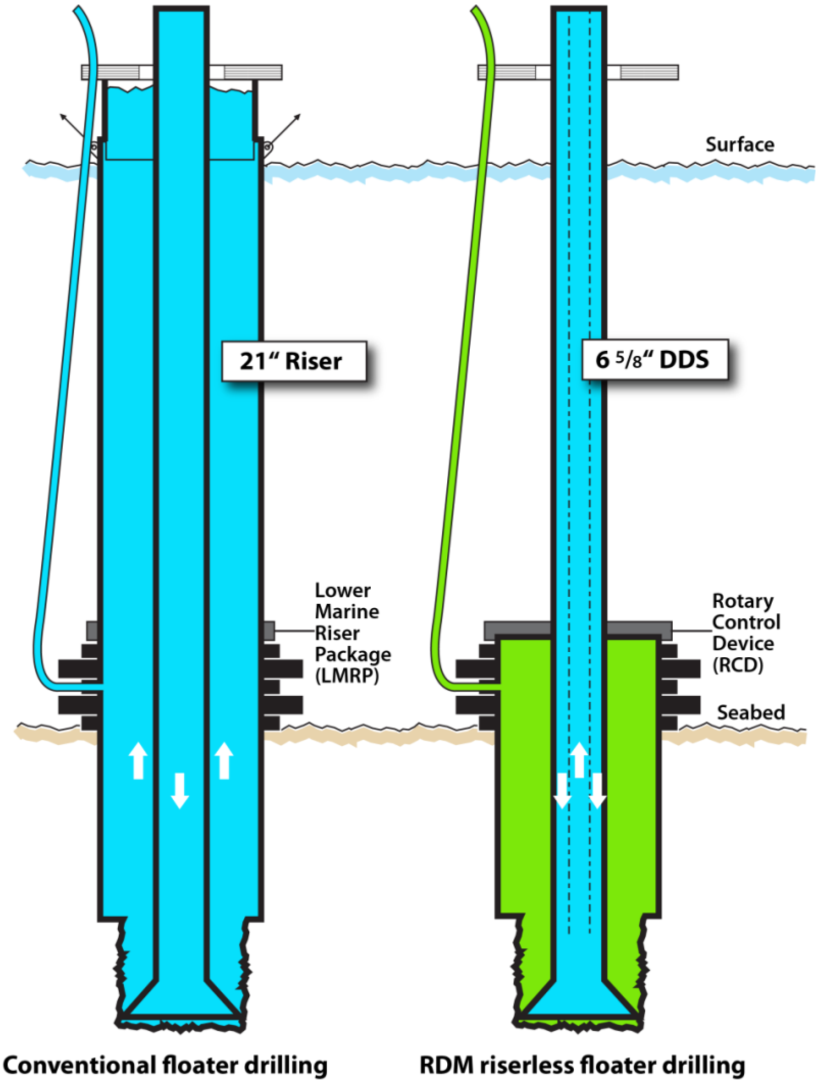

FIGURE 19: ILLUSTRATION OF CONVENTIONAL DRILLING AND RDM-RISERLESS DRILLING

The RDM has the last 5 years received the Offshore Technology Conference spotlight on new technology award. The RDM technology has already been tested and qualified at the International Research Institute of Stavanger in Norway. In addition, the method was in 2009 applied for a live shale gas well in Canada. Reelwell has also signed a technology development contract with the major exploration and production companies in Brazil. This is a special application where RDM-R system is to be qualified for drilling the salt section of presalt wells in the deep water of Santos Basin. Norwegian Research Council supports the project through the DEMO 2000 program [50].

However, there are still some issues related to the RDM-R system. The RBOP is a critical item as it needs to be designed for new operating conditions and, in addition, qualified for a continuous subsea operation. An issue with riserless drilling is that running of casing is done in open water. Therefore means are required to ensure operation in a safe and efficient manner. Since the method is new and not used in offshore operations, there are non-technical uncertainties and risks involved [50].

6.1.3 MAIN ADVANTAGES WITH RISERLESS DRILLING

Riserless drilling in deep water has great potential for future operations with many advantages compared to conventional riser drilling. To use a marine riser in deep water applications presents problems like storage and weight requirements, severe stresses in riser and difficulties with station keeping [53]. Possibly the greatest advantage with riserless drilling is the low VDL that is needed for the drilling operation. The 21" marine riser is heavy and can be up to 3600 meters long with conventional technology. Since the heavy riser with associated mud volume is not needed, the weight capacity is lowered. This implies that a smaller rig with less diesel consumption could be used to drill in deep and ultradeep water. Also a smaller rig implies less environmental forces. This means that the station keeping requirements are reduced and waiting-on-weather time may be reduced. The cost will also be reduced as the riser equipment and associated costs are eliminated [53].

The tophole RMR system allows for economical use of drilling fluids, which is treated on surface and re-used. Because of this, a more effective drilling fluid can be used, and therefore an improved borehole quality is achieved. Together the quality weighted mud system and volume monitoring allows for influx control. Observation of gains and losses together with mud weight adjustment will ensure an appropriate borehole pressure. These functions will together improve the casing setting depths and maintain stability of shallow formations. A major advantage with the RMR system is that it meets the "zero discharge" regulations, as no drilling fluids are disposed on seabed [49].

The deep water tophole RMR system provided additional benefits during the field trial in 2008. The improvements included better hole cleaning, further increased casing setting depths and more effective primary cement operation of surface casing strings. In addition were logistical limitations overcome, and an improved control of shallow hazards was accomplished though the volume monitoring [49].

According to Reelwell the RDM technology will allow for drilling through difficult zones. Reduction in well control issues and loss of drilling fluids are some of the many advantages Reelwell claims that the RDM technology will provide [52]. Managed pressure drilling will be facilitated because of the enclosed circulation system and the stagnant annulus. Together these features represent a potential to use fewer casings and facilitate the use of standard 13-5/8" wellhead systems. This might result in a 50% weight reduction of BOP, Xmas tree and associated equipment [50].

6.2 SLIM WELL DRILLING

The slim well drilling method has the potential to reduce required rig size as less weight is needed for the drilling operation. This is mainly because of the reduced riser, riser tension and mud in riser and well. This will indirectly result in lower air emissions as smaller rigs have less power requirements.

Slim well drilling has been used since the 1940s. Drilling slim wells/holes has been the standard drilling method for the construction and mining industry. Slim wells were earlier drilled by the oil and gas industry, but only when there was no other choice. Not until late 1980s were slim well experiments performed on a continuous basis for the oil and gas industry. During the early 1990s were several companies prepared to experiment with slim well drilling. Also an offshore “retrofit” slim well project by Shell and Baker Hughes INTEQ was in the early 1990s presented. In over 3 000 m was high pressure wells drilled, which resulted in 10-15% cost reductions [54].

Subsea wells are usually drilled with an 18-3/4” wellhead system. Conventional is an 18-3/4” subsea BOP used in combination with a 21” marine riser. The riser is heavy as it needs to withstand the expected bending, tension and pressure loads. For slim well drilling are typically a 13-5/8” wellhead system used together with a 13-5/8” BOP and a 16” riser. This smaller diameter pipe may allow for a reduced wall thickness when compared to a 21” riser with the same design pressures. Therefore the steel weight will not only be reduced because of the smaller diameter, but also because of the reduced wall thickness [55].

The mud volume in riser will be less with a 16” riser. Reduced mud in riser represents lower capacity requirements for mud pit and pumps. The riser tension and buoyancy requirements will also be reduced due to the 16” light weight drilling riser with less mud volume inside. Together this will lower requirements for VDL and deck space. Therefore older and smaller generations drilling rigs can be used for deep water drilling, and with minimum amount of upgrading [55].

The 13-5/8” wellhead technology is particularly suited for deep water applications where the reservoir can be reached with one or two casing strings which are drilled through the BOP stack. Slim well drilling implies fewer and smaller diameter casings, see Table 5. This results in less removal of drill cuttings and therefore well drilling time. A limitation to the 13-5/8” wellhead system is that larger casing strings cannot pass through the wellhead [55].

TABLE 5: TYPICAL CASING SIZES FOR CONVENTIONAL AND SLIM WELL DRILLING

	Conventional		Slim well	
Casing string	Casing size	Hole size	Casing size	Hole size
Conductor pipe	30"	36"	20"	26"
Surface casing	18-5/8"	26"	13-3/8"	16"
Intermediate casing	13-3/8"	16"	9-5/8"	12-1/4"
Production casing	9-5/8"	12-1/4"	-	-
Production liner	7"	8-1/2"	7"	8-1/2"

6.3 COMPARISON OF DRILLING METHODS

The RDM-R and the slim well drilling method will in this section be compared to the conventional drilling method. Riser weights, riser tension capacities and mud volumes will in the following be evaluated. The RDM-R method will allow for smaller VDL requirements due to the low weight of the DDS compared to the 21" riser, in addition the mud weight inside the DDS will be lower. For the slim well drilling method, the riser tension capacity and mud volume in both riser and well will be lower than for the conventional method.

6.3.1 RISER AND DDS WEIGHTS

In Table 6 approximately weights of the DDS, the 16" slim riser and the 21" conventional riser are shown. The 16" slim riser will have a weight of approximately 60% of the conventional 21" riser [56]. Since the DDS is still under development an exact diameter is not available. A realistic assumption is a diameter of approximately 6" and a weight in the range of 80 kg/m. For all three cases the weight of riser/DDS and auxiliary lines are included. The air weight of the buoyancy is also included for the 16" and 21" riser. This is not included for the DDS as buoyancy is not required for riserless drilling. The weight reductions are significantly compared to a conventional 21" riser.

TABLE 6: RISER AND DDS WEIGHTS [57]

Drilling method	Size [in.]	Weight [kg/m]	Weight in 2750 m [mT]	Weight reduction [%]
RDM-R	~6	~80	~220	~90
Slim well	16	~460	~1 265	~40
Conventional	21	~770	~2 117	-

The DDS has a 90% reduced weight compared to a conventional riser with auxiliary lines and buoyancy. The 16" riser has a reduction of 40% compared to the conventional riser. Both will allow for reduced VDL requirements. It will further be assumed that the riser weights are implemented as a part of the riser tension. However, the DDS do not need riser tension and therefore the weight of the 21" riser tension is removed from the VDL.

6.3.2 RISER TENSION

The same rigs considered making the VDL graphs in section 3.3 are used to estimate the corresponding 16" riser tension capacity. The conventional riser tension capacities for the rigs considered are collected from RigLogix [8] and listed in Appendix A. Some values as described in section 3.3 are removed to give a more accurate result. The average values are listed in Appendix D. The average riser tension capacity varies as the values are taken based on the rigs displacements and not the water depth capacity. However, the rigs displacements often reflect the water depth. A typical sixth generation semi-submersible with a displacement of 53 000 mT and a modern drillship with a typical displacement of 84 000 mT, is used in the following examples, see Figure 20 and 21.

