CHALMERS

Regasification Vessels with Power Generation

Requirements and recommendations for gas power generation vessels

Master of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2012
Report No. X-12/278

A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

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Abstract

Today, the natural gas consumption is substantially increasing and the forecast for the future indicates that the consumption will keep on increasing. The result of this is that new innovative solutions are introduced to satisfy the demand from the customers. One of the latest ideas is to use a so-called FSRU GTW-unit, which is a floating unit that contains all the necessary process steps to produce electricity from LNG. This means that the unit will import LNG from a shuttle tanker and export electricity to shore.

The objective with this thesis is to identify the hazards relevant to an FSRU GTW-concept and present requirements and recommendations. The hazards in question are those that can risk the safety of personnel, operability and structural integrity. The requirements and recommendations are based on an evaluation of how the hazards are addressed in existing rules and regulations provided by DNV and IMO. This can then be used as input to future rule development.

In order to present relevant requirements and recommendations, it is essential to study existing rules in order to find what is applicable on an FSRU GTW-unit, and if there are any gaps or contradictions that need consideration. The rules and regulations that are thoroughly analysed are those provided by DNV and IMO. This analysis is preceded by a thorough study of related technologies and an evaluation of what hazards that are explicitly related to an FSRU GTW-unit. This is done according to IMO's FSA-methodology with the aid of experts in the fields of electrical equipment, rotating machinery and offshore gas projects at DNV in Hövik, Norway. The FSA-methodology is a risk-based approach used for developing rules and the parts used in this work are those concerning the identification of hazards.

It is concluded that there are contradictions and gaps in DNV's present rules and regulations when applying these on an FSRU GTW-unit. It is, for example, stated by IMO in the IGC Code that boilers, machinery and such should be segregated from the storage facilities. This imposes a problem since the power plant, which consists of such equipment, will most probably be mounted on top of the storage tanks. Furthermore, there exist no explicit rules or design guidelines concerning electrical transmission through a turret. These kinds of contradictions and gaps show that there is a need for assembling various applicable rules and design guidelines together with additional requirements in a Classification Note for regasification vessels with power generation.

Keywords: FSRU GTW, gas to wire, hazard identification, LNG, power generation, risk-based design, rule development.

Preface

This thesis is a part of the requirements for the master's degree in Naval Architecture at Chalmers University of Technology, Gothenburg. This master's thesis has been carried out from January to June 2012 at Det Norske Veritas, Høvik, Norway, at the Department of Marine & Process Systems. The work at DNV's headquarters has been very stimulating and all the experienced personnel have been a great resource during the project.

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Gothenburg, June, 2012
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List of abbreviations

AC	Alternating Current
API	Application Programming Interface
CC	Combined-cycle plant
CCNR	Central Commission for the Navigation of the Rhine
CO_2	Carbon dioxide
DC	Direct Current
DNV	Det Norske Veritas
ESD	Emergency Shutdown
FSA	Formal Safety Assessment
FSRU	Floating Storage and Regasification Unit
FSRU GTW	Floating Storage and Regasification Unit with power generation
GM	Metacentric height
GT	Gas turbine power plant
GTW	Gas To Wire
HAZID	Hazard Identification
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HRSG	Heat Recovery Steam Generator
IGC	International Gas Carrier
IMO	International Maritime Organization
ISDS	Integrated Software-Dependent System
ISO	International Organisation for Standardization
LNG	Liquefied Natural Gas
LNGC	Liquefied Natural Gas Carrier
OCIMF	Oil Companies International Marine Forum
OS	Offshore Standard
RP	Recommended Practice
SOLAS	Safety Of Life At Sea
ST	Steam turbine
ST-RC	Reheat steam turbine

1. Introduction

Floating storage and a regasification unit with power generation, FSRU GTW, is a new idea of how to generate electricity with natural gas as fuel in areas where it otherwise might be difficult to get power. The FSRU GTW-unit is a novel concept, which means that existing rules and regulations need to be reviewed in order to be fully applicable.

1.1. Background

According to the U.S. Energy Information Administration [1] the demand for natural gas increases every year and therefore the technology has to be improved to satisfy the demand from the market. The development of the world's natural gas consumption can be seen in Fig. 1. The sources of natural gas are not necessarily located near the consuming area or in an area with an available pipeline system, according to Charpentier [2]. Therefore, there is a need to find a way of transporting the energy to these areas. The gas can be transported from the well either as natural gas in pipelines or as liquefied natural gas, LNG. The transportation of LNG instead of natural gas is, in certain circumstances, more convenient and offers the possibility of distributing the gas to markets all around the world without any transoceanic pipelines. It also enables a wider range of feasible regions where LNG can be delivered.

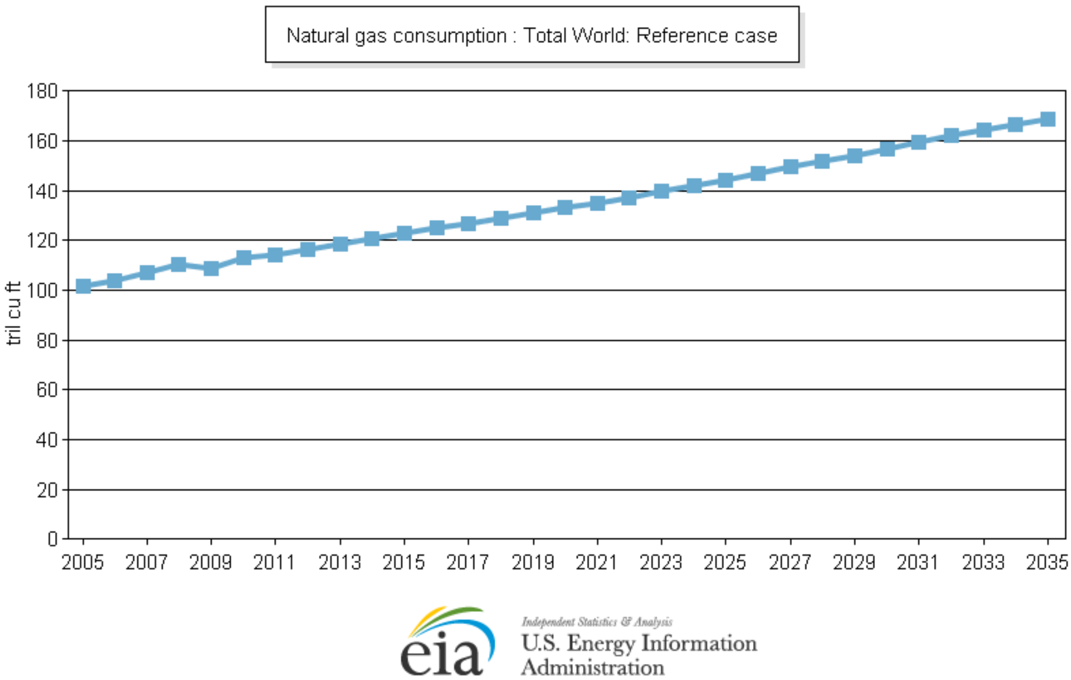

Fig. 1. The graph shows the natural gas consumption outlook [1].

Today, LNG is transported to a regasification plant, which can be located on land or at sea, where the liquefied gas is vapourized. The offshore application converts the liquid to gas that is then transported ashore with the use of a pipeline. These offshore units are called Floating Storage and Regasification Units, FSRU, as described by DNV [3][4].

According to DNV [3], the transportation of gas through pipelines is not possible in all areas because of insurmountable challenges such as the distance between source and consumer, economics, or the lack of infrastructure, often where there is also a great need for power supply. Using a pipeline system also requires a compliant government in the supplying country or in a transit country. For example, there are governments that more or less annually stop the flow through their pipelines for different reasons. This will of course affect the consuming countries.

As explained above there are markets where there are no pipeline services available and there are areas where the infrastructure is so bad that there are few possibilities of moving and/or generating electricity. To solve this problem, floating power plants that can be placed near the coastline in an area in need of electric power have been discussed. This can be used both in developing countries but also countries that have suffered a natural catastrophe such as flooding, earthquakes, etc. It may also be relevant for seasonal or short- term applications where the power demand is temporarily increased.

According to Eskola [5], the society offers floating power plants that use different types of petroleum, but currently no natural gas driven unit with regasification equipment exists. The concept would be an FSRU in combination with the concept Gas to Wire, GTW. The GTW-concept is, as described by Watanabe et al. [6], when electricity is produced from gas directly from the source and then exported through a cable to the consumer. The combined FSRU GTW-concept, however, produces electricity from LNG delivered from a shuttle tanker. The use of this FSRU GTW-concept has been widely discussed since it would give a great opportunity to move energy from one place in the world to another. If it could replace an onshore-based coal-fired power plant it would also mean a great reduction of CO_2 emissions since a natural gas fuelled power plant, according to Olajire [7], emits half as much CO_2 as a coal-fired one does per MW.

The environmental impact of the concept is an important issue in today's society where sustainability is a key issue. A floating power supply unit will impact the nearby environment less than a land-based facility. This is because there is no need for a big construction site with its entire infrastructure, for example. pipelines for transporting the natural gas and roads for the site workers. However, sustainability does not only consider environmental aspects, but also our society and its economy. Electrical power is an essential part of today's societies and of the economic framework. Therefore, it is important that energy supply can be maintained even during critical situations, for example natural disasters. In these situations, where the power is impaired, an FSRU GTW-unit can help to meet the power demand and consequently preserve progress in our society without interruption of essential parts of the local industry.

When designing a novel technology like this, the approach more and more used today is to apply goal-based regulations instead of prescriptive ones, according to Papanikolaou [8]. Examples taken from Hoppe [9] for how goal-based and prescriptive regulations can be expressed are as follows; "People must be prevented from falling over the edge of a cliff" and "You must install a 1metre high rail at the edge of the cliff". The first example is the goal-based regulation and as can be seen, this way of formulating regulations offers much more room for innovative ideas of how to handle safety and environmental issues. Prescriptive regulations are mostly based on previous experience and, according to Skjong [10], there is a risk that prescriptive regulations become out of date and therefore no longer relevant, since new technology is developed faster than experience can be gained. Goal-based or risk-based design is the methodology often used by the classification societies when developing new rules. This approach can generate more sustainable rules and regulations.

If the FRSU GTW-concept is realized and new rules are developed, it would be the solution to many of the problems that have been discussed above and hopefully give a better and more sustainable energy sector.

1.2. Objectives and limitations

The objective with this thesis is to identify the risks relevant to an FSRU GTW-concept and present requirements and recommendations based on an evaluation of how these risks are handled in existing rules and regulations. The main rules and design guidelines that are to be reviewed are the IGC Code, the DNV Classification Note No. 61.3 for regasification vessels and DNV's Rules for Classification of Ships. This will provide a basis for future development of rules for an FSRU GTW-unit.

As the objective implies, the project is limited to the first and last step of the Formal Safety Assessment method, FSA; hazard identification, HAZID, and requirements and recommendations. The FSA-methodology is thoroughly described in Appendix A.

To perform a HAZID, the project needs to have substantial knowledge about the FSRU GTW-unit. Therefore, a thorough technical and theoretical literature study is carried out concerning the unit. However, since it consists of numerous different technologies and complex process systems, these studies could be extremely wide and extensive. Therefore, the studies of these systems and technologies are limited to a level that provides the project with relevant information to be able to perform a HAZID with results that can be further analysed against existing rules and regulations. Further limitations concerning the technologies to study are set during the project and are explained accordingly.

1.3. Methodology

In order to present relevant requirements and recommendations that can be used as input to future rule development, it is essential to study existing rules in an attempt to find what is applicable on an FSRU GTW-unit, and if there are any gaps or contradictions that need consideration.

The method used for fulfilling the objectives of the thesis is a risk-based design, an approach that is more and more used today [8]. The reason for this is that since economic and environmental interests drive technology towards more innovative ideas, it is difficult to use prescriptive regulations. The solution is to apply a risk-based design, which leaves more room for innovative ideas and still reaches the same level of safety. More precisely, it is IMO's FSA-methodology [11] that is used in this project. This thesis is limited to the first and last step of an FSA, i.e. a HAZID, and requirements and recommendations. The other steps as well as a more thorough description of an FSA can be seen in Appendix A. Furthermore, an example of how the method is used can also be seen in this appendix.

In Fig. 2, the working process for fulfilling the objectives is visualized and here it can be seen that the work can be divided into four main parts:

- A comprehensive literature study of the various technologies and systems of an FSRU GTW-unit for gaining substantial knowledge about the concept. This is in order to identify hazards associated with the unit, which is done in the next step.
- A HAZID executed by the authors with the aid of experts in the fields of electrical equipment, rotating machinery and offshore gas projects at DNV. The aim of this step is to identify additional hazards of an FSRU GTW-unit compared to an FSRU.
- A thorough analysis of existing rules and regulations in order to find what is applicable on an FSRU GTW-unit as well as to find gaps and contradictions therein. The rules and regulations the authors focus on are DNV's Rules for Classification of Ships and IMO's International Gas Carrier Code.
- Present requirements and recommendations based on the results of the preceding steps. This will provide a basis for future development of rules for an FSRU GTW-unit.

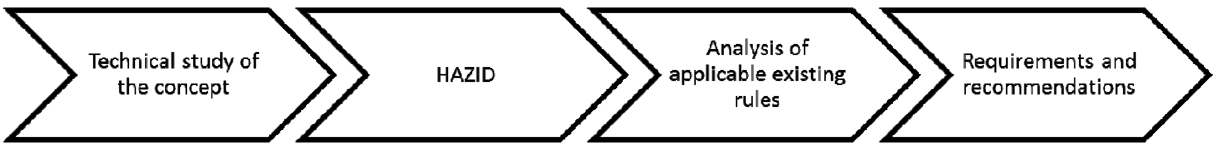

Fig. 2. The four main steps of this thesis.