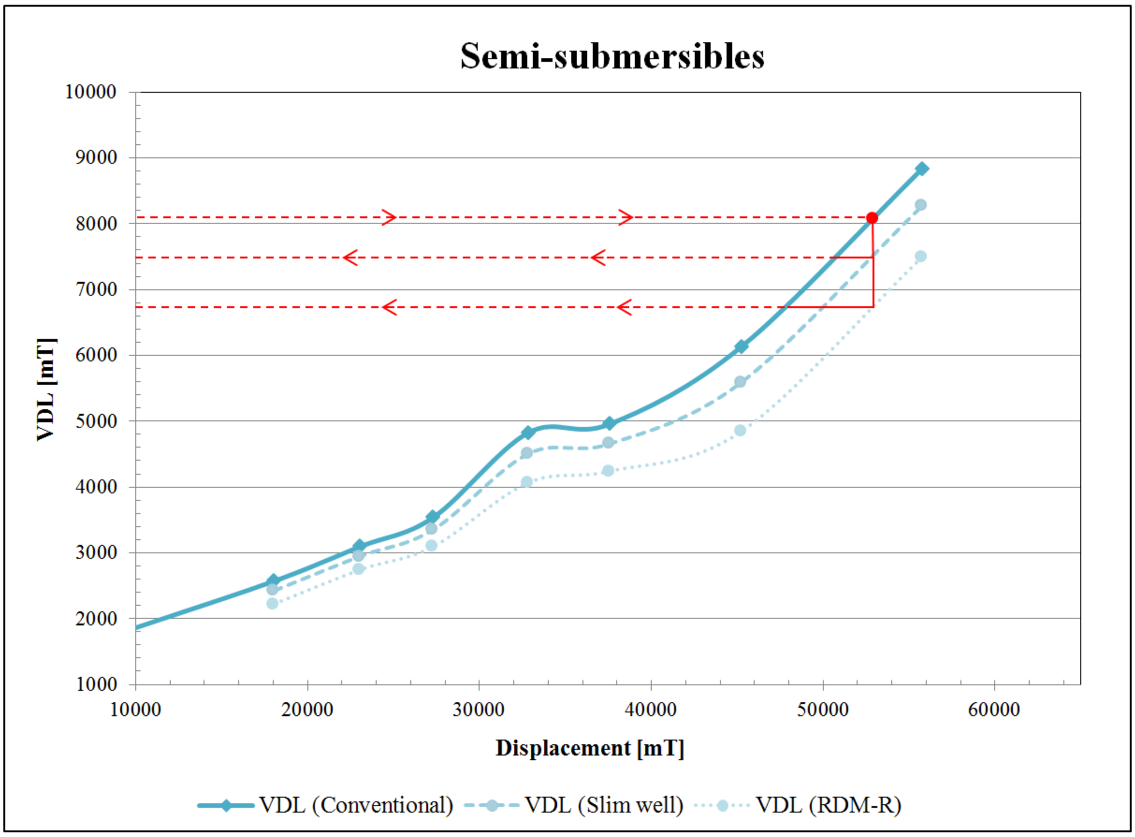

FIGURE 20: NEW VDL LINES FOR SEMI-SUBMERSIBLES DUE TO REDUCED/REMOVED RISER TENSION

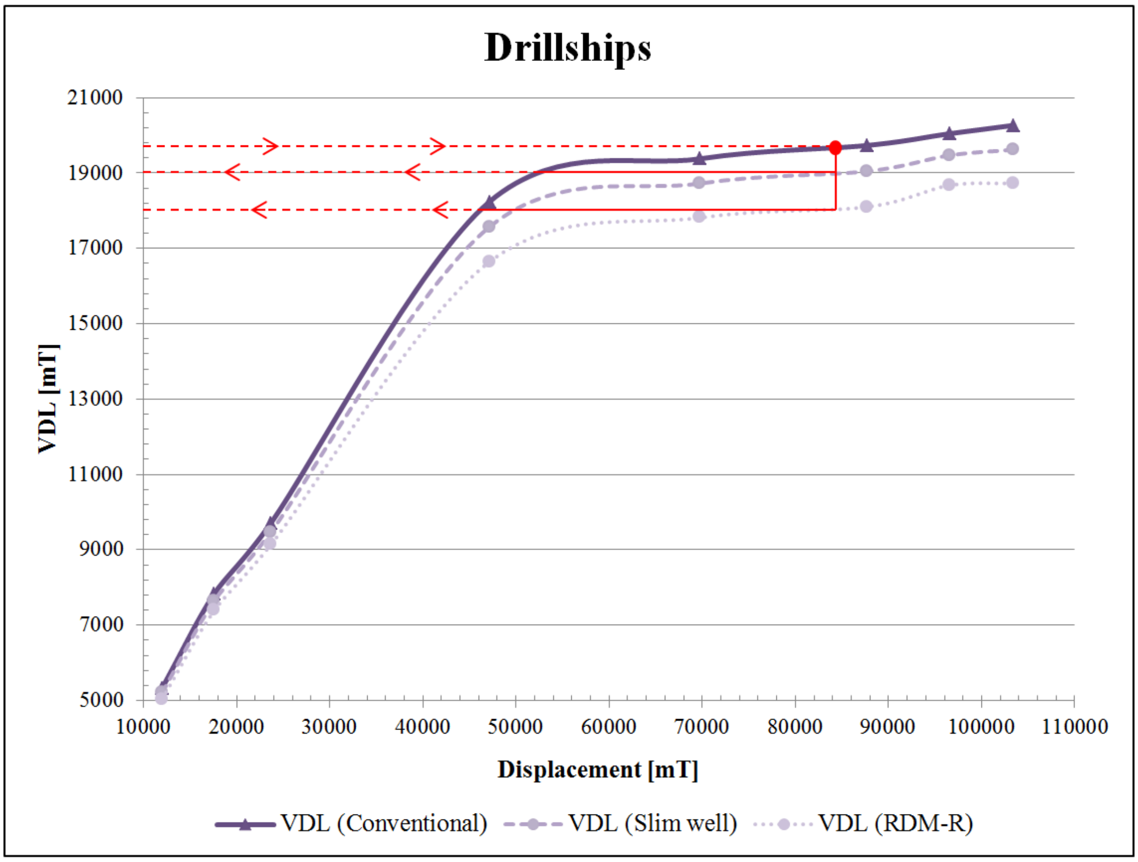

FIGURE 21: NEW VDL LINES FOR DRILLSHIPS DUE TO REDUCED/REMOVED RISER TENSION

The equation below is used to give a rough approximation of the 16” riser tension capacity:

$T_{16} = T_{21} \cdot \left(\frac{16}{21}\right)^2$, where;

T_{21} is the average 21” riser tension capacity.

In Figure 21 and 22 the new VDL lines for both the slim well drilling method and the RDM-R drilling method are shown. As expected, the new VDL lines follow the conventional VDL line. This is because the riser tension capacity is mainly dependent on water depth capacity and thus the VDL capacity. The difference between the 16” riser tension and 21” riser tension is subtracted from the conventional VDL, to create the slim well VDL line. The 21” riser tension is removed from the VDL for the RDM-R method, as no riser tension is needed for the DDS. The semi-submersible considered has a starting VDL of approximately 8 100 mT and the drillship considered has an approximately VDL of 19 700 mT.

From Figure 21 one can see that the VDL requirements for semi-submersibles are approximately 625 mT lower for the 16” slim riser due to lower riser tension requirements. The RDM-R method allows for an approximately reduction of 1 350 mT as no riser tension is implemented as part of the VDL. As seen in the graph the reduced VDL is larger for higher displacements. This is because the water depth capacity and wall thickness of riser increases for larger rigs.

In Figure 22 one can see that the 16” riser tension allows for an approximately VDL reduction of 700 mT for the drillship considered. With no riser tension the VDL can be reduced with approximately 1 700 mT, as shown with the VDL line for the RDM-R method. Note that the VDL lines on the right hand of the graph are not linear. This is because the rigs considered on the left hand, of the flattened part on the graph, have higher water depth capabilities than those on the right hand.

Both drilling methods can provide considerably lower VDL requirements due to reduced or remover riser tension. In addition, the reduced diameters will allow for smaller wall thicknesses to be used.

6.3.3 *MUD VOLUMES*

A 6-5/8” pipe with ID of 140 mm is presented in a base case from Reelwell [58]. These base case parameters from Reelwell will be used in the following calculations, as the DDS is still under development. A conventional riser normally has a 21” OD and a wall thickness between 0,50” and 0,875” (13 mm ~ 22 mm) [55]. In the following it is assumed that the a wall thickness of 0,8” (~20 mm) is needed since the pressure is high for deep water applications. As the 16” riser can allow for a smaller wall thickness, compared to a 21” riser in same water depth, a 0,75” (~19 mm) wall thickness is chosen for the calculation. The mud volumes inside risers and the DDS are presented in Table 7 on next page.

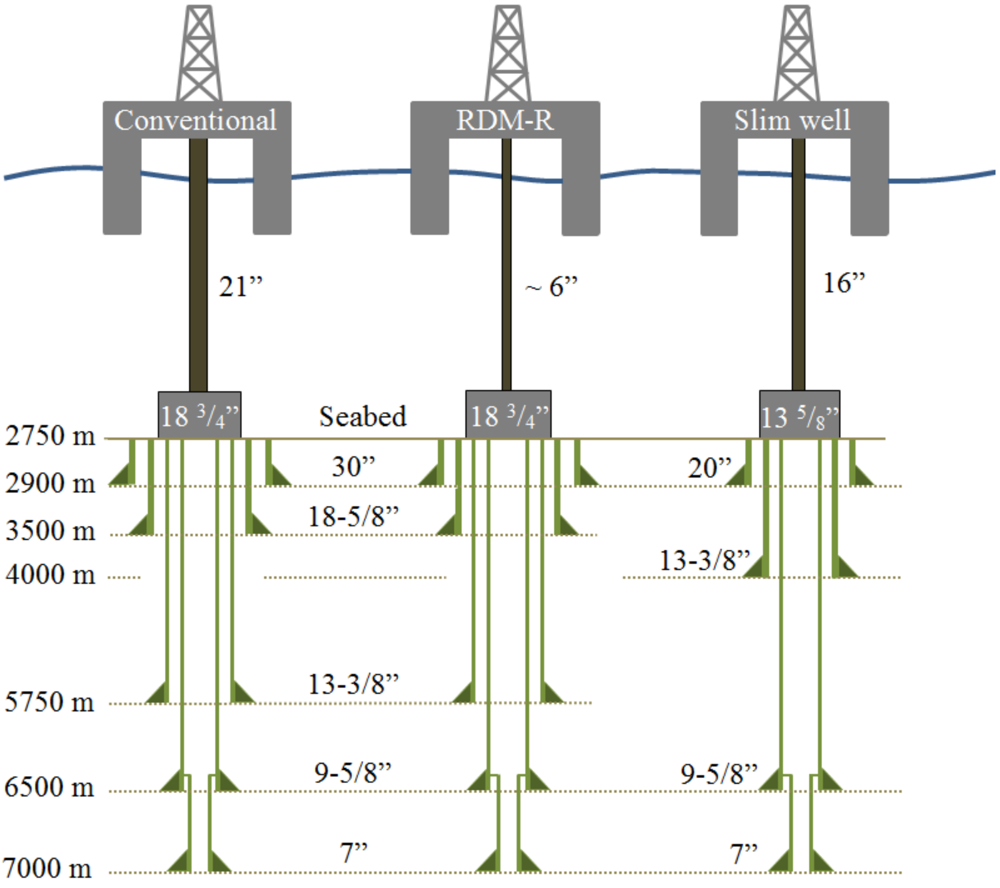

FIGURE 22: CASING PROGRAM FOR THE CONVENTIONAL WELL AND THE SLIM WELL

For both the conventional well and the slim well the mud volume inside the well hole and the casing strings are calculated. The simplified calculation adds the total volume needed to fill the well hole and the casings strings. The casing programs and the lengths of each section are illustrated in Figure 22. The water depth is 2 750 m and the drilling target depth is 7 000 m below the surface, which means that a 4 750 m long well is considered in the calculations. Both casing programs reach target depth with a 7” liner. In addition, four casing stings are used for the conventional well and three casing strings are used for the slim well.

The first two holes to be drilled are usually drilled with a tophole operation. The mud is then dispersed onto seabed. Therefore the mud inside the first to hole sections and the first casing section are not part of the calculation. Figure 23 shows the different mud volumes to be summarized together. The left hand of the figure represents a conventional well and the right hand represents a slim well. All casings are routed back to seabed but not the liner which is hung off from inside the intermediate casing. In the calculations, it is assumed that only mud is inside the casing strings. Inner diameter is found from API specification 5CT / ISO 11960 [59]. It is assumed that a relatively large wall thickness is needed as the pressure is high in ultradeep drilling. The relevant parameters are found in Appendix C.