2. Presentation of an FSRU GTW-unit

An FSRU GTW-concept is an FSRU that imports LNG and exports electricity instead of gas to a consumer. When discussing a GTW-concept the export product is the same but the import product is natural gas directly from the source instead of LNG from a shuttle tanker, as described by Watanabe et al. [6]. So the differences between an FSRU GTW- and a GTW-unit are that there is a need to handle LNG and vaporize it before generating power with natural gas as fuel on an FSRU GTW-unit. An example of what an FSRU GTW-unit could look like can be seen in Fig. 3, where the blue box symbolises a power generation system. The weight of an FSRU can, for example, be around 50,000 tons and the size of the power generation system will obviously be dependent on the required power generation capacity and the size of the vessel.

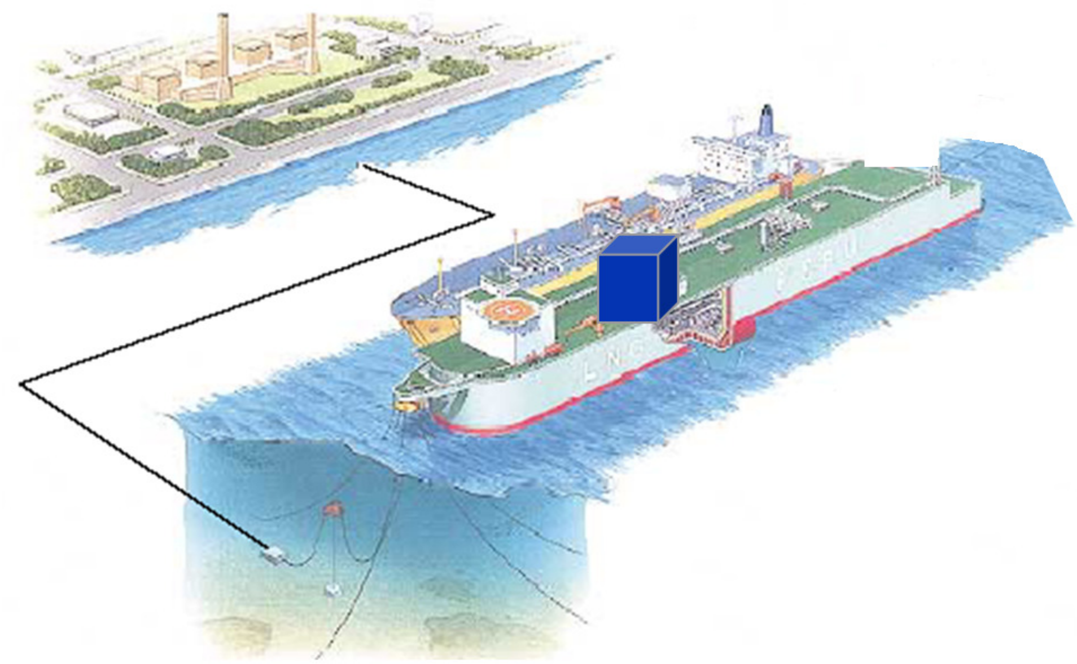

Fig. 3. An FSRU with the power plant illustrated as a blue box.

For simplicity, the FSRU GTW-unit can be described as a system with four main subsystems. These are storage and transferring, regasification, power generation and power export. These subsystems will be further described in Section 3.

One of the attractive aspects of an FSRU GTW-unit is that there is no need for export of natural gas through pipelines since it will be used for producing electricity on board. A viable approach when constructing such a unit could be to convert an existing LNG-Carrier, LNGC. However, according to DNV [3], there might be a problem in finding suitable candidates for a conversion. The available storage capacity of a conversion candidate would be an important parameter. There also has to be an economic incentive to justify the loss of an LNGC that a conversion would imply.

The areas where a floating power generation unit can be considered to operate are, according to Frangos [12] and Eskola [5], places where there is a lack of space to build a power plant on shore or no possibility of connecting to the local grid. Other reasons might be that a natural disaster has terminated the existing power supply. The concept has not yet been tried but as can be seen in the articles of Frangos [12] and Eskola [5], there are some petroleum fuelled power barges in different locations in the world. However, according to DNV [3], FSRUs have now been proposed for use as floating power stations, i.e. an FSRU GTW-unit with natural gas as the energy source.

2.1. Location of operation

For a specific area in the world there are, according to DNV [3], mainly two possible operational locations. Either the unit can be located offshore and moored to the seabed or near-shore and moored to a jetty. The most important differences between the locations are the mooring system, the environmental conditions and the way to transfer the electricity to shore. Which one of the two that is relevant is very site specific.

When an FSRU GTW-unit is located offshore, the risk of being subjected to harsh weather conditions is significantly larger compared to if the unit is located near the shore. If the FSRU GTW-unit is subjected to a storm, this will obviously affect the motions of the unit. The motions can have both a structural impact on the FSRU GTW-unit and it can also affect the liquids that are stored within the vessel. The motions can cause sloshing in the storage tanks, since the filling level of the tanks will vary due to continuous LNG consumption. Sloshing can cause structural damage inside the tanks as well as stability issues of the whole unit. The stability problem, however, is thought to be of minor significance, while the issues of structural damage imposed by impact loads are more severe. These issues would not be of major concern if the unit is located near-shore, but will be considered further on in the report.

When the unit is located offshore the most commonly used way of mooring is to have a turret-moored unit or a spread-moored unit as described by DNV [3]. A turret-moored unit could look like the vessel in Fig. 4.

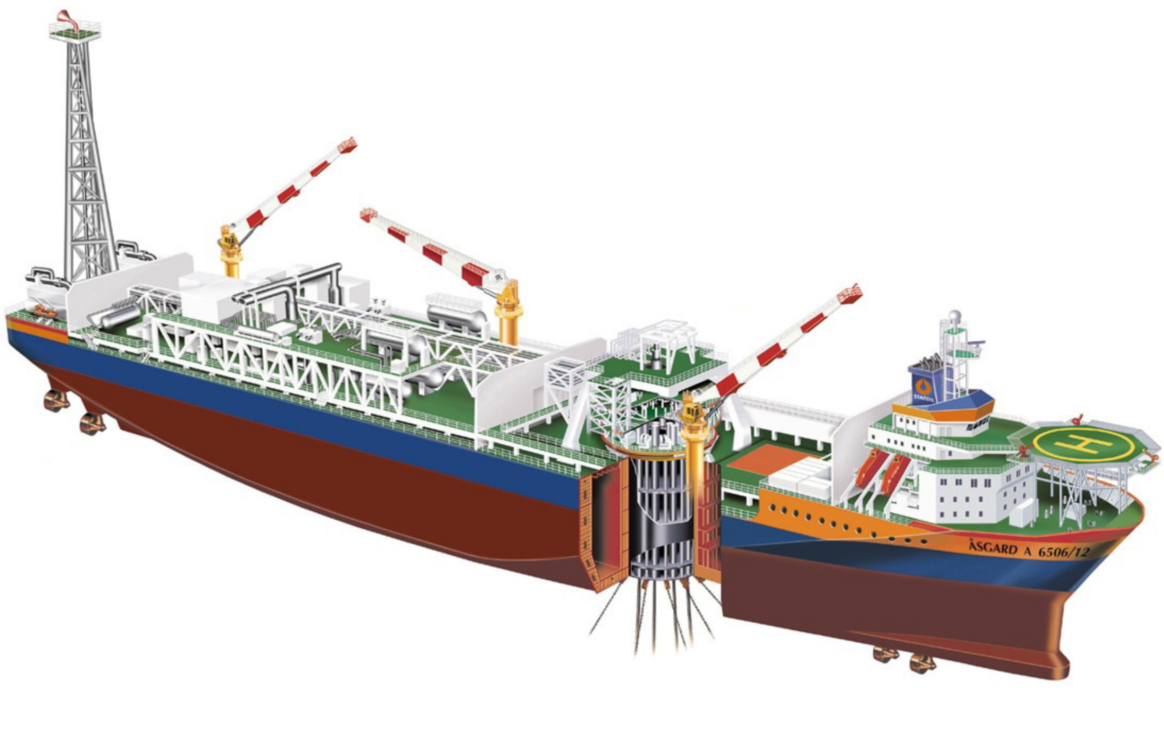

Fig. 4. Vessel moored with an internal turret system – Courtesy of Statoil.

According to DNV standards [13], the turret-moored solution is more convenient in harsh weather areas compared to a spread-moored one, since it makes it possible to rotate the vessel to a more favourable position. This minimizes the effect of wind and waves. The turret-moored unit will be forced to offload the electricity, for technical reasons, through the turret with the use of a swivel. This type of offloading equipment will be additional in comparison with a unit that is moored quayside or spread-moored. The swivel is described in Section 3.4.1.

Another major difference between the two operational locations is what type of current that is exported. If the unit is moored to a jetty and therefore located directly at the shore, the electricity will be transferred as alternating current, which is the same as the land based electricity. If the unit is located offshore it might not be possible or appropriate to transfer the electricity as alternating current due to the longer distance. If the offshore based unit will transfer the electricity as alternating current or direct current is, according to Larruskain et al. [14], dependent on the actual distance it is transported.

2.2. Existing rules and regulations

The objective with the report is to present requirements and recommendations that can be used as input for future rule development for an FSRU GTW-unit. This implies that an analysis of existing rules is needed. The main rules and design guidelines that might be applicable to an FSRU GTW-unit are the IGC Code and the DNV Classification Note No. 61.3 for regasification vessels. These are described in the following sections and will be further analysed after identifying additional hazards.

2.2.1. International Gas Carrier Code, IGC

The IGC Code [15] is an international standard for the safety of transporting liquefied gases and other substances by sea as bulk. The aim with the IGC Code is to minimize risks related to this type of cargo as far as possible with current technology and knowledge. Since this certain technology is both complex and rapidly evolving, the IGC Code should not remain static. It is therefore regularly reviewed so that it is updated with new experience and developments. It concerns all ships regardless of their size and it addresses the ship design and its equipment. This also includes ships below 500 gross tonnage as long as they carry liquefied gases, or other types of this cargo that are covered by the IGC Code, and that have a vapour pressure exceeding 2.8 bar at a temperature of 37.8 degrees Celsius.

The hazards that are covered by the IGC Code are fire, toxicity, corrosivity, reactivity, low temperature and pressure. The specific solutions required by the IGC Code are possible to fulfil by other solutions as long as they have an equivalent level of safety as the specific solution that is required by the IGC Code. This code is developed to address gas carriers and not FSRUs. This suggests that there might be conflicts when applying the IGC Code on an FSRU GTW-unit.

2.2.2. Regasification vessels

FSRUs are a relatively novel technology and therefore DNV does not yet have its own section for this type of vessel in DNV's Rules for Classification of Ships. However, DNV has created a Classification Note [4], which is applicable for all vessels engaged in regasification operations. This Note explains requirements for classification of regasification systems and offloading systems for natural gas through a submerged turret buoy offshore or through dedicated gas unloading manifolds.

It works as an addition to the DNV Rules for Classification of Ships as long as the vessel can be considered a ship or ship like vessel. What this means is that the unit should comply with requirements from applicable parts of DNV's Rules for Classification of Ships related to gas services as well as the requirements described in the Classification Note No. 61.3 Regasification vessels.

3. Subsystems of an FSRU GTW-unit

As mentioned in Section 2, the FSRU GTW-concept consists of four parts that are essential for the complete production chain from LNG to electricity. These parts are transferring and storage, regasification, power generation and power export. Figure 5 shows a schematic image of the process chain for the unit. These subsystems explain the whole process from the arriving LNG carrier to the delivery of electricity to the consumer onshore. To simplify, the HAZID that will be performed on the FSRU GTW-unit, it will be performed on each subsystem individually as well as on the whole system in general. Therefore, the following sections will describe each of the subsystems in detail in order to give a good theoretical and technical background to perform the following HAZID.

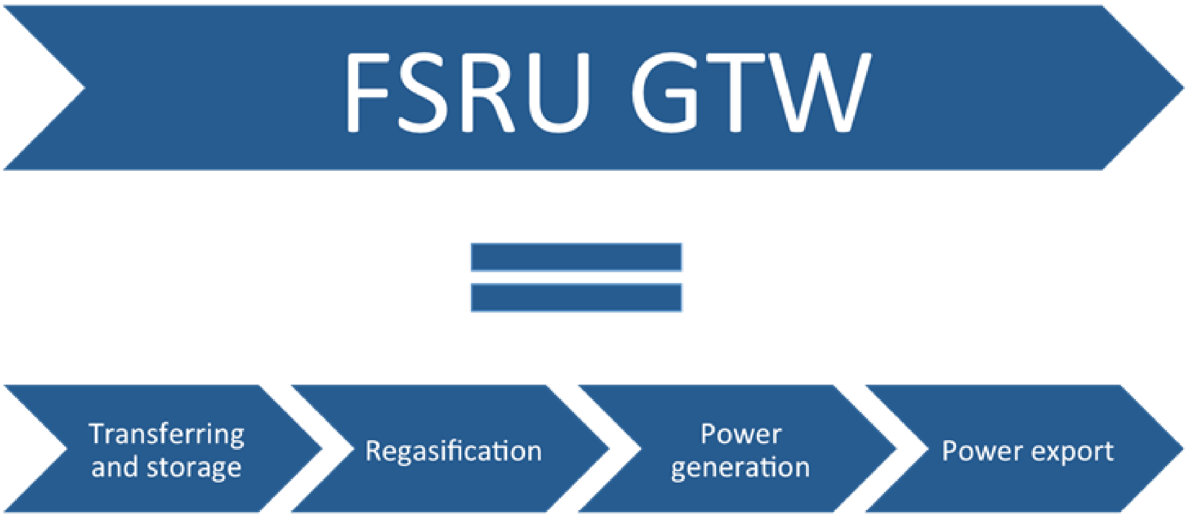

Fig. 5. Schematic image of the FSRU GTW-units subsystems.

3.1. Transferring and storage of LNG

This section explains the details in the process of transferring LNG between an LNGC and an FSRU and the storage systems used on an FSRU, which is the first step in the process chain.

3.1.1. Transfer systems

When transferring LNG between two floating units there are, according to DNV [3], two main options of how to do this; side-by-side transfer or tandem transfer.

Side-by-side transfer means that the shuttle carrier is manoeuvred alongside the FSRU where they are moored together during the transfer operation. The vessels are separated by fenders that have a diameter of approximately 5m. The main transfer technology used for side-by-side transfer is made up of either aerial hoses or rigid arms with extended envelopes and assisted connection. A side-by-side transfer operation between two vessels can be seen in Fig. 6.

Fig. 6. Side-by-side transfer operation – Courtesy of Höegh LNG.

The tandem transfer method is performed by connecting the vessels by stern and bow. The shuttle tanker is connected at the bow by hawser lines from the stern of the FSRU. To transfer the LNG between the vessels; aerial, submerged and floating hoses can be used. Another method is to use motion compensating structures incorporating rigid arms. In Fig. 7 an example of a tandem transfer system with aerial hoses is shown.

Fig. 7. Tandem offloading system – Courtesy of FRAMO.

DNV [3] states that there are different challenges depending on which method that is used. The side-by-side method is well proven and non-dedicated shuttle tankers can be used for delivering the LNG. On the other hand, this method is relatively sensitive to the sea state and there are challenges when manoeuvring and mooring to another vessel in open water. These difficulties can be managed with the use of tandem transfer, but, instead, there is a need for dedicated shuttle tankers. This means that the shuttle tanker needs to have special transfer equipment in contrast to vessels using side-by-side as transfer method. Therefore, in this work, it is assumed that the most probable transfer method is side-by-side, which is the method that the project will be limited to.

3.1.2. Storage system

IMO [15] designates a number of tanks that can be seen in Fig. 8. Their characteristics are as follows:

- Type A – Full secondary barrier.
- Type B – Reduced secondary barrier.
- Type C – No secondary barrier.
- Membrane tanks – Full secondary barrier.

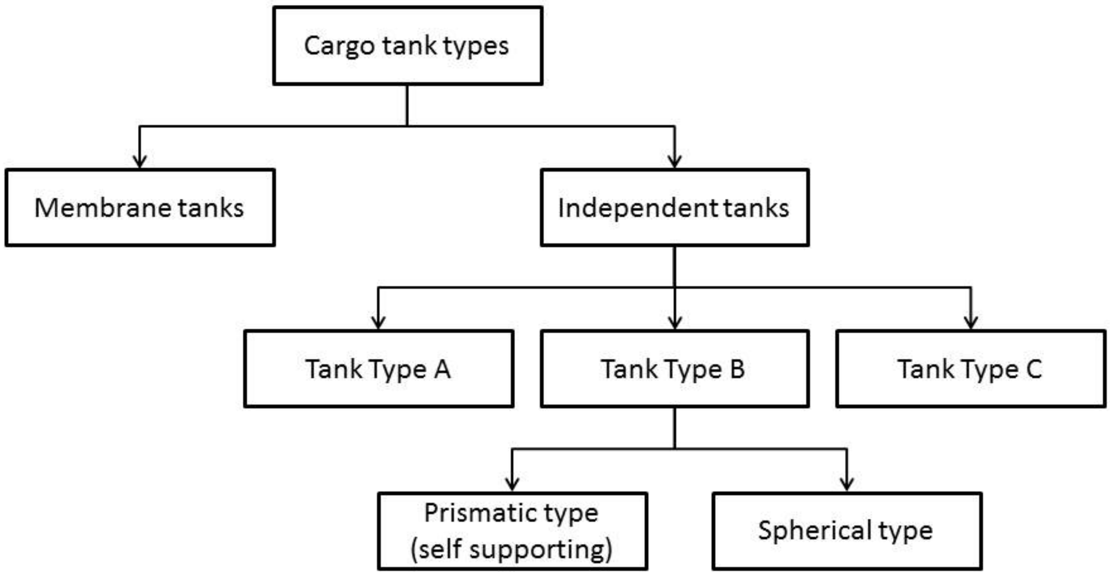

Fig. 8. Type of cargo tanks for an offshore liquefied gas terminal.

Membrane and type B tanks are typical LNG tanks according to CCNR and OCIMF [16]. These are also the type of tanks that according to DNV [3] are most commonly used for this area of application. Because of this, membrane and type B tanks will be the types of tanks further evaluated in this section.

Prismatic tank

The prismatic tank type, see Fig. 9, is, according to DNV [3], self-supporting and is not a part of the ship's hull. The primary barrier is built in a similar way as an ordinary hull structure with stiffeners, web frames, etc. Mostly, the material used for the primary barrier is stainless steel, aluminium or 9% nickel steel. The primary barrier is surrounded by insulation and drip trays. The insulation is, in turn, connected to the tank support.

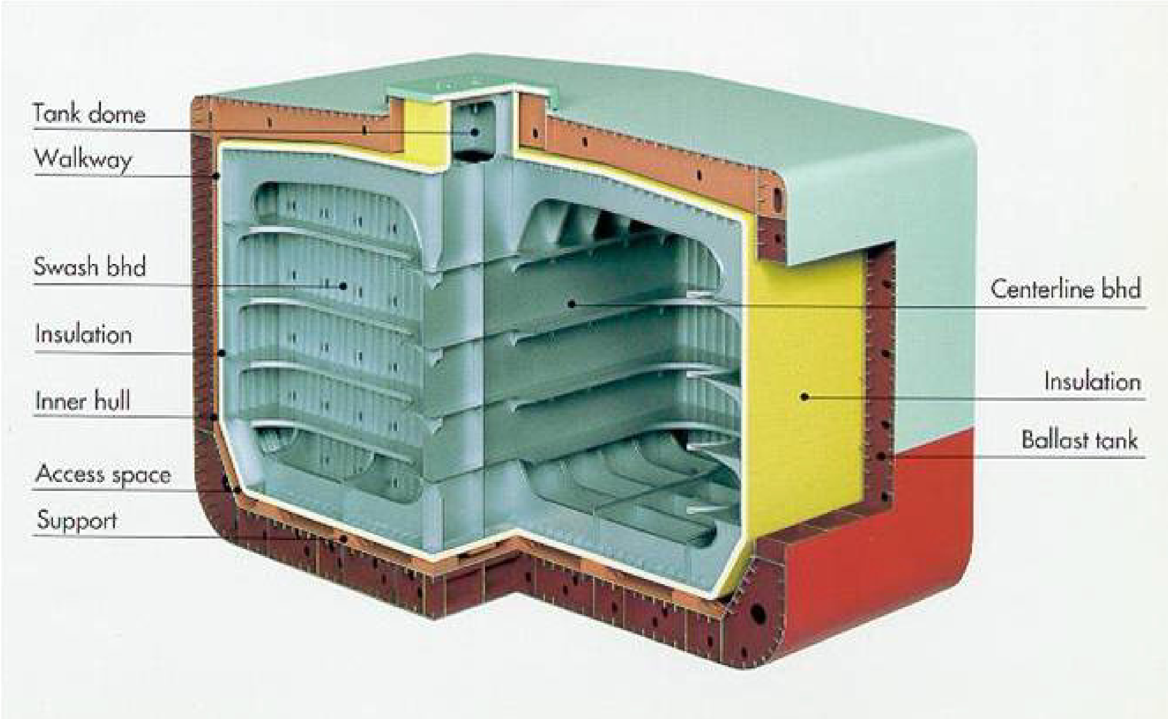

Fig. 9. Prismatic Tank – Courtesy of IHI Marine United Inc.

Spherical tank
The spherical tank type is, according to DNV [3], like the prismatic tank, self-supported, see Fig. 10. The primary barrier is made of aluminium and is covered in insulation. Below the centre of the tank there is a drip tray. In the centre of the tank the pump tower is installed vertically, with the pump equipment at the bottom of the tank.

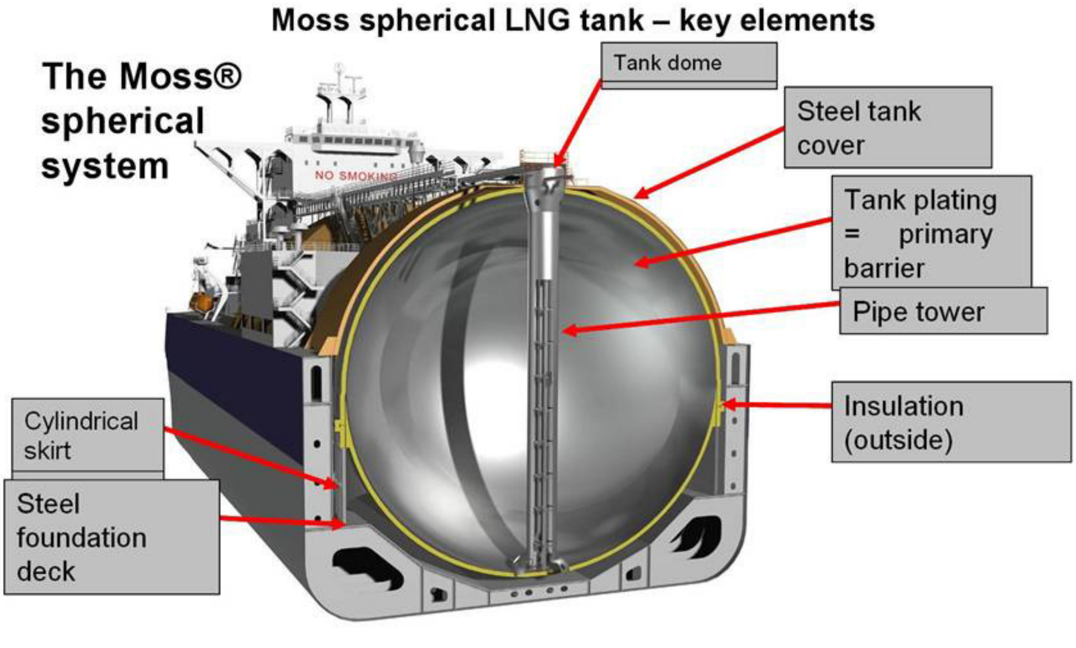

Fig. 10. Spherical Tank – Courtesy of Moss Maritime.

Membrane tanks

The membrane tanks are, according to DNV [3], not self-supporting and are therefore surrounded by the double hull ship structure, see Fig. 11. The membrane tanks consist of two membranes, the first and the secondary, which are designed to resist stresses from expansion and contraction from thermal loads. In between the first and the secondary membrane there is insulation and between the secondary membrane and the ship's hull there is also insulation. This will protect the LNG from being heated, but will also protect the hull structure from getting dangerously cold.

Fig. 11. Generic Membrane Tank [3].

The three types of tanks described above have different properties that make them more or less suitable on an FSRU GTW-unit. According to DNV [3], the spherical tank may not allow sufficient deck space on the topside to be able to mount the necessary equipment that is needed for an FSRU GTW-unit. Concerning the prismatic tank, the design with flat surfaces of stainless steel might not be optimal since stainless steel subjected to thermal loads will experience thermal fatigue according to a study by Hayashi [17]. Therefore, it can be assumed that the prismatic tanks will not withstand contraction and expansion caused by thermal loads as well as membrane tanks. This is why this study will assume the membrane tank to be the most convenient tank for an FSRU GTW-unit and will be the type considered in the HAZID.

3.2. Regasification unit

In order to vapourize the LNG there are a number of possible technologies and some of them are heated vapourizers, ambient vapourizers and remote heated vapourizers.

According to DNV [3], the heated vapourizer system uses a direct heat procedure with natural gas as fuel. The gas is combusted to get heat, which is used to vapourize the LNG. Since this system uses natural gas as fuel the result will be CO_2 and pollutants in the air.

The ambient vapourizers receive, according to DNV [3], the heat from naturally occurring sources. This could, for example be air or sea water. A commonly used method is the open-loop water-based system where LNG is heated by sea water that is taken from the surrounding sea. After the sea water is consumed as the heating medium it is removed from the regasification unit and transferred over board and back to the sea. This type of approach is possible as long as the surrounding sea is warm enough, which could be a problem when operating in the North Sea. Another concern with this type of vapourizer is that the water, after the heat exchanging process, will be heavily chilled. Therefore, the output water will be very cold in relation to the surrounding water, especially in a warmer climate. The environmental impact, both longterm and shortterm, of this cold water emission needs to be considered for the area where it is supposed to operate. An example of an open-loop water-based system can be seen in Fig. 12.

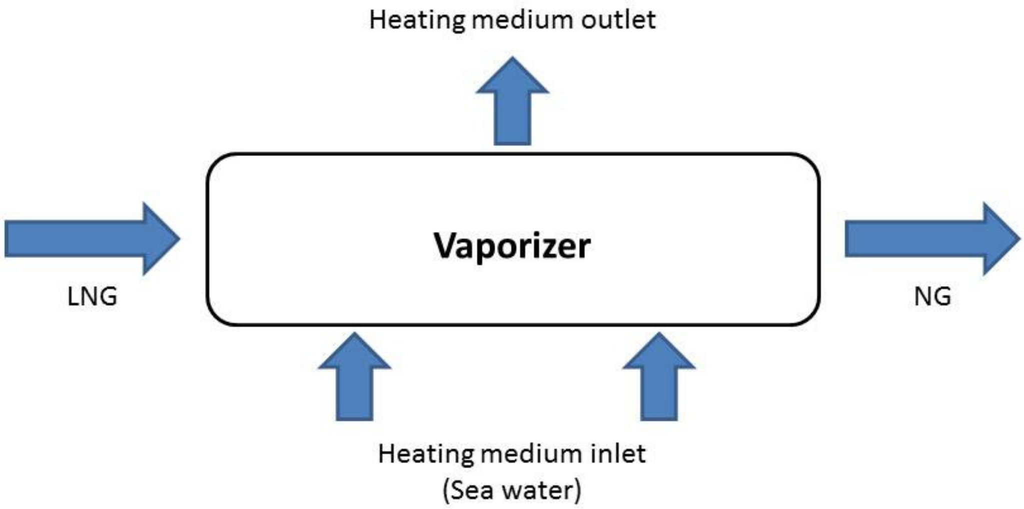

Fig. 12. Schematic image of an open-loop water-based regasification system.