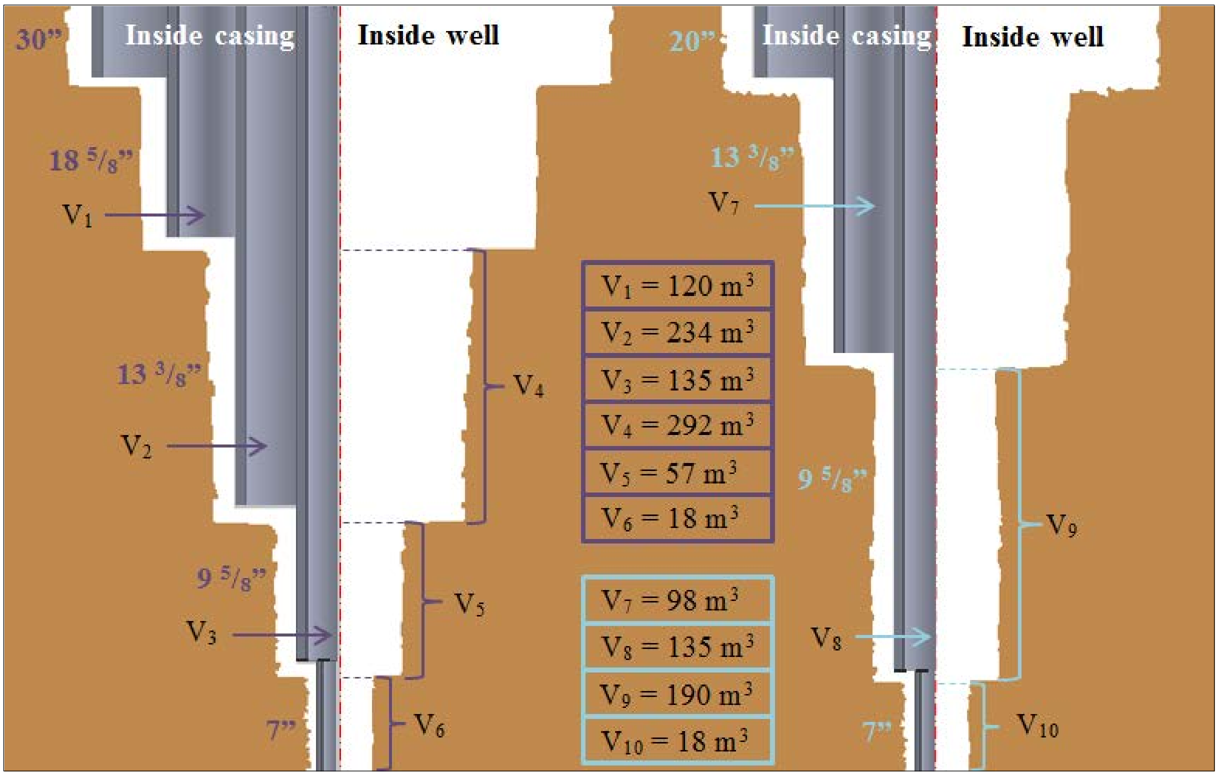

FIGURE 23: MUD VOLUMES INSIDE CASING STRINGS AND WELLS

The results are given in Table 7. Both the RDM-R method and the slim well drilling method have the potential to reduce required rig size for ultradeep water and ultradeep drilling applications. It is assumed that the mud has an average weight of 12,5 ppg (1,5 kg/l). The weight reduction is 35% for the RDM-R method and 47% for the slim well drilling method.

TABLE 7: TOTAL MUD VOLUMES AND WEIGHTS FOR THE DIFFERENT DRILLING METHODS

Drilling method	Mud volumes [m3]		Total volume of mud [m^3]	Weight of mud [mT]	Reduction of weight [%]
	In riser/DDS	In well			
RDM-R	42	856	898	1 347	35
Slim well	293	441	734	1 101	47
Conventional	524	856	1 380	2 070	-

It is further assumed that the weight reduction is equal to the reduced requirement of the conventional liquid mud capacities, collected from RigLogix [8]. The reduced VDL for semi-submersibles and drillships due to lower mud requirements are presented in Figure 24 and 25. Note that this is valid for well/riser alone. Reductions will also be reflected in lower volumes topside.

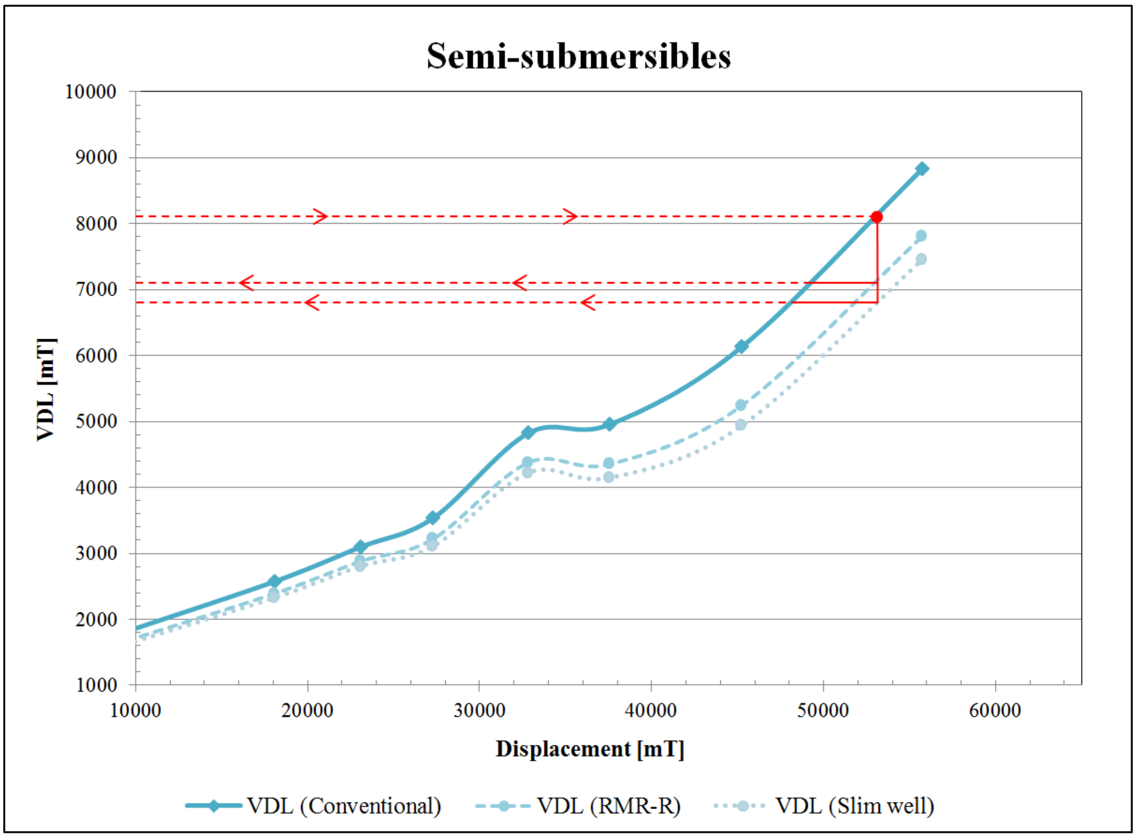

FIGURE 24: LOWER VDL REQUIREMENTS FOR SEMI-SUBMERSIBLES DUE TO REDUCED MUD VOLUMES

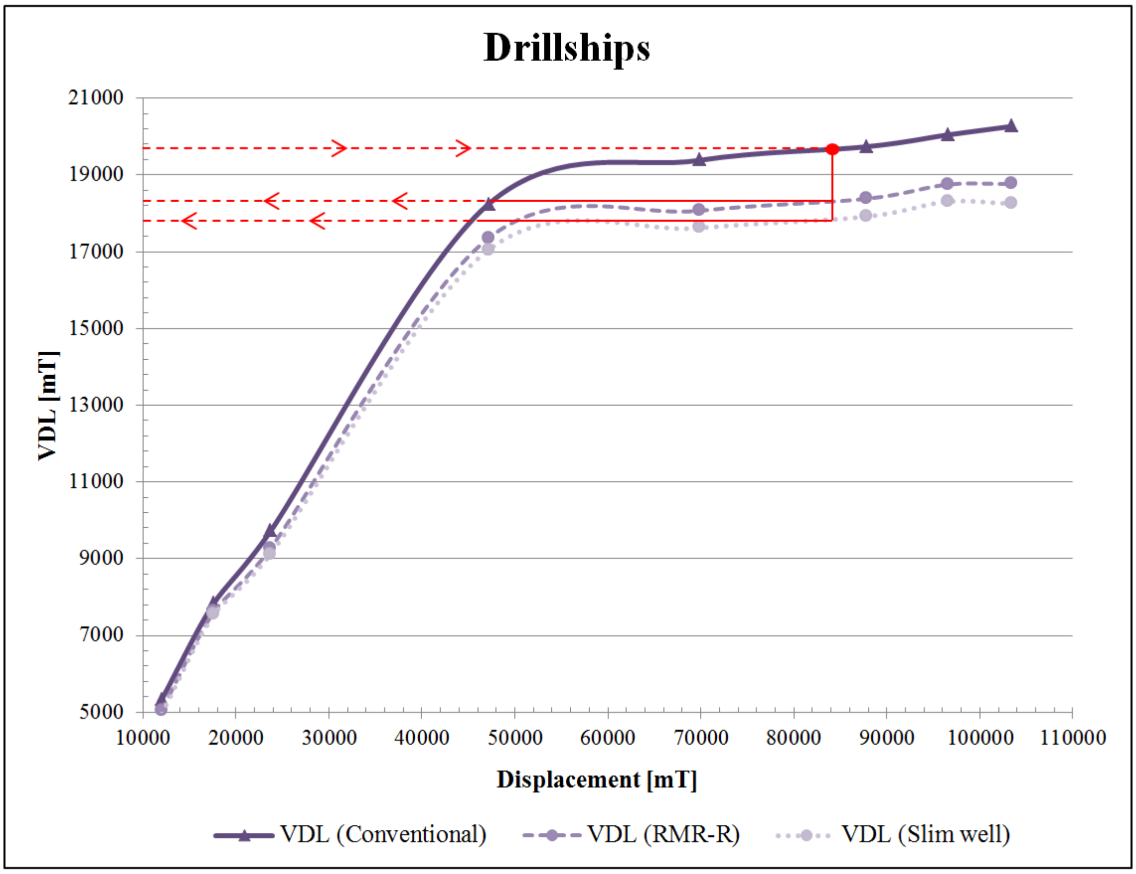

FIGURE 25: LOWER VDL REQUIREMENTS FOR DRILLSHIPS DUE TO REDUCED MUD VOLUMES

The graphs in Figure 24 and 25 are plotted as explained for the riser tension capacity in section 6.3.2. From the figures one can see that the mud capacity is larger after the discontinuity in both curves. This is as expected as the water depth capacity and the drilling depth capacity are higher for the rigs considered after the discontinuities. However as explained earlier, the rigs considered on right hand of Figure 24 have smaller water depth capacities than those considered on left hand of the flattened part in the graph.

From Figure 24 one can see that the VDL requirements for the given semi-submersible approximately will be 1 000 mT lower for the RDM-R method and 1 300 mT for the slim well drilling method. The VDL requirements for the considered drillship are approximately reduced with 1 400 mT for the RDM-R method and 1 900 mT for the slim well drilling method, see Figure 25.

6.3.4 TOTAL REDUCTION OF VDL

Both the RDM-R method and the slim well drilling method have been compared to the conventional drilling method. Both methods have the potential to significantly reduce the VDL requirements. The results for the examples previously presented are given in Table 8. For the RDM-R method is the reduced riser tension equal to the 21” riser tension as no riser tensions is needed for the drilling operation.

TABLE 8: TOTAL VDL REDUCTION DUE TO REDUCED/REMOVED RISER TENSION AND MUD VOLUMES

Type of rig	VDL reduction (riser tension + mud) [mT]		Total VDL requirements [mT]		
	RDM-R	Slim well	Conventional	RDM-R	Slim well
Semisub	1 350 + 1 000	625 + 1 300	8 100	5 750	6 175
Drillship	1 700 + 1 400	700 + 1 900	19 700	16 600	17 100

From Figure 26 and 27 on next page one can see the total reduced VDL and the corresponding displacement for both the semi-submersible and the drillship considered. As shown in Figure 26, a semi-submersible with approximately displacement of 43 000-46 000 mT will be able to drill in ultradeep waters, when implementing the RDM-R or the slim well drilling method. This implies that a typical fourth generation rig can be used to drill in ultradeep waters. As discussed in section 6.5 this will allow for reduced air emissions. However, this is indicative only as a lot of parameters and conditions are not considered in these simplified calculations.

A drillship with a displacement between 41 000 mT and 43 000 mT will be sufficient for ultradeep water drilling, when implementing the RDM-R or the slim well drilling method, see Figure 27. However, if a drillship with a displacement of about 60 000 mT was chosen for the example would not the reduction not be as large. This is because the VDL is approximately constant for higher values.