The third type of vapourizer is the remote heated vaporizer. This uses, according to DNV [3], intermediate fluid to transmit the heat from the primary heat source to the vapourizer. For instance, a closed water loop can be used to transfer the heat from the heat sources to the heat exchanger in a remote heated vapourizer. As can be seen in Fig. 13, the heating source can be air since this results in a minimum environmental impact. Another solution might be to use the heated cooling water from the power plant's cooling system and then let it go back into the power plant again for cooling, forming a closed loop. In addition to the remote heating medium a glycol heater can be used if the water loop is not warm enough. Even though, Fagan[1] claims that this technology is not the most commonly used for vapourization of LNG, it is the most environmentally friendly and since this is something the world strives at, this is a solution that should be considered in the future.

Concerning the regasification subsystem, the project is not limited to a certain technology since there are no obvious reasons for choosing one vapourizer instead of another. Thus, the regasification process will be analysed in general terms.

[1] Conn Fagan (Business development manager for offshore gas projects, DNV, Hövik) stated in personal communication during the project time January-June 2012.

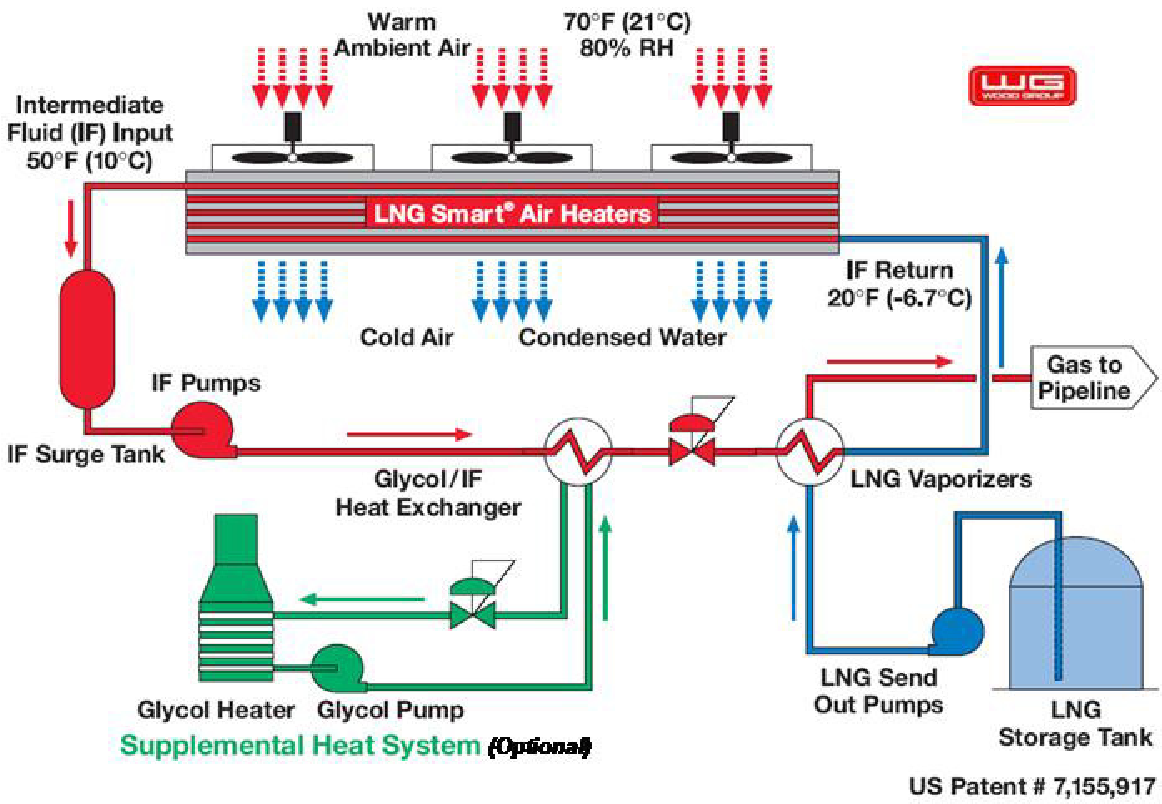

Fig. 13. Air Intermediate Fluid Vapouriser – Courtesy of Wood Group/Mustang Engineering.

3.3. Power generation

The power generating capacity of an FSRU GTW-unit is assumed by the authors to be 200-400 MW. There are several different combustion methods that can be used for power generation. In this project, the piston engine and gas turbine are assumed to be the most conventional. The most concerned difference between a gas turbine and a piston engine is the power-to-weight ratio. A gas turbine has a significantly higher power-to-weight ratio than a piston engine, based on a comparison between Siemens Energy Gas Turbines [18] and Wärtsilä Dual Fuel Engines [19]. Since space is a major issue on most offshore production units, this study will be limited to an FSRU GTW-concept that uses gas turbines. The weight of a gas turbine with a capacity of approximately 375 MW is about 440 tons, according to Siemens Energy Gas Turbines [18].

3.3.1. Gas turbine

When using a gas turbine, see Fig. 14, as the combustor it can, according to Kehlhofer [20], be built among other things as a simple cycle or a combined cycle. Both systems use a gas turbine for combustion of the natural gas but a combined cycle also has a steam turbine in addition to gas turbines for power generation.

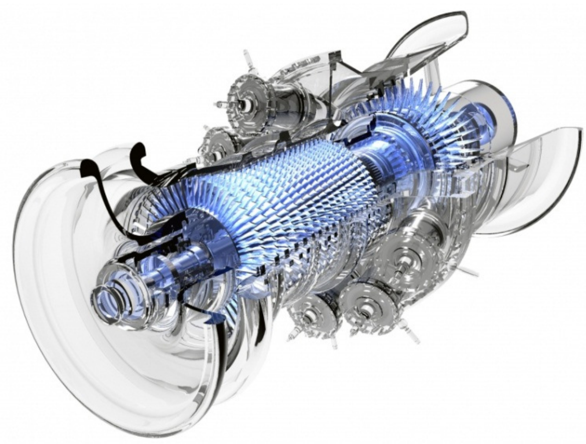

Fig. 14. Gas turbine – Courtesy of Engineer Live [21].

A simple cycle procedure starts with a compressor that compresses the combustion air to between 10 to 20 bar according to Boyce [22]. The fuel gas line has a pressure of around 54 bar. A mixture of the air and natural gas will be combusted in the turbine's combustion chamber. At this stage, according to Saravanamuttoo et al. [23], the temperature at the turbine inlet is around 1,500 degrees and therefore the exhaust gas will contain a lot of energy. This energy will rotate the impeller in the gas turbine, which in turn is connected to an electric generator through a shaft. The exhaust is then released through the exhaust duct. At this stage, the combined cycle differs from the simple cycle system. The exhaust gas that has, according to Kehlhofer [20], a temperature of around 500 degrees is used to heat up water in the steam turbine. This additional system is called Heat Recovery Steam Generator, HRSG. In the exhaust system there is a heat exchanger where water is heated from the exhaust gases. The vapourized water can then be used in a steam turbine, which is also connected to a generator through a shaft. When the exhausts have passed the HRSG they have, according to Kehlhofer [20], a temperature of 320 degrees instead of around 500 degrees. This step will significantly increase the efficiency of the process. A combined cycle process is shown in Fig. 15 and a comparison between the simple cycle and combined cycle setup is discussed in the next section. The weight of a combined cycle is difficult to estimate since there are many different setups and the differences between these are beyond the scope of this thesis.

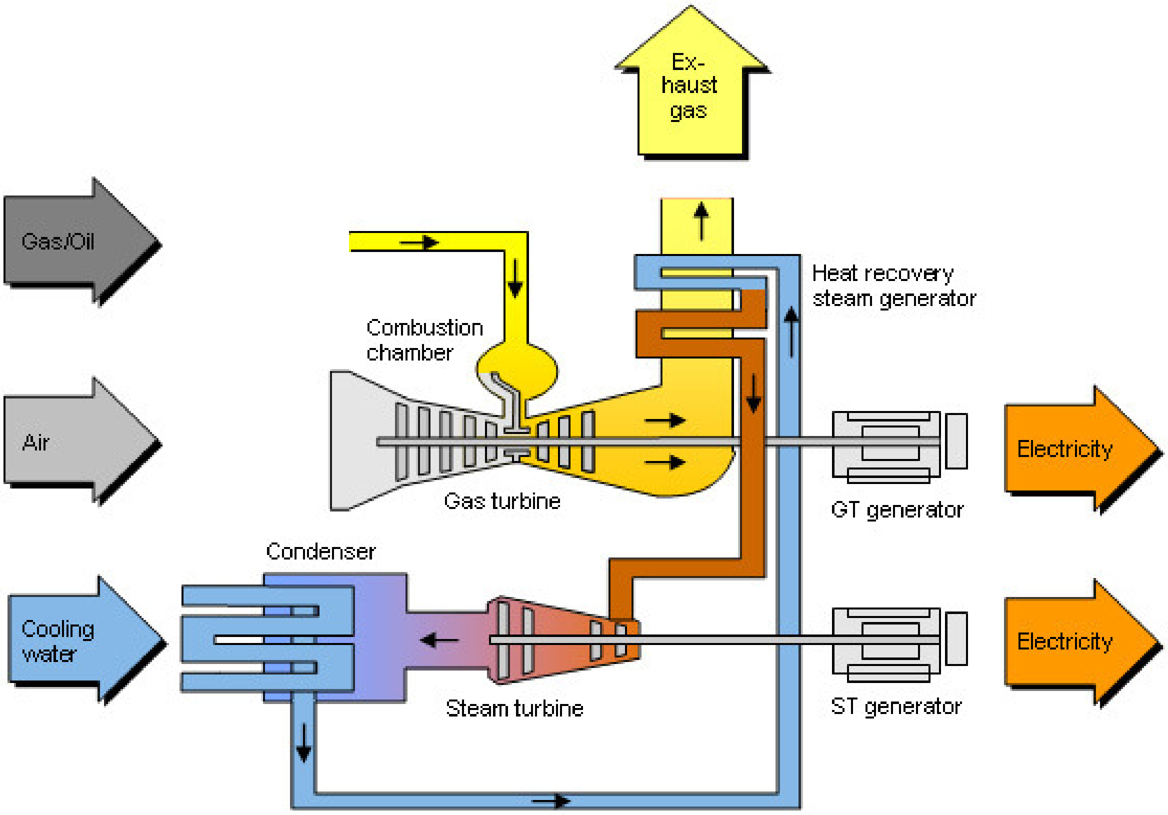

Fig. 15. Siemens Combined Cycle Process – Courtesy of Siemens Energy.

3.3.2. Combined cycle compared with simple cycle

According to Kehlhofer [20], a combined cycle can have an efficiency of 52% compared to a traditional simple cycle, which can have an efficiency of a maximum of 36%. Compared to a simple cycle, a combined cycle is very large and heavy, which will obviously result in higher demands on the carrying structures and deck space. Compared to the simple cycle system, the initial cost is higher, but in a longterm perspective the profit is much better. Furthermore, the combined cycle also generates more power per amount of fuel, which will result in more power per amount of CO_2 emitted. As many countries have taxes based on the amount of CO_2 in the emissions there are more benefits than just the efficiency of using a combined cycle instead of a simple cycle. A combined cycle will produce around 30% less CO_2 per kWh generated, based on a study by Ishikawa [24].

The air temperature has a large impact on the output energy. A higher air temperature will decrease the density and therefore lower the air mass flow. According to Kehlhofer [20] this will affect the efficiency of the gas turbine. A higher air temperature will lower the gas turbine efficiency and will give a lower energy output. However, a higher air temperature will increase the temperature of the exhaust gases and therefore also the energy in these. If a combined cycle is used instead of a simple cycle, there are benefits with having a high exhaust gas temperature since this high level of energy can be used in the steam turbine. Even though a very high air temperature will have a major decrease in efficiency the steam turbine will have an even higher increase. Therefore, the total energy output will be higher with a high air temperature in the combustion. In Fig. 16, the relative differences in efficiency depending on air temperature is shown.

As the FSRU GTW-unit is a solution to problems in areas where there is lack of electrical power supply, this might also include an operational area with a tropical climate with a high air temperature. Therefore, a high air temperature is obviously an aspect to take into account, and in that perspective a combined cycle is more suitable to use then a simple cycle on an FSRU GTW-unit because of its large field of application.