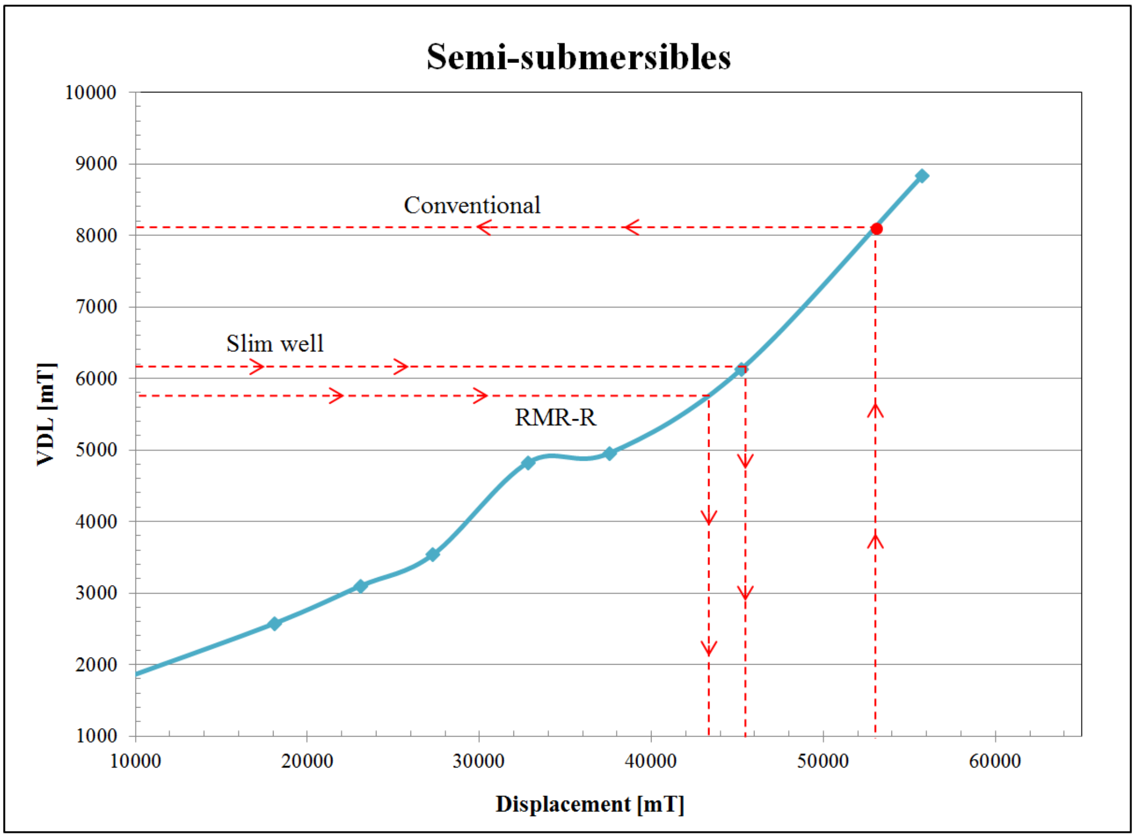

FIGURE 26: REDUCED VDL AND DISPLACEMENT FOR THE SEMI-SUBMERSIBLE CONSIDERED

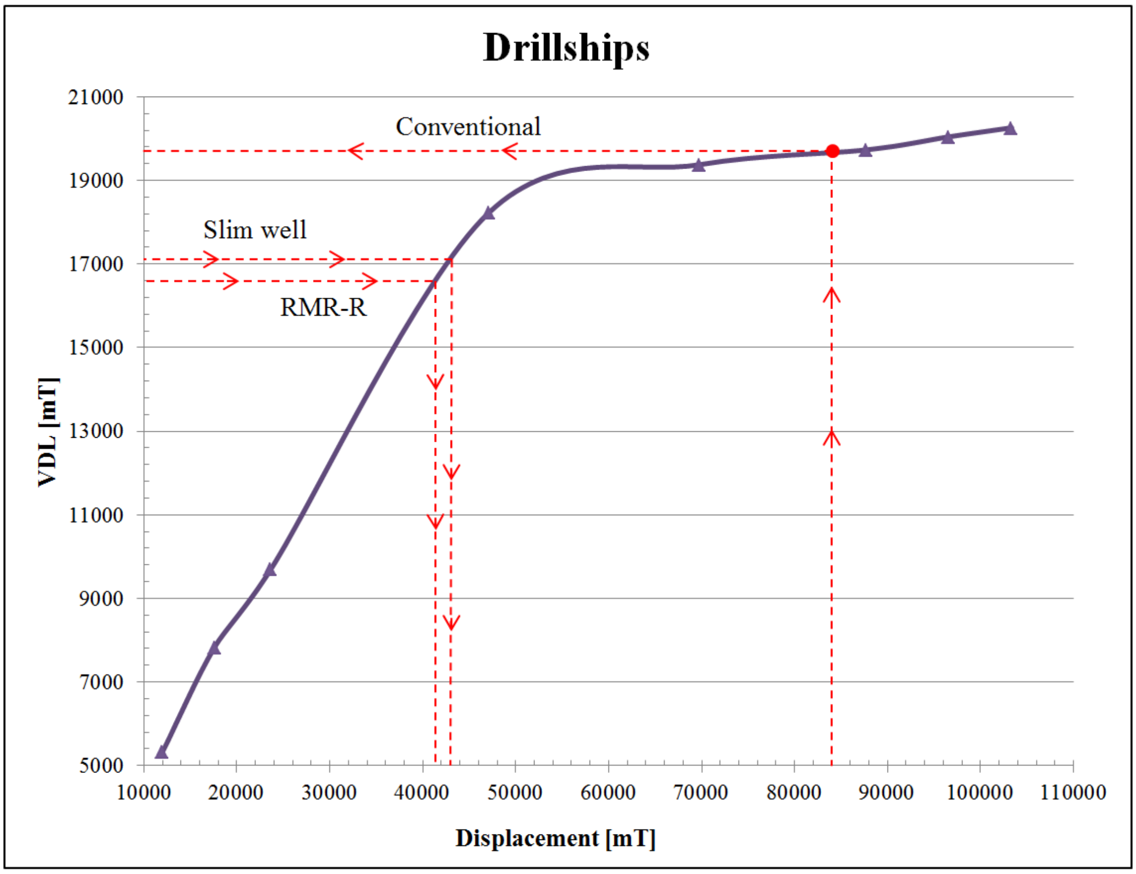

FIGURE 27: REDUCED VDL AND DISPLACEMENT FOR THE DRILLSHIP CONSIDERED

6.4 COMBINATION OF DRILLING METHODS

RDM-R is a managed pressure drilling system due to the enclosed circulation. It may facilitate use of fewer casing strings, a 13-5/8” wellhead system and thereby slim well drilling. As the methods have the potential to be combined, the rig size reduction when combined will further be evaluated.

When combining RDM-R with a slim well, the DDS weight and the mud weight inside are summarized with the total mud weight inside the slim well. The new mud volume and weight with 12,5 ppg is given in Table 9. From the table one can see that the combined weight reduction is significant compared to the reductions of the separate drilling methods. It is as in section 6.3.3 assumed that the weight reduction is equal to the reduced requirement of the liquid mud capacity.

TABLE 9: TOTAL MUD VOLUMES AND WEIGHTS FOR THE COMBINATION OF DRILLING METHODS

Drilling method	Mud volumes [m3]		Total volume of mud [m^3]	Weight of mud [mT]	Reduction of weight [%]
	In riser/DDS	In well			
RDM-R	42	856	898	1 347	35
Slim well	293	441	734	1 101	47
Conventional	524	856	1 380	2 070	-
Combination	42	441	483	725	65

In Figure 28 and 29 the new VDL lines when both drilling methods are combined are shown. The 21” riser tension is removed and the difference in mud weight are subtracted from the conventional VDL line, see Appendix D for specific mud values. The required VDL for the semi-submersible considered in the last sections is approximately 3 200 mT lower than the conventional VDL. The corresponding displacement is approximately 36 800 mT. This implies that small fourth generation semi-submersible can be used for ultradeep water drilling when both methods are combined. However, the VDL reduction will be even larger if reduced equipment weighs are included. Reduced mud capacity require less pumping capacity, in addition BOP, Xmas tree and associated equipment will be smaller when a 13-5/8” wellhead system is to be used. This may indicate that a third generation semi-submersible will be sufficient for drilling in ultradeep water. Please note that this is indicative only as a lot of parameters and conditions are not considered in these simplified calculations.

The reduced equipment weights will also apply for the drillships. For the drillship considered in the last sections has a reduced VDL of approximately 4 200 mT. The reduced displacement is about 45 500 mT which implies that a drillship with a displacement of 38 000 mT could be used for ultradeep water drilling. The reduction of rig size is significant as more than 50% of the displacement can be reduced. However, as explained earlier the reduction will not be as large for a drillship with a displacement of about 60 000 mT as VDL is approximately constant for higher values.