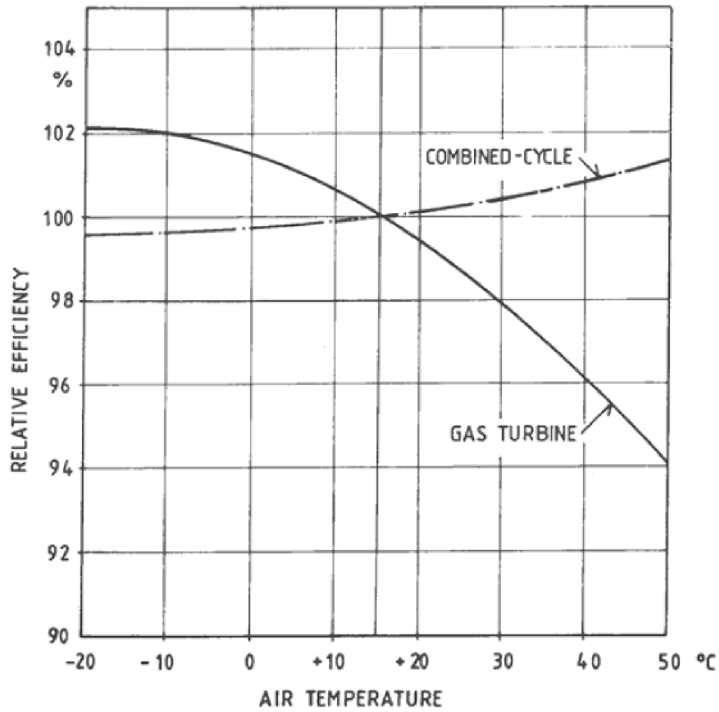

Fig. 16. Inlet air temperature in relation to efficiency [20].

3.3.3. Gas turbine system in an economic perspective

The cost for producing power on a power plant can be divided into three types of costs:

- Capital costs.
- Fuel costs.
- Operational and administrative costs.

In an economic perspective, the thermal efficiency is a very important factor when trying to distinguish which solution that is the best one from an economic point of view. A combined cycle has a substantially higher efficiency than a simple cycle, based on Kehlhofer [20]. This can be seen in Fig. 17.

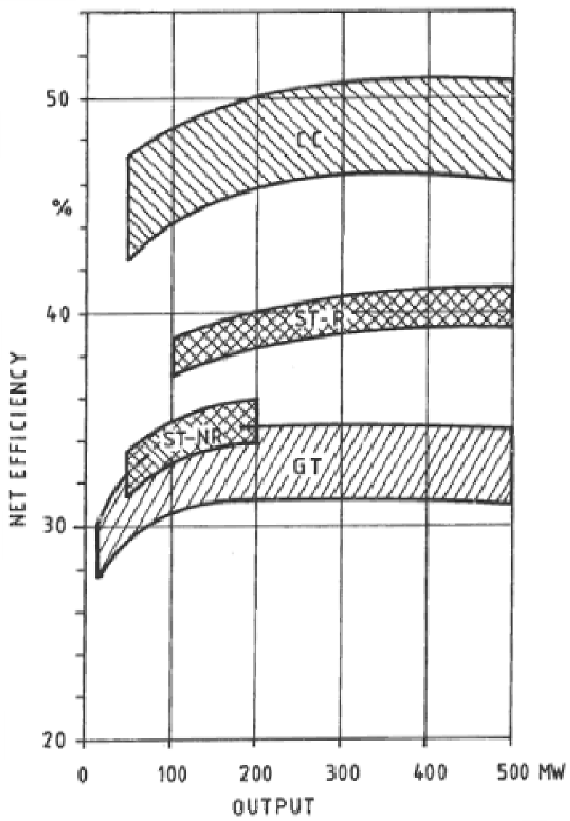

Fig. 17. Net efficiency of different cycles [20]:
CC - combined-cycle plant; ST-RC - reheat steam turbine plant, coal-fired;
ST - steam turbine plant, oil or gas-fired; GT - gas turbine power plant.

The investment price of the different cycles is also crucial in the choice of which one is the most suitable. The investment price is shown in Fig. 18. The exact price showed in the graph should be read with a sceptical mind. The values are old and there is a large amount of different causes that can affect the price. But the relative difference can be seen as relevant for distinguishing the power plants from each other. As can be seen in Fig. 19, the simple cycle has a shorter building time than a combined cycle. From this it can be assumed that a simple cycle also has a lower investment cost compared to the combined cycle, which makes it more attractive for a customer.

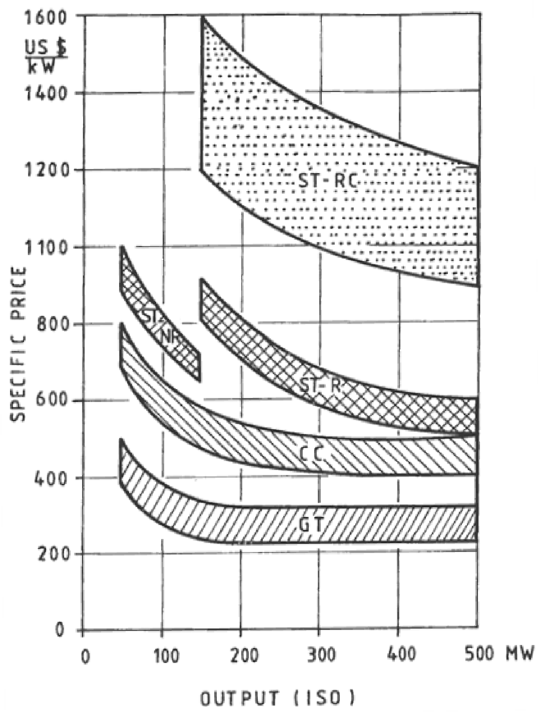

Fig. 18. Price comparison [20].

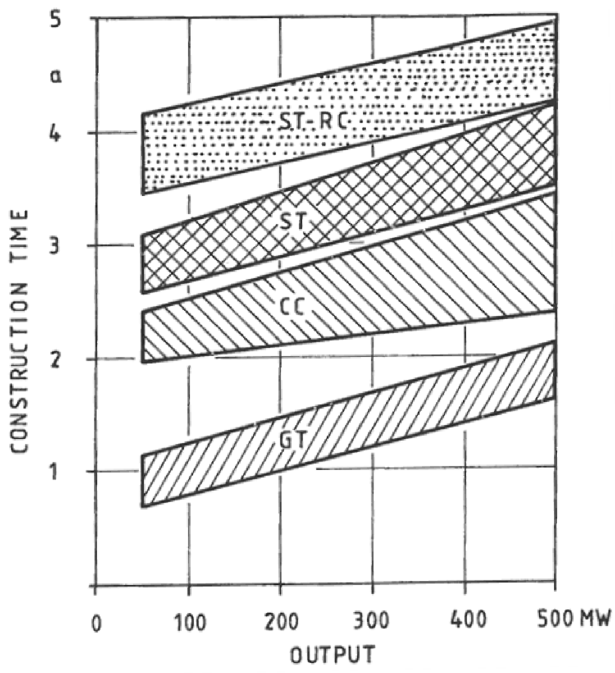

Fig. 19. Comparison of construction time [20].

According to Kehlhofer [20], the difference in operational costs between a simple cycle and a combined cycle can been seen as negligible since this cost is only around 5 to 10 % of the power plant's fuel costs (5% to 10% of fuel in 1991, most probably even lower today). The availability for an ordinary simple cycle gas turbine is between 88-95% compared to a combined cycle plant, which has a lower availability, between 85-90%. The reason for this is that a combined cycle process is more complex and has more components that can malfunction.

According to the data from the comparison between a simple cycle and a combined cycle the most probable choice would be a combined cycle. The only reason for not choosing a combined cycle is the investment cost, which is higher than a simple cycle. Therefore, this study will limit the research to an FSRU GTW-unit with a combined cycle power plant.

3.4. Power export system

The power export system can be divided into two main parts: swivel and power cable. These will be described below.

3.4.1. Swivel

For a location where the FSRU GTW-unit needs to be moored, a turret with a swivel is one of the technologies that can withstand weathervane, based on DNV Report [25]. The swivel is filled with insulating dielectric oil and it is built up of slip rings, which are in contact with brushes to allow rotation without losing conductivity. The main advantage is that the unit can rotate so that it can meet bad weather in a more favourable position and its main limitation is the power ratio.

Regarding the power rating of the HV swivel, SBM Offshore [26] has a 1st generation swivel with a capacity of 24 kV, 1800 A in 450 A modules and is qualified up to 52 kV. This rating is not enough for a power production and exportation of 300-400 MW. However, there is a 2nd generation of HV swivels with a higher power rating of 132 kV, 1600 A AC. This would probably be enough for an FSRU GTW-unit.

3.4.2. Power cable

For the power export system there is the question of whether to use an Alternating Current, AC, or Direct Current, DC, cable. This is generally a matter of transmission distance. According to Larruskain [14], the problem with AC is that it has a theoretical maximum distance it can be transported. For the HVDC power cable, however, it is more of an economic issue than a technical one. The distance for sub-sea cables where HVAC starts to be less efficient than HVDC is approximately 50 km, even though it will be necessary to transform the DC electricity back to AC when onshore, which involves losses. Since the distance according to Fagan[2] will seldom exceed 50 km, this implies that for an FSRU GTW-unit the most probable type of cable is the HVAC cable. However, since the authors assume that there might be an application for the HVDC system in the future, this will still be briefly analysed in order to cover a larger field of interest. The design of an HVDC and HVAC cable can be seen in Fig. 20 and 21, respectively.

[2] Conn Fagan (Business development manager for offshore gas projects, DNV, Hövik) stated in personal communication during the project time January-June 2012.

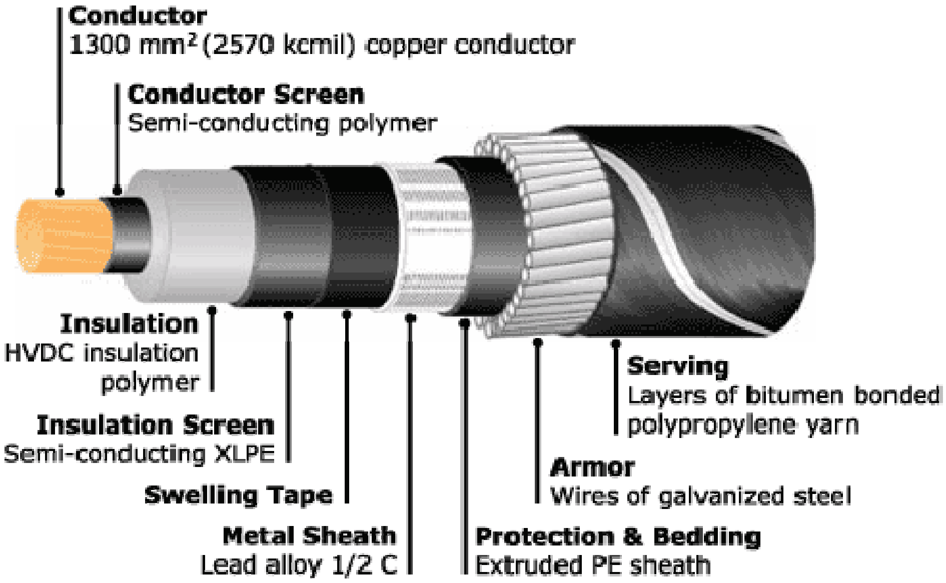

Fig. 20. Anatomy of a single-core XLPE cable – Courtesy of ABB.

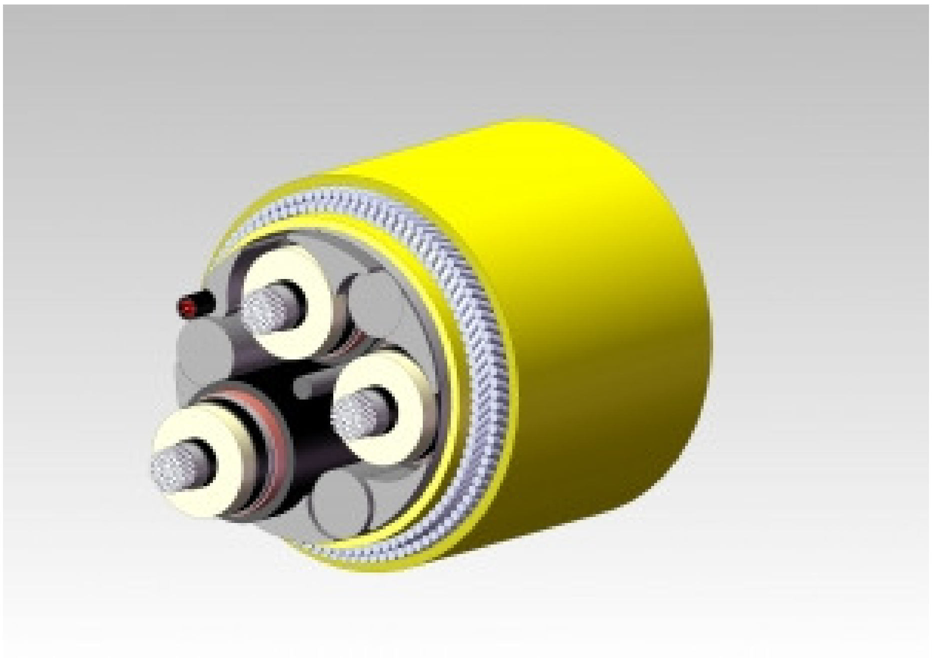

Fig. 21. AC Power Cable design – Courtesy of Engineering Live [21].

For the case where the unit is not located quayside the first connection will be from the FSRU GTW-unit to a dynamic power cable. This will then hang down to the sea floor supported by floaters to ease the tension. The dynamic power cable will connect to a static one that will rest on the seabed. In the same way, the static power cable will connect with a dynamic, which then connects to the shore, according to DNV's Recommended Practice [27]. Also according to DNV's Recommended Practice [27], there are some considerations when designing an HVAC cable, these are:

- Insulation system.
- Thermal conditions.

- Longitudinal static strength of cable.
- Fatigue strength of cable.
- Hydrostatic strength.

Based on AkerSolution [28] an offshore deep water cable has the following challenges that need to be considered:

- Tensile capacity.
- Crush load capacity, i.e. grip force from tensioner during installation.
- Fatigue capacity of water barrier.

Concerning the electric load capacity of the cables there should be an overcapacity for safety reasons. The maximum load depends on the production capacity and customer demand and may be assumed to vary between 200-400 MW.

3.5. Integrated software-dependent system, ISDS

According to DNV [3], software and systems in the maritime sector are becoming more complex because of the technology development and more demanding customers. All the software embedded systems need to work with each other and be integrated into a single system, which is called ISDS. According to DNV's Recommended Practice [29], the main purpose of an ISDS is to be an integrated system the behaviour of which is dependent on its software components, called ISDS-elements. An ISDS-element can be a subsystem, a component or a control circuit, etc., and these are the elements that build up the ISDS. The ISDS-elements can directly interact with each other depending on the specific system design. The main challenges are to gather the various system elements into one single system that fulfils all the requirements, such as safety, functionality, reliability, etc. It is not enough for each subsystem to provide safety, functionality, reliability, etc., but the whole integrated system needs to provide the same level of these attributes.

When building an ISDS all the functions of the system can be assigned a confidence level, which is dependent on how critical each function is to the whole system operation. Each of the functions can be assigned a confidential level and also the whole system is assigned a confidential level. An example of how a component's level is assigned is shown in Fig. 22. The level can, for example, be based on safety problems and environmental and business impacts. To find out the level, one of the possible approaches that can be used is HAZID. When considering the business impact, not only the financial cost of restoring the production to normal order but also the impact on the business reputation is taken into account.

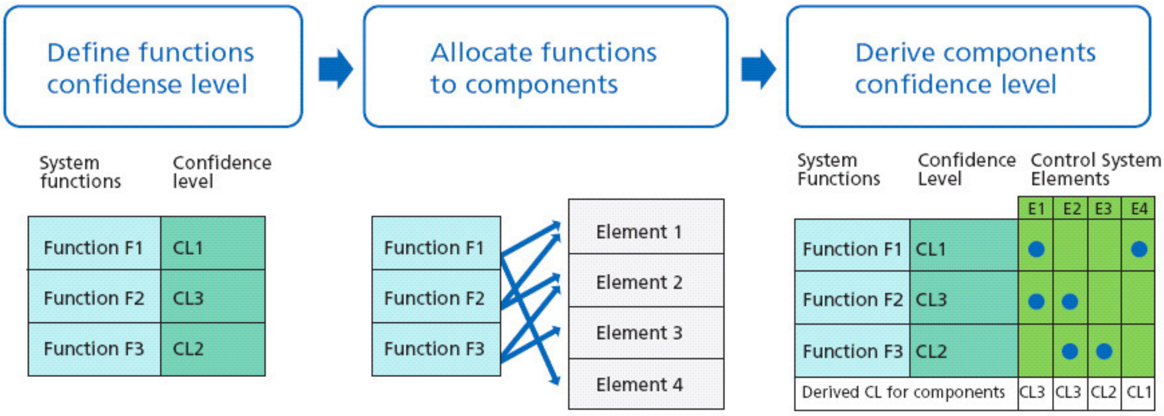

Fig. 22. ISDS Elements Confidence Level assessment – Courtesy of DNV [29].

A FSRU GTW-unit consists of many different systems that need to interact with each other, which will be very demanding for the ISDS, but it also offers great benefits in terms of operability, functionality and availability. Therefore, DNV [3] states that it is crucial to have a properly designed ISDS in order to maintain the operability, functionality, availability as well as the safety of the personnel. A failure of the ISDS can be catastrophic.

3.6. A summary of technologies on an FSRU GTW-unit

From the earlier sections of Section 3, the various systems of an FSRU GTW-unit have now been analysed and described. To summarize the section, the unit that will be further analysed in the report is an FSRU GTW-unit with a side-by-side transfer, membrane tanks as storage system, a choice of different vapourizers for the regasification system and gas turbines in a combined cycle for power generation. As for the power export system, it is dependent on the location of operation. If the unit operates offshore and is turret-moored there is a need to use an HV swivel and if it is located more than 50 km from shore a DC transmission cable is to be used, otherwise AC is the type of current to be preferred. If the unit is situated quayside there is no need for turret-mooring and therefore no HV swivel. Both locations of operation are considered in the following analysis even though a turret-moored unit located offshore is assumed to be an extreme application. The result of this is that this report will not only discuss the most common application but also the most challenging one. A schematic view of an FSRU GTW-unit with selected technologies can be seen in Fig. 23.

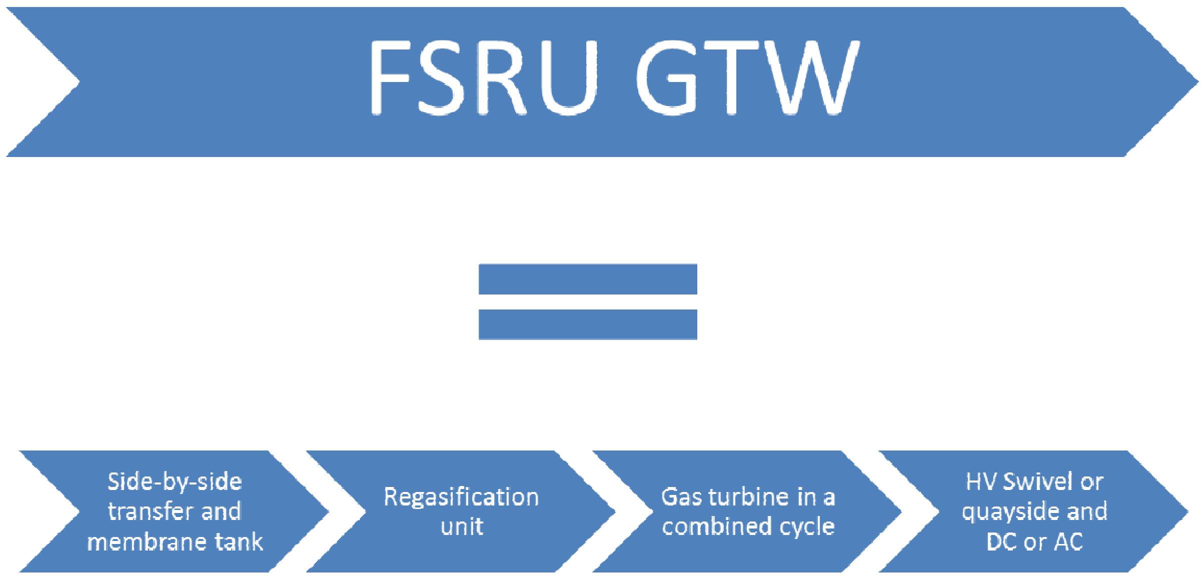

Fig. 23. Schematic view of an FSRU GTW-unit with specified systems.

4. Analysis of hazards and existing rules and regulations

With the technical equipment that the FSRU GTW-unit will be comprised of and has been presented in the previous section, it is now possible to perform a HAZID. As more thoroughly described in Appendix A and IMO FSA [11], the HAZID process comprises one creative part and one part that is based on previously identified hazards. The creative part is a proactive process with the purpose of finding any new hazards associated with this technology. This part will be the most important part for the FSRU GTW-concept because it is a novel technology. In Appendix A, the FSA-methodology is more thoroughly described and there is also an example of how the method is used.

In order to make it easier to identify the hazards, the concept has been divided into the four subsystems. These subsystems are thought to represent the most important systems of an FSRU GTW-unit. In Appendix B, the results of the HAZID for each of the subsystems are presented. A HAZID of the whole system has also been performed and is presented in Appendix B. This general HAZID is needed in order to find hazards not directly associated with a certain subsystem, such as terrorism, collisions, etc.

The HAZID was done by the authors with the aid of a group of experts from DNV working in the fields of electrical equipment, rotating machinery systems on board offshore units and offshore gas projects. The group discussed possible hazards that could be associated to each of the subsystems as well as to the concept in general. There are some hazards that can almost always be associated to floating units with machinery. These were found after studying internal risk assessments made by DNV in cooperation with customers and are, for example, fire, explosions, collisions, etc. The hazards identified are then evaluated in order to specify why they occur and what the consequence might be if they do The HAZID tables in Appendix B are hence divided into three columns designated; Hazards, Cause and Consequence.

The objective with this thesis is to identify the risks relevant to an FSRU GTW-concept, to evaluate how these are handled in existing rules and regulations and finally to present requirements and recommendations for future rule development. This implies that it is necessary to distinguish which of the identified hazards that are additional for an FSRU GTW-unit compared to an FSRU. The results can be seen in Table 1. In addition to the columns Hazard, Cause and Consequence, two other columns designated Safeguard and Section have been added. In the Safeguard column, it is suggested what precautions should be taken in order to reduce the risk associated with a certain hazardous event. In the FSA-methodology this is referred to as step 3 Risk Control Options. More about this is to be found in Appendix A. The section-column refers to which section the hazard is analysed against rules and regulations.

Table 1. Additional hazards for an FSRU GTW-unit compared to an FSRU.

No.	Hazards	Cause	Consequence	Safeguard	Section
1	Stability issues	Decreased GM due to installed weight above CG. Sloshing Green water Incorrect loading operation. Water ingress because of structural damage	Increased consequence of initial instability. Can cause roll, pitch and list of the unit. Can cause structural damage to the equipment place on deck due to significant heel.	Intact stability and damage stability calculations. Active and passive stabilizers.	4.1.1
2	Fire/ Explosion	Ignition from power plant in addition to gas leak, that will reach the lower explosion limit, from any subsystem	Fatalities and major material damage	Sufficient gas detectors in hazardous zones. Fire fighting system. Emergency shutdown system, ESD.	4.1.2
3	Terrorism	Terrorists Pirates	Fire/explosion Personnel injuries and fatalities Economic losses	Analyse the risk of terrorism in the considered operational area.	4.1.3
4	Turbine blade damage	Due to particles in the combustion air or other impurities fatigue cracks can occur	Can cause vibration in structure. Can cause an uneven flow through the turbine.	Control and monitoring systems that can shut down the gas turbine.	4.1.4
5	Gas fuel supply failure	Failure in valves and pumps Failure in regasification system or earlier in the flow chain.	The power plant will not generate any electricity	Regularity in maintenance.	4.1.5
6	Excessive vibrations	Unbalanced turbine setup Can escalate if the rotors are damaged in the turbine	Fatigue in the ship structure. Fatigue in process structure. Working environment is affected by vibrations.	Measure the vibrations in sensitive areas.	4.1.6

7	Incomplete combustion	Wrong proportions of combustion air and gas fuel.	Will release methane trough exhaust system, which is a dangerous green gas. The methane can ignite because of the heat in the exhaust system. Possible fire in HRSG Loss of production	Gas detectors in air inlet. Monitoring and control system for the fuel supply.	4.1.7
8	Leak of CO2 in to combustion chamber	Caused by excessive exhaust gas leak.	Incomplete or no combustion. Loss of production.	CO2 in machinery spaces.	4.1.7
9	Boiler explosion	Overpressure in steam boiler	Explosion/fire Injuries and fatalities	Overpressure valves	4.1.8
10	Over speed in steam turbine	Boiler in HRSG too hot	Rotor failure in steam turbine.	Suitable IS-limiter and transformers	4.1.9
11	Flame arc/short circuit	Contamination of insulating oil. Mechanical breakdown that leads to contact between slip rings.	Insulation oil evaporate Internal pressure increase	Over dimensioning of cable.	4.1.10
12	Cable failure	Too high current in the export cable.	Production failure Environmental impact and 3rd party impact.		4.1.10
13	Transformer explosion	Vapourization of cooling and insulating oil	Injuries of personnel and structural damage	Maintenance and adequately tested during installation.	4.1.10
14	Failure in ISDS	Compatibility problems. Electrical failure.	Might be catastrophic since many operations are monitored and controlled by this system.		4.1.11

Shown below are the answers to why these hazards are considered to be additional in comparison with an FSRU:

1. Stability issues: Since the most probable option will be to place the power plants or power generation housing above the storage tanks, i.e. placed on deck, the centre of gravity will have a longer distance from the base line of the vessel. Therefore, the metacentric height, GM, will decrease. The power plant installation will also affect the wind forces that are acting on the vessel.

2. Fire and explosion: Fires and explosions are hazards that exist on almost any type of technical equipment or structure. There are many safety measures on board an offshore structure or ship to avoid the occurrence of such devastating events.

On an FSRU GTW-unit, the fire/explosion hazard is additional in the sense that there is, because of the power plant, another source of ignition and flammable leakage.

3. Terrorism: Terrorism is considered to be an additional hazard since there is a greater incentive in attacking a power-generating unit than an FSRU, since this would probably lead to more damage for the consumers.

4. Turbine blade damage: The consequence of severe turbine blade damage could result in a turbine blade missile. This could damage other equipment on board, such as pipes, storage tanks, etc., leading to leakages. It is additional in the sense that even if an FSRU might have gas turbines on board for power generation it will not be of the same magnitude as on an FSRU GTW-unit.

5. Gasfuel supply failure: By gas fuel supply failure is meant that the fuel supplied to the power plant is interrupted. Since it directly affects the power plant, it is considered as additional compared to an FSRU.