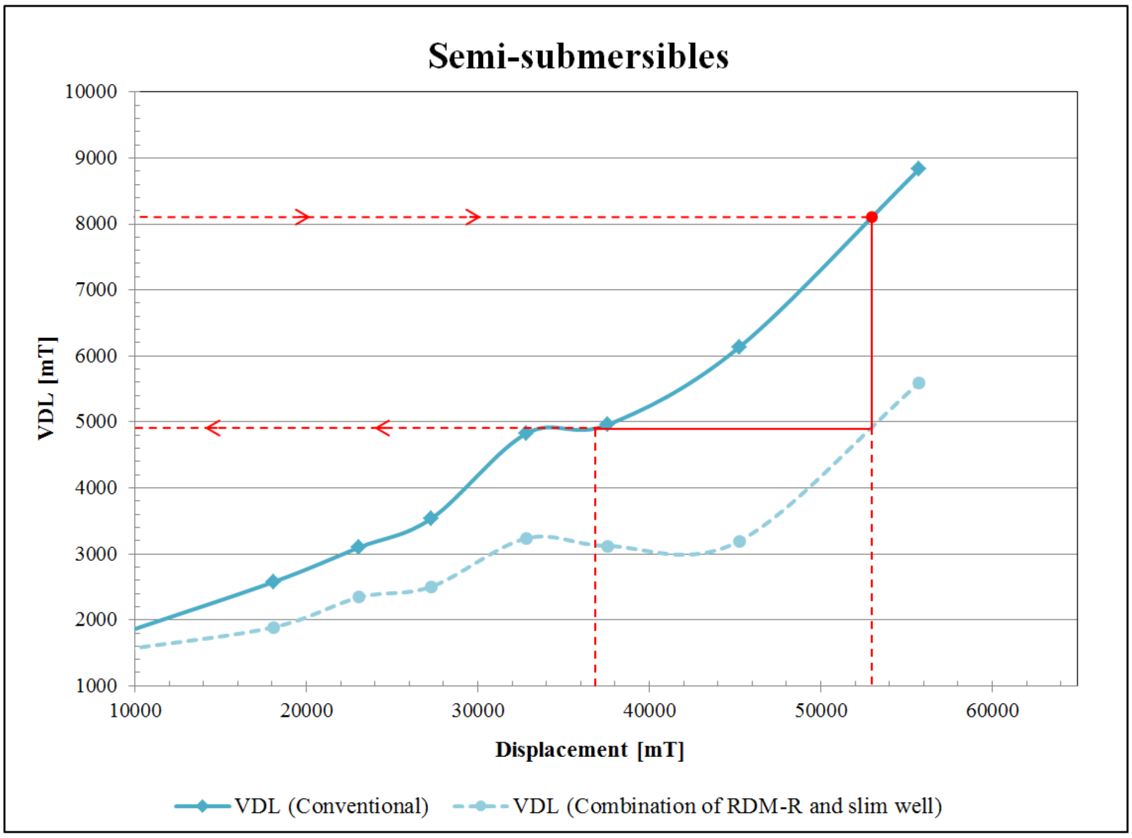

FIGURE 28: REDUCED VDL AND DISPLACEMENT FOR SEMI-SUBMERSIBLES WHEN COMBINED

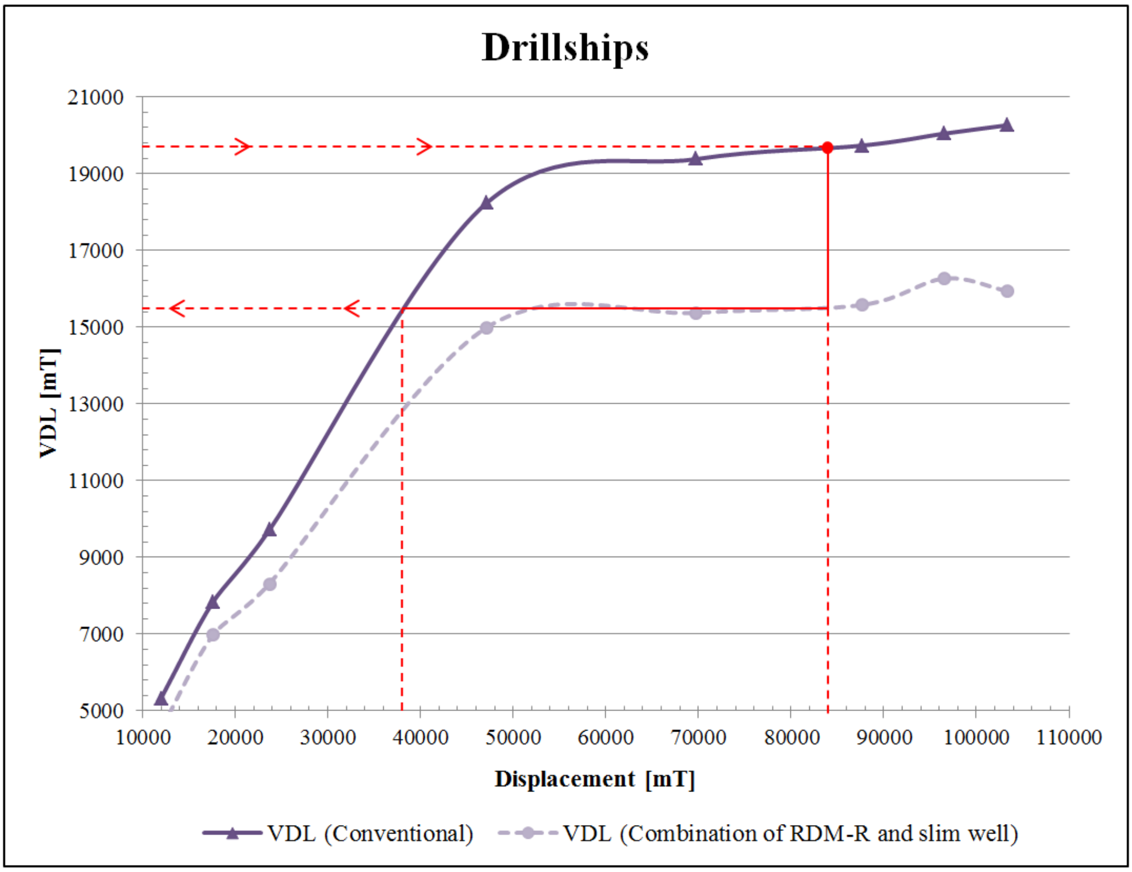

FIGURE 29: REDUCED VDL AND DISPLACEMENT FOR DRILLSHIPS WHEN COMBINED

6.5 REDUCTION OF AIR EMISSIONS

The fuel consumption graph presented in section 4.3 will further be used to estimate the reduced air emissions. The reduced displacement is only based on the weight reduction from mud and riser tension. A semi-submersible with a typical displacement of 53 000 mT and a drillship with a displacement of 84 000 mT will most likely have advanced DP systems. Therefore the reduced displacements already have the weight of advanced DP systems included. Because of this, it will further be assumed that all rigs use 45% of the total installed vessel power, as opposed to 30% for smaller semi-submersibles in section 4.3. In Figure 30 and 31 on next page the calculated fuel consumption for semi-submersibles and drillships are shown. The displacements and corresponding fuel consumption values from the figures are given in Table 10.

TABLE 10: RIG DISPLACEMENT AND CORRESPONDING FUEL CONSUMPTION

Drilling method	Type of rig	Displacement [mT]	Calculated fuel consumption [mT/yr]	Fuel consumption reduction [%]
RDM-R	Semisub	43 300	21 000	24
Slim well	Semisub	45 500	22 500	19
Conventional	Semisub	53 000	27 750	-
Combination	Semisub	36 800	15 950	43
RDM-R	Drillship	41 300	18 800	33
Slim well	Drillship	43 000	19 450	31
Conventional	Drillship	84 000	28 150	-
Combination	Drillship	38 000	17 400	38

From the table one can see that the RDM-R method have the highest potential of the two drilling methods. However, when the RDM-R method and the slim well method are combined the potential to reduce rig size are even larger. The drillship considered allows for higher VDL reduction than the semi-submersible when the drilling methods are separate. However, due to shape of the curves the percentage VDL reduction will be largest for the semi-submersible when both drilling methods are combined.

The reductions are significant especially when both methods are combined. The reduced fuel consumption will reduce the air emissions. In addition, lower fuel cost are to be expected when less fuel are needed to power the MODU. This is a great advantage as implementations to reduce air emissions are often associated with higher costs.

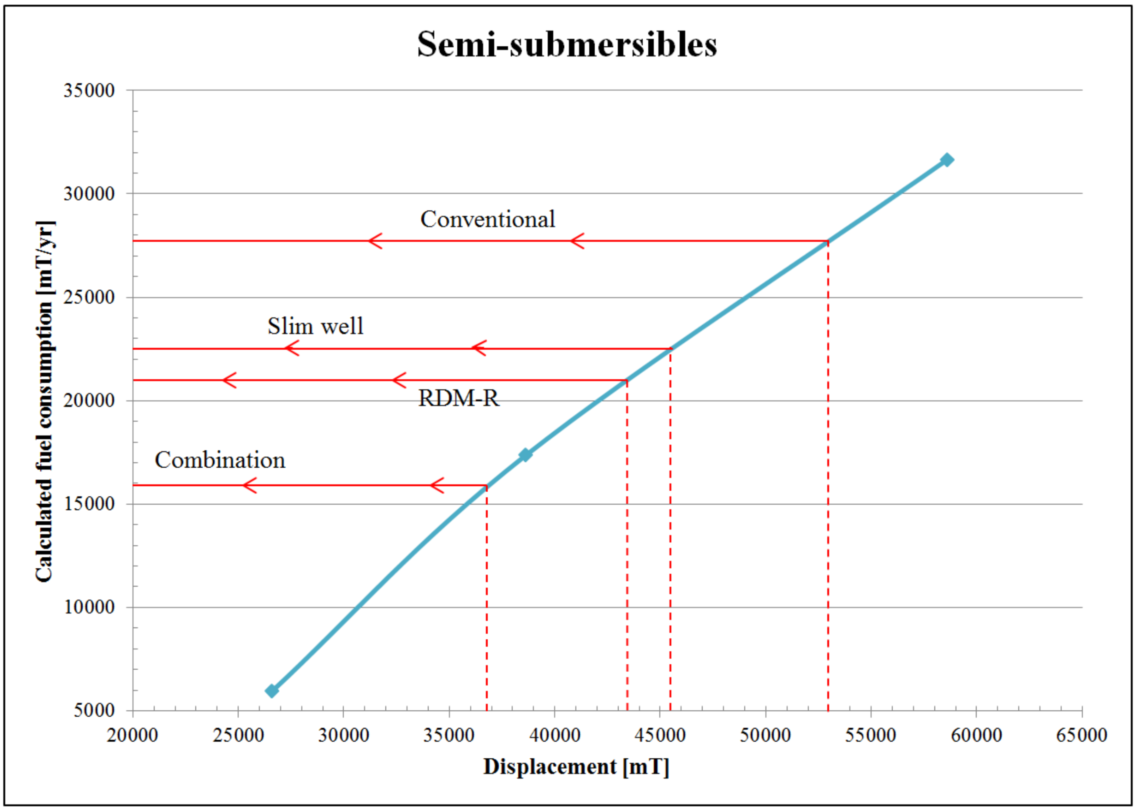

FIGURE 30: REDUCED FUEL CONSUMPTION FOR THE SEMI-SUBMERSIBLE CONSIDERED

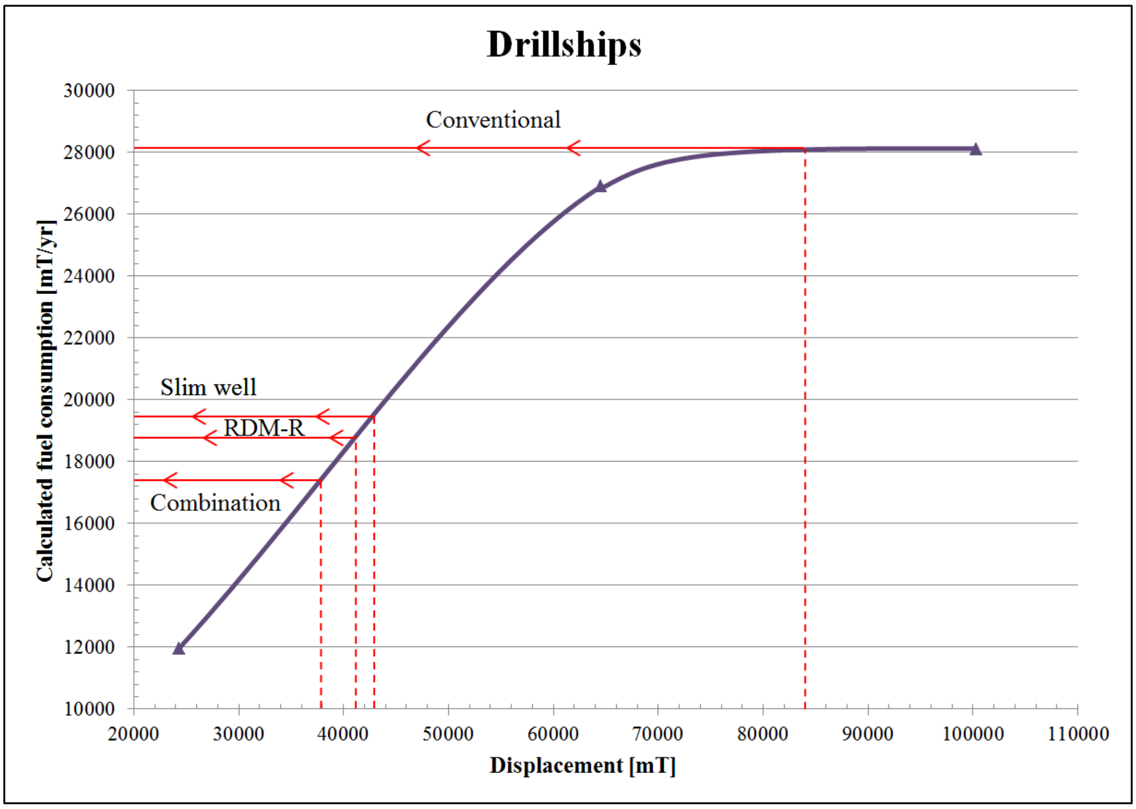

FIGURE 31: REDUCED FUEL CONSUMPTION FOR THE DRILLSHIP CONSIDERED

The percentage of reduced fuel consumption will correspond to the reduced air emissions, as the emissions factors are calculated based on the fuel consumption. One mT of diesel fuel will approximately give 3 170 kg CO_2, 0,8 kg CH_4, 1,196 kg SO_x and 5 kg nmVOC. Also NO_x are released during drilling. The amount of NO_x emission varies from rig to rig. For instance West Epsilon (jack-up) releases 9,70 kg NO_x per mT and West Phoenix (semi-submersible) releases 58 kg NO_x per mT diesel consumed [15]. The reductions of air emissions are given in Table 11, in addition the NO_x emissions will be reduced significantly.

TABLE 11: ESTIMATED REDUCTION OF AIR EMISSIONS PER YEAR

Type of rig	Type of emission	Gas emission conventional [mT/yr]	Gas emission reductions [mT/yr]		
			RDM-R	Slim well	Combination
Semisub	CO_2	87 968	21 398	16 643	37 407
Semisub	CH_4	22	5	4	9
Semisub	SO_x	33	8	6	14
Semisub	nmVOC	139	34	27	59
Drillship	CO_2	89 236	29 640	27 580	34 078
Drillship	CH_4	23	8	7	9
Drillship	SO_x	34	12	11	13
Drillship	nmVOC	141	47	44	54

The reductions of air emissions are significant. However, the fuel reduction is only based on the reduced weight of mud and riser. Therefore it is likely that the reductions could be even larger because associated equipment also will have reduced weights. As previously explained a 13 5/8” wellhead system might result in a 50% weight reduction of BOP, Xmas tree and associated equipment. In addition, less pumping power is required when pumping smaller volumes of mud.

The method may also allow for easier station keeping. This is because smaller rigs have less environmental forces. This may reduce the positioning requirements and thus reduce the emissions due to station keeping [44].