6. Excessive vibrations:	This is an additional hazard compared to an FSRU because there are no present FSRUs with gas turbines mounted on the deck with this amount of power generation capacity. These turbines with their connected generators are generally well balanced. But because of the size of the power generation package, vibration is still an issue which needs to be taken into consideration. Especially if the rotations are unsymmetrical or if a turbine blade is damaged in some way.
7. Incomplete combustion:	The hazard of incomplete combustion occurs in the gas turbines. Since an FSRU GTW-unit consists of more gas turbines, the probability of incomplete combustion increases compared to an FSRU, which has less or no gas turbines.
8. Leak of CO2 into combustion chamber:	The reason for being considered as an additional hazard is similar to the reason for "incomplete combustion". The probability of CO_2 leakage will increase due to a larger amount of installed gas turbines.
9. Boiler explosion:	In the combined cycle process there will be a steam boiler heated by exhaust gases. This is an additional hazard since the electricity production for an FSRU normally does not consist of a combined cycle power plant with a steam boiler.
10. Over speed in steam turbine:	The temperature in the boiler is too high leading to over speed in the steam turbine causing rotor failure. This is additional for the same reason as for a boiler explosion.
11. Flame arc or short circuit in swivel:	This hazard is considered as additional since the use of a swivel is needed for an offshore based FSRU GTW-unit. A flame arc or a short circuit in the swivel can cause the oil in the insulations to evaporate, which can result in an explosion.
12. Cable failure:	Additional, since an FSRU does not export any electricity and therefore there are no sub-sea cables.
13. Transformer failure:	Additional, since there is no need for large transformers on an FSRU. On an FSRU GTW-unit these are, however, needed and imply another source of flammable liquids.

14. Failure in ISDS: Additional, since there are more functions integrated in the ISDS than on an FSRU.

All of the above risks are to be evaluated against existing rules and regulations to find out if they are properly covered or if there are any gaps or conflictions.

4.1. Analysis of existing rules addressing the additional hazards

The FSRU GTW-concept will, according to Fagan[3], most probably be classed as a ship like vessel, which implies that the Rules for Classification of Ships should be used. This should also be combined with the DNV Classification Note 61.3 Regasification Vessels. The following rules presented are from DNV's Rules for Classification of Ships unless clearly stated otherwise.

Pt.1 Ch.1 Sec.1 *B 100 General* **101** The classification concept consists of the development and application of rules with regard to design, construction and survey of vessels. In general, the rules cover: - the structural strength (and where relevant the watertight integrity) and integrity of essential parts of the vessel's hull and its appendages, and - the safety and availability of the main functions in order to maintain essential services.

When classing a ship, the owner has to decide which class of ship it should belong to. The FSRU GTW-concept is of course a class of ship that does not yet exist. Therefore, an analysis needs to be carried out of what the Rules for Classification of Ships contain that address the additional hazards with a power plant on board an FSRU.

4.1.1. Stability

Pt.3 Ch.3 Sec.9 *A 100 Application* **101** All vessels with a length LF of 24 m and above shall comply with the stability requirements of this section, as applicable for the main class.

This rule is mandatory for ship shaped offshore units, which mean that it is applicable also on FSRU GTW-units. And the following rule explains the intact stability requirements for a ship shaped unit or a unit that is considered to be a ship.

[3] Conn Fagan (Business development manager for offshore gas projects, DNV, Hövik) stated in personal communication during the project time January-June 2012.

Pt.3 Ch.3 Sec.9
D 100 General stability criteria

101 The following criteria are given for all ships:
- The area under the righting lever curve (GZ curve) shall not be less than 0.055 metre-radians up to θ_f = 30° angle of heel and not less than 0.09 metre-radians up to θ = 40° or the angle of flooding θ_f if this angle is less than 40°. Additionally the area under the righting lever curve between the angles of heel of 30° and 40° or between 30° and θ_f, if this angle is less than 40°, shall not be less than 0.03 metre-radians.
- The righting lever (GZ) shall be at least 0.20 m at an angle of heel equal to or greater than 30°.
- The maximum righting lever should occur at an angle of heel preferably exceeding 30° but not less than 25°.
- The initial metacentric height, GM0 shall not be less than 0.15 m.

Since an FSRU GTW-unit has a large and heavy power plant mounted on the top side, affecting the centre of gravity, there might be challenges in fulfilling these requirements for stability. It should also be noted that at these angles of heel there will be significant loads on the supporting structure of the power plant, which needs to be taken into consideration.

Pt.3 Ch.3 Sec.9
D 200 Weather criterion

201 For all ships with a length LF of 24 m and above, the criteria listed below shall be complied with (based on IMO 2008 IS Code Part A Ch.2.3):
…
- the ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline, which results in a steady wind heeling lever (*l*w1)
…

As well as the comment on note D100, the power plants will affect the area which is subjected to the wind force and therefore the results from the wind calculations need to be considered.

Pt.3 Ch.3 Sec.9
D 300 Assumptions concerning intact stability criteria and calculations

301 For all loading conditions the initial metacentric height and the stability curves shall be corrected for the effect of free surface of liquid in tanks.

Since there are more or less infinitely many combinations of filling levels in the storage tank for an FSRU GTW-unit there can be some issues when using the assumption in D300.

4.1.2. Fire/explosion

According to the IGC Code, the power plant should be considered a machinery space of category A because of the example from the IGC Code below.

IMO – IGC Code
Chapter 1 General

1.3.24 "Machinery spaces of category A" are those spaces and trunks to such spaces which contain:
1. internal combustion machinery used for main propulsion; or
2. internal combustion machinery used for purposes other than main propulsion where such machinery has in the aggregate a total power output of not less than 375 kW; or
3. any oil-fired boiler or oil fuel unit.

Since the power plant is defined as a machinery space of category A there are several demands on fire safety both in the IGC Code and in DNV's Rules for Classification of Ships. These rules and regulations often refer to applicable parts of Safety of Life At Sea, SOLAS. In DNV's rules for Classification of Ships, for example, the following can be found.

Pt.4 Ch.10 Sec.2
B 400 Fixed fire-extinguishing systems

401 For ships above 350 gross tonnage, a fixed fire-extinguishing system shall be provided in machinery spaces of category A and in cargo pump rooms. The system shall be as required for ships of 500 gross tonnage and above (ref. SOLAS Ch. II-2/10.4)

The rules and regulations in SOLAS, DNV's Rules for Classification of Ships and the IGC Code thoroughly handle the fire safety issue for a machinery space of category A. The problem is that there are contradictions between the design of an FSRU GTW-unit and the rules for where and how a machinery space of category A must be placed and designed. An example of this is taken from the IGC Code and presented here.

IMO – IGC Code
Chapter 3 Ship Arrangements

3.1.1 Hold spaces should be segregated from machinery and boiler spaces, accommodation spaces, service spaces and control stations, chain lockers, drinking and domestic water tanks and from stores. Hold spaces should be located forward of machinery spaces of category A, other than those deemed necessary by the Administration for the safety or navigation of the ship.

This will come in conflict with the design since the most probable solution will be to have the power plant on top of the storage tanks, which will oppose the requirement stated above. Another issue when designing a power plant that is considered as machinery space of category A is the rule 3.2.4:

IMO – IGC Code
Chapter 3 Ship Arrangements

3.2.4 Entrances, air inlets and openings to accommodation spaces, service spaces, machinery spaces and control stations should not face the cargo area…

This will obviously affect the installation as these details on the power plant will face the cargo area since it is installed on top of the storage tanks. This will oppose the fact that is stated in the rule.

4.1.3. Terrorism

There are no rules or regulations covering the terrorism hazard, but it should always be considered as a possible issue.

4.1.4. Turbine blade damage

The use of gas turbines on board a ship is nothing new in the ship industry. What is new is their location and size. In Rules for Classification of Ships Pt.4 Ch.3 Rotating Machinery, Drivers, gas turbines as well as steam turbines are discussed

Pt.4 Ch.3 Sec.2
B 300 Component design requirements

313 Rotors
…Blade loss will be acceptable provided it can be proven that the blade or blades loss can be contained, see 306 for details. The inspection and replacement procedure to be applied in such cases shall be submitted upon request…

This rule implies that the power plant needs to be properly cased in order to prevent a blade missile from damaging tanks or other equipment. This casing is not very complex or large, so a casing will not affect the design in any negative way.

4.1.5. Gas fuel supply failure

This hazard is mostly covered by the IGC Code 16.1.1, where it is stated that natural gas is the only cargo allowed to be used as fuel.

IMO – IGC Code
Chapter 16 Use of cargo as fuel

16.1.1 Methane (LNG) is the only cargo whose vapour or boil-off gas may be utilized in machinery spaces of category A and in such spaces may be utilized only in boilers, inert gas generators, combustion engines and gas turbines.

The space where the fuel should be utilized is considered to be a machinery space of category A, according to the IGC Code. Considering that the power plant is a machinery space of category A, chapter 16 of the IGC Code covers the technical solutions and operations when using cargo as fuel.

4.1.6. Excessive vibrations

In the Rules for Classification of Ships Pt.5 Ch.5 “Liquefied Gas Carriers”, vibrations are treated as a load to be considered.

> **Pt.5 Ch.5 Sec.5**
> *A 1000 Vibration*
>
> **1001** Design of hull and cargo tanks, choice of machinery and propellers shall be aimed at keeping vibration exciting forces and vibratory stresses low. Calculations or other appropriate information pertaining to the excitation forces from machinery and propellers, may be required for membrane tanks, semi-membrane tanks and independent tanks type B, and in special cases, for independent tanks type A and C. Full-scale measurements of vibratory stresses and or frequencies may be required.

The type of tank considered in this report is the membrane tank, which implies that the rules for further analysis are those concerning this type of tank.

> **Pt.5 Ch.5 Sec.5**
> *C 100 General*
>
> **101** For membrane tanks, the effects of all static and dynamic loads shall be considered to determine the suitability of the membrane and of the associated insulation with respect to plastic deformation and fatigue.
>
> **104** Special attention shall be paid to the possible collapsing of the membrane due to an overpressure in the inner barrier space, to a possible vacuum in the tanks, to the sloshing effects and to hull vibration effects.

> **Pt.5 Ch.5 Sec.7**
> *C 300 Fixing and protection of insulating materials*
>
> **305** Where powder or granulated insulation is used, the arrangement shall be such as to prevent compacting of the material due to vibration. The design shall incorporate means to ensure that the material remains sufficiently buoyant to maintain the required thermal conductivity and also prevent any undue increase of pressure on the containment system.

In addition to the Rules in Pt.5 Ch.5 the Classification Note No. 61.3 is to be used when a regasification unit is installed on board. In this Note some additional requirements are to be taken into account. Regarding vibrations, the piping system is of main concern.

> **Classification Notes No. 61.3 Regasification Vessels**
> *3. Piping design*
>
> …
> - The effect of vibrations imposed on the piping system in the regasification plant should be evaluated when vibrations excited by thrusters or other relevant excitation sources may be expected. Suitable countermeasures shall be implemented.
> …

As can be seen in the examples from DNV rules, vibration is an issue well known and considered. However, there are no rules or design guidelines for when the vibration source is mounted on top of the tanks. Furthermore, the vibrations created by the electrical generating set will be more excessive than for traditional LNG carriers and regasification units. Therefore a look at the additional class Vibration Class is to be considered.

Pt.6 Ch.15 Sec.1
A 100 Objective

101 The objective of the vibration class notation is to reduce the risk of failure in machinery, components and structures onboard ships, caused by excessive vibration. This will be achieved through a proactive, systematic risk-based plan for survey and measurement of main components onboard. Here, one of the main components will be the power plant, which implies that how the equipment associated with it will affect the rest of the vessel is to be considered in the risk-based plan.

Pt.6 Ch.15 Sec.1
B 100 General

101 The main reasons for evaluating and avoiding shipboard vibrations are:
- Vibration may impair the proper functioning of essential machinery and equipment.
- Vibration may cause fatigue damage to important structural elements in the ship.

109 Excessive vibration levels will normally not be accepted. However, a risk-based assessment of the actual position and level will be carried out and a possible dispensation evaluated. This may require that more extensive and frequent measurements have to be carried out or some sort of monitoring has to be installed.

With the rules and regulations hereby presented from Rules for Classification of Ships, Classification Note 61.3 Regasification vessel and Vibration Class, the hazard “excessive vibration” for a FSRU GTW-unit is properly addressed.

4.1.7. Incomplete combustion and CO_2 ingress into combustion chamber

There are two main reasons for these events to occur. Either there is some problem with the air intake to the gas turbine or problems with the exhaust system so that the exhaust gases will not leave the machinery space and therefore will be used as combustion air. The gas turbine installations and incomplete combustion are mostly covered by Pt.4 Ch. 3 Sec.2.

Pt.4 Ch. 3 Sec.2
F 500 Inlet and outlet passages

501 The air intake shall be arranged and located such that the risk of ingesting foreign objects is minimised.

502 The inlet ducting and components in way of inlet airflow, such as filters, silencers and anti-icing devices shall be constructed and mounted to minimise the risk of loose parts entering the gas turbine.

503 Icing at air intake shall be prevented by suitable means.

504 When considered necessary, according to gas turbine makers' requirements for inlet air quality, the air intake system shall incorporate an effective filtration system preventing harmful particles, including sea salt and harbour dust, from entering the compressor inlet. Pressure drop across filter to be monitored in accordance with Table E1.

505 Air intakes shall be placed such that the ingestion of spray due to ship motion and weather is kept within acceptable limits. The air inlet ducts shall incorporate a system for drainage of water.

506 Air intakes and exhaust outlet shall be so arranged that re-ingestion of combustion gases are avoided.

507 The flow path of the inlet air shall be as straight and clean as possible, with a minimum of obstacles, sharp corners and duct curving. This shall minimise the creation of vortex flow, pressure drops and uneven air distribution in the compressor inlet. Inlet airflow analyses or model tests may be required in special cases.

508 Pressure losses in air intake and exhaust ducting are not to exceed the specifications of the gas turbine manufacturer.

CO_2 ingression into the combustion chamber and any possible leakage or damage to the exhaust ducts are covered by Pt.4 Ch.3 Sec.2 (F 500, H 400).

Pt.4 Ch.3 Sec.2
F 500 Inlet and outlet passages

506 Air intakes and exhaust outlet shall be so arranged that re-ingestion of combustion gases are avoided.

511 Welds in exhaust ducts are not to be located in areas with stress concentration such as corners and dimension changes.
Pt.4 Ch. 3 Sec.2

H 400 Inlet and outlet passages

401 Bolts and nuts in the inlet ducting shall be properly secured, for example by welding. Weld slag to be carefully removed from all welds in the inlet ducting.