6.6 CONCLUSION AND RECOMMENDATION – NEW DRILLING METHODS

In this chapter the riserless drilling method from Reelwell (RDM-R) and the slim well drilling method have been described and compared to the conventional drilling method. Both methods have the potential to reduce rig size and thus give lower air emissions. A semi-submersible with displacement of 53 000 mT and a drillship with displacement of 84 000 mT was used to evaluate the possible reductions of air emissions. In both the RDM-R and the slim well drilling method was only the weight reduction of mud and riser tension evaluated. The conventional 21” riser tension was used to estimate the weight reduction of the riser tension.

The RDM-R method will allow for a VDL capacity of approximately 5 750 mT for the semi-submersible considered, instead of 8 100 mT as with the conventional drilling method. Therefore a smaller rig with less power requirement could be used to drill in ultradeep waters. The reduced VDL requirement will result in a 24% reduction of fuel consumption. The reduction of fuel consumption will correspond to the reduced air emissions. The needed VDL for the semi-submersible is slightly higher for the slim well drilling method. However, the drilling method has the potential to reduce the air emissions with approximately 19%.

The RDM-R method also gives the greatest reduction in VDL for the drillship considered. The conventional method requires a VDL in the range of 19 700 mT. With the RDM-method the required VDL will approximately be 16 600 mT and with the slim well drilling method the needed VDL will be about 17 100 mT. Due to the reductions in fuel consumption the air emissions will be 33% lower for the RDM-R method compared to the conventional. A 31% reduction of air emissions are expected for drillships due to the reduced mud and riser tension.

The methods have the potential to be combined and thus reduce the air emissions further. The reduction of air emissions will for the semi-submersible be in the range of 43% when the slim well and RDM-R method are combined. This corresponds to a reduction of 37 821 mT of CO_2 per year, 9 mT of CH_4 per year, 14 mT of SO_x per year and 59 mT of nmVOC per year. In addition the NO_x emissions, which are rig specific, will be significantly reduced. For drillships the combined method will allow for a reduction in air emissions of approximately 38%, which indicates a reduction of 34 078 mT of CO_2 per year, 9 mT of CH_4 per year, 13 mT of SO_x per year and 54 mT of nmVOC per year.

When associated reduced equipment weights are to be included, the air emissions may be reduced even more. The reductions of air emissions are significant for all three methods. However, the combined method will give the highest potential to reduce air emissions. As these methods allows for a smaller rigs to be used, the day rate will be lower. This is a great advantage as the reduced air emissions in that case is associated with lower costs. This will favour initiatives to implement the new technologies. However, the reduced weights and corresponding air emissions must be evaluated for each specific rig.

7. SUMMARY AND CONCLUSION

In this thesis new technologies with the potential to reduce air emissions from floating MODUs have been evaluated. One potential is to use a cleaner fuel like LNG. Another potential is to implement new drilling methods which can allow for smaller VDL and therefore smaller rig size. This will indirectly result in lower emissions. The smaller rigs typically have 8000 h.p installed as opposed to large and newer rigs with 60 000 h.p. installed. The fuel consumption is mainly dependent on rig size and positions systems, as the power requirements are increasing with size and water depth. The fuel consumption on newer generation rigs can be in the range of 135 mT per day.

LNG is the cleanest burning fossil fuel and may reduce the CO_2 emissions with 20-25% and the SO_x emissions with 90-95%. Also the NO_x emissions will be significantly reduced if LNG is to be implemented as main source of fuel. Both dedicated natural gas engines and dual fuel engines can be implemented on new builds or existing rigs. The latter may be the best solution as it has the ability to switch to diesel operation in case of low LNG supply. The availability of LNG is a concern as mobile drilling rigs constantly are moving. In the shipping industry has LNG become widely accepted and several new bunkering stations are planned or under construction. Therefore the availability of LNG may be sufficient in the next decade. However, the bunkering of LNG to a floating rig will present problems as the fluid will freeze the transfer hose and make it brittle. An alternative method which ship operators currently are considering is the portable tank method, where a preloaded tank replaces the empty on deck. This method is intended for ships next to the dock but may be used offshore to supply rigs with LNG. However, lifting operations offshore may require long waiting on weather time. Standard and procedures must be implemented before LNG could be an attractive fuel for rig operators.

The slim well drilling method and the RDM-Riserless drilling method both have a great potential to reduce required rig size. A semi-submersible with a displacement of 53 000 mT was used to estimate reduced air emissions. The reductions are significant. The RDM-R method allows for a reduction in air emissions of approximately 24% and the slim well drilling method allows for an approximately reduction of 19%. A modern drillship with a displacement of 84 000 mT will have 33% lower emissions when implementing the RDM-R method and 31% lower emissions with the slim well drilling method. The RDM-R method will in both cases allow for largest reductions. However, the reductions will vary from rig to rig, as the VDL is not linear to the displacements of the rigs.

The RDM-R method has the potential to drill slim wells and therefore the combination of drilling methods was evaluated. The combination allowed for additional reductions in weights and air emissions. The semi-submersible considered will have 43% lower air emissions if both methods are to be combined and the drillship considered will have approximately 38% reductions in air emissions. Both methods will provide lower cost and will therefore be attractive alternatives when the development is completed. The reductions are only based on mud volumes and riser tension. Therefore the reductions can be even higher if weights of

BOP, Xmas tree, mud pumps and associated equipment are to be implemented in the calculations.

The new drilling methods may be more attractive to implement than LNG, as the reduction of weight will result in less emissions and smaller day rates. However, the LNG fuel will have higher reductions of dangerous substances like SO_x and NO_x, in addition it is a low-priced fuel compared to diesel. The combination of LNG and new drilling methods may be an attractive solution to reduce the emissions further. As retrofitting old engines to LNG engines may be costly, the combination of LNG and new drilling methods may be best for new builds.

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APPENDIX A - RIG DATA FROM RIGLOGIX

All rigs that had both VDL and displacement values have been collected from RigLogix [] within the following status categories: drilling (D), workover (W), inspection (I), enroute (E), waiting on location (WoL) and ready stacked (RS).

SEMI-SUBMERSIBLES

TABLE A-1: COLLECTED DATA FOR SEMI-SUBMERSIBLES

Name of rig	Status	Delivery year	Gene-ration	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Energy Driller	D	1977	1	305	6 096	9 448	1814	20,5	-	270
Ocean Yorktown	D	1976	3	869	7 620	15 064	2 242	21	363	318
Ocean Concord	W	1975	2	610	7 620	16 872	2 722	21	290	326
Ocean Lexington	D	1976	2	762	7 620	16 901	2 468	21	363	348
ENSCO 5000	RS	1973	2	701	6 096	17 002	2 099	21	581	410
Ocean General	D	1976	2	914	7 620	17 110	2 431	21	363	493
Ocean Saratoga	W	1976	2	671	7 620	17 110	2 087	21	290	270
Atlantic star	D	1976	2	610	6 498	17 578	2 134	21	254	419
Zagreb 1	D	1977	2	450	6 096	17 660	1 633	21	308	18
Songa Mercur	D	1989	2	549	7 620	18 126	9 285	21	290	596
ENSCO 6000	RS	1986	2	1 219	3 658	18 569	1 230	21	363	115
Noble Therald Martin	D	1977	2	1 219	7 620	19 057	2 499	19,75	290	419
Nanhai VII	D	1977	2	914	6 096	19 610	3 000	21	218	270
Ocean Winner	WoL	1976	3	1219	7 620	19 637	3 556	21	435	333
Ocean Worker	W	1982	3	1 219	7 620	19 637	4 017	21	435	429
Songa Venus	RS	1975	2	457	7 620	19 684	1 727	21	-	314
Istiglal	D	1993	2	700	6 000	19 971	3 402	21	464	409

Name of rig	Status	Delivery year	Gene-ration	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Alaskan star	D	1976	2	510	7 620	20 480	2 087	21	218	407
Olinda Star	D	1983	2	1 097	7 498	20 548	3 992	21	-	541
Nanhai II	D	1974	2	305	7 620	20 932	3 028	21	218	293
Naga 1	D	1974	2	305	9 144	21 118	2 331	21	218	394
Scarabeo 3	D	1975	2	500	7 925	21 779	2 540	21	290	348
Scarabeo 4	D	1975	2	545	9 144	21 779	2 540	21	290	348
Falcon 100	RS	1974	2	762	7 620	21 962	3 047	21	-	615
Kan Tan III	D	1984	2	201	6 096	21 990	2 693	21	145	334
Sedco 706	D	1976	2	2 000	7 620	22 686	2 449	21	871	327
Sedco 707	D	1976	4	1 981	7 620	22 713	4 253	21	726	641
Petrobras XVI	D	1984	2	457	7 620	23 005	2 313	-	290	400
Petrobras XVII	D	1984	2	701	7 620	23 005	2 313	21	363	400
Ocean Ambassador	D	1975	2	335	7 620	23 020	2 540	21	290	420
Noble Driller	D	1976	2	1 524	9 144	23 220	2 722	21	-	254
Sedco 702	D	1973	3	1 981	7 620	23 342	2 903	21	871	395
Doo Sung	E	1984	3	457	7 620	23 393	3 999	21	290	328
Sedco 704	D	1974	2	305	7 620	23 886	2 901	21	290	382
GSF Grand Banks	D	1984	2	457	7 620	24 055	5 693	21	290	392
Atwood Hunter	RS	1981	3	1 524	8 534	24 067	3 616	21	581	516
Essar Wildcat	D	1977	2	396	7 620	24 099	2 253	21	290	239
Songa Trym	D	1976	2	400	7 620	24 166	3 048	21	290	360
Borgny Dolphin	E	1977	2	533	7 620	24 184	3 201	21	290	281
Byford Dolphin	W	1974	2	457	6 096	24 280	3 069	21	290	633
GSF Rig 140	D	1983	3	457	7 620	24 309	3 447	21	435	737
ENSCO 7500	WoL	2000	5	2 438	10 668	24 314	7 711	21	-	1 936

Name of rig	Status	Delivery year	Gene-ration	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Ocean Nomad	D	1975	2	366	7 620	24 508	2 998	21	218	310
Sedco 711	D	1982	3	549	7 620	24 792	3 536	21	363	312
Sedco 712	D	1983	3	488	7 620	25 320	3 989	21	363	382
Nanhai V	D	1983	3	457	7 620	25 356	3 938	21	290	399
WilPhoenix	D	1982	3	366	7 620	25 419	2 507	21	290	277
Nanhai VI	D	1982	3	457	7 620	25 480	2 703	21	218	290
ENSCO 5001	D	1975	4	1 981	7 620	25 577	3 375	21	866	844
Petrobras X	D	1982	3	1 189	8 998	25 585	3 336	21	435	477
GSF Arctic III	D	1984	3	549	7 620	25 642	2 771	21	290	352
Ocean Guardian	D	1985	3	457	7 620	25 741	3 556	21	363	301
Transocean Winner	D	1983	3	457	7 620	25 791	3 899	21	290	341
Sedco 714	I	1983	3	488	7 620	25 932	3 446	21	363	334
Ocean Yatzy	W	1989	3	1 006	6 096	25 972	3 434	18,625	435	525
Kan Tan IV	D	1983	3	610	7 620	25 995	4 081	21	290	346
Ocean Princess	D	1975	2	457	7 620	26 100	3 257	21	218	370
Ocean Baroness	D	1973	5	2 438	10 668	26 298	5 588	21	1633	1 170
Bredford Dolphin	D	1980	2	457	7 620	26 575	3 400	21	290	528
Noble Homer Ferrington	RS	1985	4	2 195	9 144	26 585	3 629	18,75	726	978
GSF Rig 135	D	1983	3	853	7 620	26 796	3 447	21	435	591
Noble Max Smith	D	1999	4	2 134	7 620	27 230	3 629	21	726	2 188
Noble Amos Runner	D	1999	4	2 438	9 144	27 230	3 629	21	726	1 670
Bideford Dolphin	D	1975	2	457	6 096	27 297	3 128	20,5	363	1 049
WilHunter	W	1983	3	457	7 620	27 597	3 644	21	399	355
Ocean Vanguard	D	1982	3	457	7 620	27 663	2 898	21	290	513

Name of rig	Status	Delivery year	Gene-ration	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Deepsea Bergen	D	1983	3	457	7 620	27 958	2 835	21	290	639
M G Hulme Jr	D	1983	3	1 524	7 620	28 103	4 063	21	-	329
Nanhai VIII	D	1982	3	1 402	7 620	28 109	4 509	21	508	657
Actinia	D	1982	3	457	7 620	28 110	2 721	21	290	450
Songa Dee	D	1984	3	457	9 144	28 172	3 674	21	435	524
Transocean Legend	D	1983	3	1 067	7 620	28 300	2 599	21	435	391
Transocean Searcher	D	1983	3	457	7 620	28 301	3 049	21	290	333
Borgland Dolphin	D	1999	4	457	9 144	28 766	3 503	18,75	363	1 123
Noble Jim Thompson	D	1999	4	1 829	10 058	28 775	3 629	21	581	1 739
Lone Star	D	2010	6	2 438	7 498	29 030	5 869	21	1 134	762
Transocean Prospect	D	1983	3	457	7 620	29 080	3 399	21	290	424
Transocean Amirante	RS	1981	3	1 067	7 620	29 105	3 499	21	-	335
Atwood falcon	D	1983	3	1 524	7 620	29 369	3 992	21	435	358
Petrobras XXIII	D	1985	4	1 890	7 620	29 665	3 773	21	827	1 141
Transocean John Shaw	D	1982	3	549	7 620	29 689	3 199	21	363	414
Stena Spey	D	1983	3	457	7 620	29 796	4 149	21	363	358
Transocean Driller	D	1991	3	914	7 620	30 095	4 063	21	544	348
Heydar Aliyev	D	2003	4	914	9 144	30 194	4 400	21	-	650
Ocean Rover	D	1972	5	2 438	10 668	30 558	6 160	21	1 633	1 103
West Alpha	I	1986	4	610	6 706	30 699	5 289	21	435	760
Scarabeo 6	D	1984	3	1 097	7 620	31 506	3 353	21	290	341
Noble Paul Wolff	E	1999	4	2 804	9 144	31 701	4 990	21	871	1 460
Atwood Eagle	D	1982	3	1 524	7 620	32 395	4 536	21	435	576
Stena Don	D	2001	4	500	8 473	32 998	3 946	21	-	1 030
COSLInnovator	D	2011	6	762	7 620	33 022	4 000	21	-	860

Name of rig	Status	Delivery year	Generation	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
COSLPromoter	D	2012	6	762	7 620	33 022	4 000	21	-	450
Ocean Quest	D	1973	4	1 067	7 620	33 270	5 080	21	363	473
Ocean Star	D	1974	4	1 676	9 144	33 315	5 171	21	581	533
Ocean Victory	RS	1972	4	1 829	7 620	33 693	5 180	21	581	509
Cajun Express	D	2000	5	2 591	10 668	33 791	5 987	21	1 451	1 829
Blackford Dolphin	I	1974	5	2 134	9 144	33 871	4 500	21	1 089	795
Sedco Express	D	2000	5	2 286	7 620	34 470	5 998	21	907	1 720
Sedco Energy	RS	2000	5	2 286	10 668	34 470	5 998	21	1 089	1 717
Island Innovator	D	2012	6	762	8 000	34 509	4 082	21,25	-	650
Ocean Onyx	D	1973	2	1 829	9 144	35 562	5 080	21	726	1 097
Alpha star	D	2011	5	2 743	9 144	35 677	8 729	21	-	603
Gold Star	D	2009	5	2 743	9 327	35 677	8 729	21	1 134	1 071
Transocean Arctic	D	1986	4	500	7 620	36 199	4 469	21	145	175
COSLPioneer	D	2010	6	762	7 620	36 400	4 000	21	-	670
ODN Delba III	D	2011	6	2 743	9 144	36 651	3 879	-	1 134	2 512
Nanhai IX	D	1988	4	1 524	7 620	36 931	3 499	21	544	763
Noble Ton van Langeveld	D	1979	3	457	7 620	37 857	2 994	21	286	350
Scarabeo 7	D	2000	5	1 494	8 230	38 174	3 493	21	871	500
Centenario	D	2010	6	3 048	12 192	39 372	7 112	21	-	3 018
West Eclipse	D	2011	6	3 048	12 192	39 372	6 350	21	2 449	2 981
Paul B Loyd Jr	D	1987	4	610	7 620	39 502	4 196	21	308	506
Transocean Marianas	RS	1998	4	2 134	7 620	39 600	3 726	21	726	1 590
ODN Tay IV	D	1999	5	2 408	9 144	41 407	4 990	21	-	682

Name of rig	Status	Delivery year	Gene-ration	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Scarabeo 5	D	1990	4	2 000	8 992	41 998	4 500	21	-	1 090
GSF Development Driller II	E	2005	6	2 286	11 430	42 190	7 000	21	1 361	3 029
GSF Development Driller I	RS	2005	6	2 286	11 430	42 190	7 000	21	1 361	3 029
Ocean Valor	D	2009	6	3 048	12 192	42 411	7 348	21	1 633	2 753
Ocean Courage	W	2009	6	3 048	12 192	42 411	7 348	21	1 633	2 753
Ocean America	W	1988	4	1 524	9 144	42 544	7 500	21	581	1 237
Ocean Monarch	RS	1974	5	3 048	10 668	43 273	6 096	21	1 633	1 581
West Taurus	D	2008	6	3 048	11 430	43 400	7 000	21	1 998	2 989
Songa Delta	D	1981	3	701	7 620	43 520	3 700	21	290	999
Transocean Leader	D	1987	4	1 372	7 620	44 459	4 599	21	653	2 183
Ocean Valiant	RS	1988	4	1 829	9 144	44 693	6 400	21	581	448
GSF Celtic Sea	D	1998	4	1 753	7 620	46 173	5 080	21	-	1 316
Ocean Alliance	I	1988	4	2 438	10 668	46 366	3 910	21	581	474
Transocean Polar Pioneer	I	1985	4	500	7 620	46 440	4 460	21	-	983
Atwood Condor	D	2012	6	3 048	12 192	46 500	8 000	21	1 633	3 300
Ocean Confidence	E	2001	5	3 048	10 668	47 047	5 996	21	1 633	1 239
Scarabeo 9	D	2010	6	3 658	15 240	48 019	7 348	21	-	1 306
West Venture	D	2000	5	1 829	9 144	49 310	5 500	21	-	2 454
West Pegasus	D	2011	6	3 048	10 668	49 532	6 200	21	1 633	2 000
Henry Goodrich	D	1985	4	610	9 144	49 706	4 999	-	-	525
Atwood Osprey	D	2011	6	2 499	10 668	49 750	8 992	21	1 633	2 536
Deepsea Atlantic	D	2009	6	3 048	11 430	49 986	7 500	21	1 450	380
Leiv Eiriksson	D	2001	5	2 499	9 144	52 597	6 250	21	1 089	1 668

Name of rig	Status	Delivery year	Gene-ration	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Eirik Raude	D	2001	5	3 048	9 144	52 597	6 250	21	1 451	1 668
Noble Danny Adkins	D	2009	6	3 658	11 278	52 597	6 713	22	1 134	2 035
Jack Bates	I	1986	4	1 829	9 144	52 843	6 109	21	-	636
Maersk Deliverer	D	2010	6	3 048	9 144	53 000	13 500	21	1 361	3 005
Maersk Developer	D	2009	6	3 048	9 144	53 000	13 500	21	1 361	3 005
Maersk Discoverer	D	2009	6	3 048	9 144	53 000	13500	21	1 361	3 005
Development Driller III	I	2009	6	2 286	11 430	53 717	13 500	21	1 361	1 876
Deepsea Stavanger	D	2010	6	3 048	11 430	55 066	7 500	21	1 450	780
Noble Jim Day	D	2010	6	3 658	11 278	55 429	7 257	21	1 134	2 035
Transocean Barents	D	2009	6	3 048	10 668	64 600	7 000	21	1 453	1 700
Transocean Spitsbergen	D	2009	6	3 048	10 668	64 600	7 000	21	1 453	1 700

DRILLSHIPS

TABLE A-2: COLLECTED DATA FOR DRILLSHIPS

Name of rig	Status	Delivery year	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
PetroSaudi Discoverer	RS	1977	457	6 096	11 998	5 326	21	290	529
PetroSaudi Saturn	D	1983	1 158	7 620	15 572	6 884	-	-	108
Aban Abraham	D	1976	2 012	7 620	16 485	7 620	21	363	464
SC Lancer	D	1977	1 500	6 000	17 792	9 192	18,625	435	378
Noble Phoenix	D	1979	1 524	7 620	18 499	7 999	18,625	435	385
Peregrine I	RS	1983	1 585	7 620	19 692	7 500	18,625	544	472
Jasper Explorer	RS	1973	1 524	7 620	20 140	6 550	21	726	712
Noble Duchess	D	1975	457	7 620	21 966	11 554	21	218	793
Energy Searcher	D	1982	762	7 620	22 461	9 299	21	363	376
Discoverer Seven Seas	D	1976	2 134	7 620	22 887	8 634	21	726	731
Deepwater Expedition	D	1999	2 591	9 144	24 125	7 709	21	1 089	1 718
Deepwater Navigator	D	1971	2 195	9 144	24 929	11 162	21	871	729
Noble Roger Eason	D	1977	2 195	6 096	25 154	11 229	21	581	668
Ocean Clipper	D	1977	2 395	7 620	25 406	10 473	21	871	1 245
Aban Ice	D	1975	610	6 096	26 155	10 810	20	218	671
Discoverer India	D	2010	3 658	12 192	40 000	20 000	21	2 177	3 180
ENSCO DS-1	D	1999	3 048	9 601	42 014	17 700	21	-	575
ENSCO DS-2	D	2000	3 048	9 601	42 014	17 700	21	1 633	586
GSF Explorer	D	1998	2 377	9 144	50 782	21 349	21	907	1 033
Noble Globetrotter I	D	2011	3 048	12 192	53 977	16 329	21	1 633	2 385
Noble Globetrotter II	D	2013	3 658	12 192	53 977	16 329	21	1 633	2 385
Belford Dolphin	D	2000	3 048	12 000	66 043	11 340	21,5	1 451	2 496

Name of rig	Status	Delivery year	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
GSF CR Luigs	D	2000	3 048	10 668	68 039	25 999	22	-	2 109
Bolette Dolphin	E	2014	3 658	12 192	68 946	18 144	-	-	2 800
GSF Jack Ryan	D	2000	3 048	10 668	69 046	25 999	22	1 361	2 109
Rowan Renaissance	D	2014	3 658	12 192	69 899	20 000	21,25	1 814	3 000
Ocean BlackHawk	I	2014	3 658	12 192	70 455	19 999	21	1 633	3 737
ENSCO DS-3	D	2010	3 658	12 192	87 090	20 000	21	1 633	2 660
ENSCO DS-5	D	2011	3 658	12 192	87 090	20 000	21	1 633	-
ENSCO DS-6	D	2012	3 658	12 192	87 090	20 000	21	1 633	-
ENSCO DS-4	I	2010	3 658	12 192	87 090	20 000	21	1 633	-
Maersk Viking	I	2014	3 658	12 192	87 090	18 144	21	-	1 910
Discoverer Clear Leader	D	2009	3 658	12 192	89 286	20 000	21	2 177	3 180
Discoverer Inspiration	D	2009	3 658	12 192	89 286	20 000	21	2 177	318
Norbe VIII	D	2011	3 048	9 144	92 533	22 050	21	1 451	3 222
Discoverer Spirit	D	2000	3 048	10 668	94 351	19 994	21	-	2 449
Pacific Bora	D	2010	3 048	11 430	95 980	20 000	21	-	2 477
Pacific Khamsin	D	2013	3 658	12 192	95 980	21 092	21	-	2 477
Pacific Mistral	D	2011	3 658	11 430	95 980	20 000	21	1 451	2 477
Pacific Santa Ana	D	2011	3 658	12 192	95 980	20 000	21	-	2 565
Petrobras 10000	D	2009	3 658	11 430	95 999	20 000	21	-	2 253
Stena Carron	D	2008	3 048	10 668	96 000	20 000	21	1 134	2 400
Saipem 10000	D	2000	3 048	9 144	96 435	19 996	21	1 451	1 956
Stena Forth	D	2009	3 048	10 668	97 000	20 000	21	-	-
Deepwater Discovery	D	2000	3 048	9 144	97 976	19 994	21	1 451	2 385
Stena DrillMax ICE	D	2012	3 048	10 668	98 000	17 500	21	1 134	-

Name of rig	Status	Delivery year	Water depth capacity [m]	Drilling depth capacity [m]	Operating displacement [mT]	VDL [mT]	Riser size [in.]	Riser tension [mT]	Liquid mud capacity [m^3]
Amaralina Star	D	2012	3 048	12 192	99 661	20 000	21	1 451	1 206
Laguna Star	D	2012	3 048	12 192	99 661	20 000	21	1 451	1 206
Deepwater Asgard	D	2014	3 658	12 192	101 999	11 000	21	1 814	3 192
Deepwater Invictus	I	2014	3 658	12 192	101 999	11 000	21	1 814	3 192
Carolina	D	2011	3 048	12 192	102 809	20 000	21	1 451	-
Deepwater Frontier	D	1999	3 048	9 144	103 000	20 799	21	1 161	810
Atwood Advantage	W	2013	3 658	12 192	104 000	23 000	21	1 814	2 871
Deepwater Millennium	D	1999	3 048	9 144	104 185	19 994	21	1 161	2 172

APPENDIX B – VESSEL POWER

The data for are collected from RigLogix [] and Offshore []. In addition are the rig fleets from Transocean [] and Diamond Offshores [] are used to find vessel power for some of the drillships.

SEMI-SUBMERSIBLES

TABLE B-1: INSTALLED POWER, THRUSTER POWER AND FUEL CONSUMPTION FOR SEMI-SUBMERSIBLES

Name of rig	Water depth capacity [m]	Operating displacement [mT]	Installed power [h.p.]	Thruster power [h.p.]	Thruster power [%]	30% fuel consumption [mT/yr]	45% fuel consumption [mT/yr]
Sedco 704	305	23 886	15 800	6 400	41	5 666	8 499
Songa Trym	400	24 166	8 800	3 400	39	3 156	4 734
Ocean Nomad	366	24 508	9 500	-	-	3 407	5 110
Sedco 711	549	24 792	9 700	6 400	66	3 479	5 218
Sedco 712	488	25 320	9 600	6 000	63	3 443	5 164
WilPhoenix	366	25 419	10 608	-	-	3 804	5 706
GSF Arctic III	549	25 642	10 460	-	-	3 751	5 627
Ocean Guardian	457	25 741	13 000	-	-	4 662	6 993
Transocean Winner	457	25 791	12 240	6 400	52	4 389	6 584
Sedco 714	488	25 932	9 700	6 000	62	3 479	5 218
Ocean Princess	457	26 100	9 800	-	-	3 514	5 272
Bideford Dolphin	457	27 297	8 800	-	-	3 156	4 734
WilHunter	457	27 597	13 280	-	-	4 762	7 144
Ocean Vanguard	457	27 663	9 400	-	-	3 371	5 056
Deepsea Bergen	457	27 958	13 800	7 880	57	4 949	7 423
Songa Dee	457	28 172	14 280	6 800	48	5 121	7 682
Transocean Searcher	457	28 301	12 900	-	-	4 626	6 939

Name of rig	Water depth capacity [m]	Operating displacement [mT]	Installed power [h.p.]	Thruster power [h.p.]	Thruster power [%]	30% fuel consumption [mT/yr]	45% fuel consumption [mT/yr]
Borgland Dolphin	457	28 766	8 800	3 350	38	3 156	4 734
Transocean Prospect	457	29 080	11 732	6 264	53	4 207	6 311
Transocean John Shaw	549	29 689	8 800	-	-	3 156	4 734
West Alpha	610	30 699	16 200	-	-	5 810	8 714
Stena Don	500	32 998	42 242	26 550	63	15 149	22 723
COSLInnovator	762	33 022	41 094	25 734	63	14 737	22 106
COSLPromoter	762	33 022	41 094	25 734	63	14 737	22 106
Island Innovator	762	34 509	38 922	30 882	79	13 958	20 937
Transocean Arctic	500	36 199	11 760	-	-	4 217	6 326
COSLPioneer	762	36 400	41 094	25 734	63	14 737	22 106
Noble Ton van Langeveld	457	37 857	10 200	-	-	3 658	5 487
Paul B Loyd Jr	610	39 502	38 400	-	-	13 771	20 656
Scarabeo 5	2 000	41 998	51 500	25 200	49	18 469	27 703
Songa Delta	701	43 520	16 888	-	-	6 056	9 084
Transocean Leader	1 372	44 459	17 760	14 000	79	6 369	9 554
Transocean Polar Pioneer	500	46 440	19 450	-	-	6 975	10 463
West Venture	1 829	49 310	43 000	34 800	81	15 421	23 131
Deepsea Atlantic	3 048	49 986	59 000	21 840	37	21 158	31 738
Eirik Raude	3 048	52 597	61 200	44 220	72	-	32 921
Leiv Eiriksson	2 499	52 597	61 200	44 220	72	-	32 921
Transocean Barents	3 048	64 600	56 500	48 000	85	-	30 393
Transocean Spitsbergen	3 048	64 600	56 500	48 000	85	-	30 393
West Hercules	3 048	-	50 400	36 992	73	-	27 111
West Phoenix	3 048	-	50 500	35 880	71	-	27 165

DRILLSHIPS

TABLE B-2: INSTALLED POWER, THRUSTER POWER AND FUEL CONSUMPTION FOR DRILLSHIPS

Name of rig	Water depth capacity [m]	Operating displacement [mT]	Installed power [h.p.]	Thruster power [h.p.]	Thruster power [%]	45% fuel consumption [mT/yr]
Discoverer Seven Seas	2 134	22 887	21 520	15 000	70	11 576
Deepwater Expedition	2 591	24 125	26 000	22 530	87	13 986
Deepwater Navigator	2 195	24 929	24 000	16 800	70	12 910
Ocean Clipper	2 395	25 406	17 500	-	-	9 414
Discoverer India	3 658	40 000	54 069	44 256	82	29 085
GSF Explorer	2 377	50 782	36 780	-	-	19 785
GSF CR Luigs	3 048	68 039	46 320	-	-	24 917
GSF Jack Ryan	3 048	69 046	46 320	40 500	87	24 917
Ocean BlackHawk	3 658	70 455	60 345	40 200	67	32 461
Discoverer Clear Leader	3 658	89 286	56 322	42 000	75	30 297
Discoverer Spirit	3 048	94 351	89 241	42 000	47	48 005
Petrobras 10000	3 658	95 999	56 322	-	-	30 297
Stena Carron	3 048	96 000	59 508	44 232	74	32 011
Deepwater Discovery	3 048	97 976	57 530	44 220	77	30 947
West Navigator	2 438	100 979	43 000	24 480	57	23 131
Deepwater Frontier	3 048	103 000	51 413	32 160	63	27 656
Deepwater Millennium	3 048	104 185	46 797	32 160	69	25 173
Deepwater Pathfinder	3 048	104 206	51 413	32 400	63	27 656

AVERAGE VALUES

TABLE B-3: AVERAGE VALUES OF INSTALLED POWER, THRUSTER POWER AND FUEL CONSUMPTION

Type of rig	Displacement range [mT]	No. of data points	Operational displacement [mT]	Installed power [h.p.]	30% fuel consumption [mT/yr]	45% fuel consumption [mT/yr]	No. of data points	Thruster power [h.p]	Thruster power [%]
Semisub	20 000 - 29 999	20	26 591	11 050	3 963	5 944	10	5 889	52
Semisub	30 000 - 49 999	13	38 621	32 262	11 570	17 354	8	26 079	67
Semisub	50 000 - 64 999	4	58 598	58 850	-	31 657	4	46 110	79
Drillship	20 000 - 30 000	4	24 337	22 255	-	11 972	3	18 110	75
Drillship	40 000 - 89 999	6	64 601	50 026	-	26 910	4	41 739	78
Drillship	90 000 - 104 999	7	100 335	52 283	-	28 125	6	34 942	67

APPENDIX C - MUD VOLUME CALCULATIONS

The volume of a cylinder is:

$V = \left(\frac{\pi}{4}\right) \cdot D^2 \cdot h$, where;

V is the volume [m^3]
D is the (inner) diameter of riser/casing/hole [m]
h is the length of the different riser/casing/hole sections

MUD VOLUMES INSIDE RISERS AND DDS

TABLE C-1: CALCULATED MUD VOLUMES INSIDE RISERS AND DDS

Risers and DDS					
Size	OD [mm]	2t [mm]	ID [m]	h [m]	V [m3]
6-5/8	168,3	28,3	0,140	2 750	42
16	406,4	38,1	0,368	2 750	293
21	533,4	40,6	0,493	2 750	524

MUD VOLUMES IN WELLS

CONVENTIONAL WELL

TABLE C-2: TOTAL MUD VOLUME INSIDE THE CASING STRINGS IN THE CONVENTIONAL WELL

Conventional well						
Volume no.	Casing size ["]	OD [mm]	2t [mm]	ID [m]	h [m]	V [m^3]
V1	18-5/8	473,08	22,10	0,451	750	120
V2	13-3/8	339,72	24,38	0,315	3 000	234
V3	9-5/8	244,48	30,22	0,214	3 750	135
					Total	489

TABLE C-3: TOTAL MUD VOLUME INSIDE THE CONVENTIONAL WELL HOLE

Conventional well				
Volume no.	Hull size ["]	D [m]	h [m]	V [m^3]
V4	16	0,406	2 250	292
V5	12-1/4	0,311	750	57
V6	8-1/2	0,216	500	18
			Total	367

SLIM WELL

TABLE C-4: TOTAL MUD VOLUME INSIDE THE CASING STRINGS IN THE SLIM WELL

Slim well						
Volume no.	Casing size ["]	OD [mm]	2t [mm]	ID [m]	h [m]	V [m^3]
V7	13-3/8	339,72	24,38	0,315	1 250	98
V8	9-5/8	244,48	30,22	0,214	3 750	135
					Total	233

TABLE C-5: TOTAL MUD VOLUME INSIDE THE SLIM WELL HOLE

Slim well				
Volume no.	Hull size ["]	D [m]	h [m]	V [m^3]
V9	12-1/4	0,311	2 500	190
V10	8-1/2	0,216	500	18
			total	208

TOTAL MUD VOLUMES

TABLE C-6: TOTAL MUD VOLUME NEEDED TO DRILL THE WELLS

Drilling method	Mud volumes [m3]			Total volume of mud [m^3]
	In riser/DDS	In casing strings	In well hole	
Riserless	42	489	367	898
Slim well	293	233	208	734
Conventional	524	489	367	1 380
Combination	42	233	208	483

APPENDIX D – AVERAGE AND ESTIMATED VALUES

TABLE D-1: AVERAGE VALUES AND ESTIMATED VALUES FROM COLLECTED DATA

Type of rig	Displacement range [mT]	No. of data points	Operational displacement [mT]	VDL [mT]	No. of data points	Riser tension [mT]		No. of data points	Liquid mud capacity [mT]			
						21"	16"		conventional	RDM-R	slim well	combination
Semisub	0 - 14 999	1	9 448	1 814	0	-	-	1	405	263	215	142
Semisub	15 000 - 19 999	14	18 064	2 573	13	347	201	14	522	339	277	183
Semisub	20 000 - 24 999	25	23 074	3 097	21	352	205	25	620	403	328	217
Semisub	25 000 - 29 999	36	27 307	3 538	34	443	257	36	908	590	481	318
Semisub	30 000 - 34 999	16	32 845	4 826	11	759	440	16	1 278	831	677	447
Semisub	35 000 - 39 999	11	37 585	4 958	8	716	416	11	1 724	1 121	914	603
Semisub	40 000 - 49 999	21	45 241	6 132	14	1 286	746	21	2 543	1 653	1 348	890
Semisub	50 000 - 64 999	10	55 745	8 833	9	1 341	778	10	2 921	1 899	1 548	1 022
Drillship	0 - 14 999	1	11 998	5 326	1	290	168	1	794	516	421	278
Drillship	15 000 - 19 999	5	17 608	7 839	4	444	258	5	638	414	338	223
Drillship	20 000 - 29 999	9	23 691	9 713	8	572	332	9	1 274	828	675	446
Drillship	30 000 - 39 999	0	-	-	0	-	-	0	-	-	-	-
Drillship	40 000 - 59 999	6	47 127	18 235	5	1 597	927	6	2 537	1 649	1 344	888
Drillship	60 000 - 79 999	3	69 767	19 381	4	1 565	908	5	3 755	2 440	1 990	1 314
Drillship	80 000 - 89 999	7	87 717	19 735	4	1 633	948	3	3 875	2 518	2 053	1 356
Drillship	90 000 - 99 999	14	96 538	20 045	8	1 372	796	10	3 699	2 404	1 960	1 295
Drillship	100 000-104 999	3	103 331	20 264	6	1 536	892	4	4 286	2 786	2 271	1 500