402 It shall be verified that no leakage exist in exhaust ducting and flexible bellow. The vicinity of the flexible bellow is not to include potentials for wear and chafe.

403 Welds in exhaust ducting shall be checked by relevant NDT method and be performed in accordance with quality requirements in ISO 5817 or equivalent. The manufacturer's acceptance criteria shall be fulfilled.

In addition to Pt.4 Ch.3 Sec.2 (F 500, H 400) the leakage of exhaust gases are further covered by Pt.4 Ch.3 Sec.1 (C 300).

Pt.4 Ch.3 Sec.1
C 300 Testing and inspection of parts

304 Cylinder or engine block, cylinder jacket or frame and exhaust valve housings shall be tested for leakage at the working pressure of the cooling medium.

As can be from the selections above the hazards are well addressed by existing rules.

4.1.8. Boiler explosion

The boiler explosion hazard is mainly a control and monitoring issue. If these systems work properly the event of a boiler explosion should not be a risk. The exhaust temperature is not to exceed a specified limit as stated in the following rule.

Pt.4 Ch.3 Sec.1
B 1600 Type testing data collection

1703 Stage B - Type test
...
c) The maximum average exhaust temperature is not to exceed the specified limit.
…

4.1.9. Over speed in steam turbine

This problem is mainly something that occurs as a result of monitoring control system failure. If the temperature is too high in the boiler, with over pressure as a result of this, there should be valves to release the pressure and prevent over speed. In the rules there is an example of how control measures should work:

> **Pt.4 Ch.3 Sec.2**
> *B 300 Component design requirements*
>
> **304** Bladed disks
>
> …in the event of a shaft or coupling failure, the resultant over speed should be limited by mechanical braking, such as intermesh.
> …

Some more examples of what DNV rules say about control and monitoring to prevent over speed is:

> **Pt.4 Ch.3 Sec.3**
> *E 300 Safety functions and devices*
>
> **302** Where exhaust steam from auxiliary systems is led to the propulsion turbine, the steam supply must be cut off at activation of the over-speed protective device.

> **Pt.4 Ch.3 Sec.2**
> *B 300 Component design requirements*
>
> **313** Rotors
> …
> Rotors shall be able to withstand instantaneous coupling shaft failure at full load. Rotor disk or shaft failure or separation as result of the ensuing over speed is not acceptable. See also 304. Blade loss will be acceptable provided it can be proven that the blade or blades loss can be contained, see 306 for details. The inspection and replacement procedure to be applied in such cases shall be submitted upon request.
> …

As can be seen from the cited rules above the risk of over speed is well covered as long as it can be shown that blade loss as a result of over speed can be contained.

4.1.10. Power export equipment concerns

There are no rules addressing the concerns and risks associated with the use of a swivel for export of electricity through a turret. However, the hazards related with a swivel are significant.

For the cable and transformer equipment there are no rules that directly address the use of these. There is, however, a recommended practice for the use of HVAC sub-sea cables, which is called DNV-RP-F401 "Electrical power cables in sub-sea applications".

> **DNV-RP-F401 Electrical power cables in sub-sea applications**
> **Sec. 1**
> *1. Introduction*
>
> This Recommended Practice is to be used as a supplement to ISO 13 628-5 /1/ with regards to electrical power cables. This ISO standard does not give requirements to such cables on a detailed level. This RP covers additional requirements for power cables being submerged in seawater at large water depths and/or being exposed to dynamic excitation, e.g. when suspended from floating production units.
>
> The RP is intended to be used together with /1/. In case of conflict between the ISO standard and this document the ISO standard shall prevail.
>
> It is a pre-requisite that power cables are designed and fabricated according to existing IEC standards.

This recommended practice only covers cables used for AC transmission. DC cables are not covered. For the DC cables there are no rules or recommended practices that directly address the design. There are, however, rules for designing pipeline systems and sub-sea umbilicals that might be sufficient together with ISO/API standards.

4.1.11. Integrated software-dependent systems

To avoid hazards caused by failure of the control systems on the FSRU GTW-unit, the unit could apply to the DNV-OS-D203 "Integrated Software-Dependent System", which today is tentative. The purpose of this standard is cited below.

> **DNV-OS-D203 Integrated Software-Dependent System (ISDS)**
> **Ch.3 Sec.3**
> *A 100 General*
>
> **101** The purpose of the classification process is to assure that the process and method requirements are satisfied in practice. Objective evidence shall be provided by all responsible parties involved in the integration of the integrated software-dependent systems. Objective evidence shall include documentation, electronic information and information gathered from interviews with personnel directly performing the activities.
>
> **102** In order to obtain the ISDS notation, it shall be demonstrated to the satisfaction of the Society that the activities required by the processes are effectively and efficiently applied in practice.

5. Results with requirements and recommendations

This section presents the results with requirements and recommendations based on the analysis of the additional hazards and associated rules and regulations as well as the preceding technical report.

5.1. General

An FSRU GTW-vessel is intended to store and vapourize LNG to be able to use natural gas as fuel for a power plant, which generates electricity for export to shore. This vessel is most probably located quayside or in shallow water even though offshore based could also be considered. For the best use of ship volume and for the easiest mounting of equipment topside, the kind of tanks preferably used are membrane tanks. Since the FSRU GTW-vessel is normally considered to be a moored ship like vessel, it should comply with applicable parts of the DNV's Rules for Classification of Ships related to gas services, as well as DNV's Classification Note No. 61.3 for Regasification vessels.

The gas carrier design might be affected by the need for the continuous production and export of electricity. Furthermore, the various types of equipment might affect the design when fitted to places where, on an ordinary LNGC, there is no equipment.

The regasification part of the FSRU GTW-unit is addressed in a regasification notation, Classification Note 61.3, which needs to be complied with. For the power plant and power export parts, a new notation should be considered. In this note the FSRU GTW-concept should be treated as a novel design and therefore a risk-based approach including HAZID techniques should be used.

5.2. Application

The application of the requirements and recommendations would be as an addition to DNV's Rules for Classification of Ships. It would also be additional or include the requirements from the Classification Note 61.3 (REGAS) with some exceptions. The REGAS includes issues concerning the high pressure export of natural gas. This is not an issue on an FSRU GTW-unit and therefore it is unnecessary to consider it in a potential classification note for an FSRU GTW-unit.

5.3. Power plant

The combined cycle power plant needs, as a minimum, to fulfil Pt.4 Ch.3 (Rotating Machinery). Also, if the total power output exceeds 375 kW it will be considered as a machinery space of category A and therefore needs to comply with Pt.5 Ch.5 Sec.16 and anticipatory requirements when using the cargo as fuel. The rules and regulations concerning machinery space of category A is in some part not possible to comply with depending on the arrangement and placement of the power plant. The purpose of these regulations is that a sufficient level of safety is obtained. For a concept such as the FSRU GTW-unit, this conflict between design and regulations is a problem. It is recommended that instead of using prescriptive regulations, implementing a risk-based design method should be used where a proper risk assessment is performed, proving that the same level of safety is obtained without fully complying with the rules. According to Fagan[4], for example, there in existence offshore

[4] Conn Fagan (Business development manager for offshore gas projects, DNV, Hövik) stated in personal communication during the project time January-June 2012.

installations with power generating units on top of the storage tanks where adequate safety has been documented.

5.4. Power export equipment

The requirements and recommendations for the power export equipment are discussed in this section.

Swivel

Where a swivel is used, there are some concerns that need to be addressed. Since the technology is new there are no rules or regulations in existence regarding this type of equipment. The swivel will be the main additional concern of an offshore FSRU GTW-unit. This is the part that is most sensitive to current fluctuations and if a short circuit or flame arc occurs it can threaten the safety of the personnel and the functionality of the unit. A thorough risk assessment of a swivel installation and the effect of a transformer and IS-limiter need to be conducted and analysed before installing such equipment. SBM Offshore has developed some HV swivels with a capacity of almost 300 MW. These have not yet been tested on any kind of offshore vessel so further analysis is needed.

Furthermore, the temperature between the slip ring and the brushes might be an issue to analyse and if found that the temperature risks being too high, some monitoring device has to be installed. How this is to be done and at what temperature such a safety measure should cut off the power flow is to be properly designed.

Cable

For the deep water application, the cables need to be designed with a crush load capacity, tensile capacity, collapse resistance of the water barrier and fatigue capacity of the water barrier in mind. There is a lack of standards for sub-sea DC power cables even though these have been in use for many years. There are some ISO/API standards and acceptance criteria and some DNV standards, for example the ISO 13628-5 Sub-sea Umbilicals. For AC transmission the recommended practice, DNV-RP-F401, is sufficient for AC cable design. Both AC and DC transmission cables should be designed with an overcapacity to be able to withstand current fluctuations.

Transformer

Transformers are something that have been used on board offshore units before. However, a risk assessment should be conducted in order to decide how large the risk is for ignition of the oil in the transformers. A comparison of the consequence of an explosion between a transformer mounted topside with free space around it and a transformer put below deck in a relatively confined space should also be conducted.

5.5. General safety

Risk assessment

Since this is novel technology a risk assessment should be conducted and at least include the following:

- Collision.
- Fire and explosion.
- Dropped object.
- Cryogenic leakage.
- Vibration.
- Effect on structural strength and fatigue from a power plant when an FSRU is converted to FSRU GTW.
- Impact on stability characteristics when an FSRU is converted to FSRU GTW.

It is worth noting that in the Classification Note No. 61.3 for Regasification vessels it is stated that a high pressure gas leak is a hazard that needs attention in a risk assessment. This hazard exists because the FSRU exports natural gas to shore through pipelines, which is done under high pressure. This is not the case for an FSRU GTW-vessel since it exports electricity instead of natural gas and therefore this risk will probably be discarded as a negligible risk when performing a risk assessment.

Control and monitoring

The control and monitoring system shall be in accordance with DNV's Rules for Classification of Ship Pt.4 Ch.9. Furthermore, the FSRU GTW-unit will most probably have a very complex ISDS, which needs to be taken into consideration. It is recommended to have the vessel designed according to the additional class DNV-OS-D203 "Integrated Software-Dependent Systems"

5.6. Implications on standard gas ship design

The design of the gas carrier has to be revised in order to withstand the effects from continuous power production. The most essential areas are addressed in the following text.

Environmental conditions

The impact on the environment and the local regulations need to be taken into consideration. For example, the open-loop water-based power plant and the effect on the local ecosystem from emitting cold water need to be analysed.

Structural support

How the mounting of heavy rotating machinery and other equipment associated with the power plant affects the structural design of the membrane tanks needs to be considered. The weight of the power-generating package will be significant, which implies that calculations with regard to structural strength and fatigue need to be more extensive.

Due to the installed power plant and electrical equipment, such as transformer and generator, stability calculations need to be performed. The power plants and electrical equipment will have a significant weight that will affect the stability properties of the unit. This needs to be calculated according to Pt3. Ch3 to confirm that sufficient measures have been taken when designing the unit.

Sloshing
Operating the FSRU GTW-unit will mean that the tanks will have various filling levels. This causes damages due to of sloshing more probable. The design of the ship with regard to sloshing should be made according to DNV Classification Note No. 30.9 and No. 61.3.

Vibrations
In DNV's Rules for Classification of Ships Pt.5 Ch.5 Liquefied Gas Carriers it is stated that full-scale measurements of vibratory stresses and or frequencies may be required. For an FSRU GTW-unit with more potential vibration sources such measurement will, not may, be required.

Measurements need to be carried out in order to ensure that the vibration is at an acceptable limit, and this might be done by compliance with the vibration class. Therefore, the potential classification note will cover the rules and regulations covered by the Vibration Class stated in Pt.6 Ch.15.

Stability
The vessel needs to comply with the Rules for Classification of Ships Pt.3 Ch.3 Sec.9 and due to the modification of the ship, such as added weight and increased area that can be affected by the wind, a narrow stability calculation has to be performed.

The damage stability demands will put requirements on the top side structure due to the inclination of the unit. This needs to be considered when installing the top side equipment and its supporting structure.

Depending on the operational location of the FSRU GTW-unit some rules and regulations concerning stability might not need to be fulfilled since the level of safety can be proven as being preserved. For example, if the FSRU GTW-unit is located in a sheltered area, parts of "DNV-OS-C301 Stability and Watertight Integrity" might not be necessary to comply with in order to preserve sufficient safety from a stability perspective.

6. Conclusions

As the demand for energy derived from natural gas is increasing worldwide, new innovative ideas for delivering it have been developed. The FSRU GTW-concept is a result of this increasing interest in natural gas fuelled energy supply. In comparison with an FSRU it has the same equipment on board. The addition is that a power plant is mounted on the deck with the objective of producing electricity for export to shore instead of natural gas as is the case for an FSRU.

The objective with this thesis is to identify the risks relevant to an FSRU GTW-concept and present requirements and recommendations. These are based on an evaluation of how these risks are handled in existing rules and regulations and will provide a basis for future development of rules for an FSRU GTW-unit.

The method for fulfilling the objective is the IMO's FSA methodology, which is a well established approach for decision-making. As a step towards recommendations for decision-making it provides guidelines and tools for how to identify hazards and how they are caused and what the consequences might be. It is concluded that if these guidelines and tools are properly used, it can provide relevant requirements and recommendations as a basis for rule development.

It is concluded that the overall main challenge with this concept are the new hazards introduced by the power plant. Additionally, for the extreme case of an offshore turret-moored application the main technical challenge is the power export system. This requires the use of an HV swivel, which is a very novel technology and has not yet been thoroughly tested in operation. This equipment implies a major risk contribution to the whole unit if no proper risk control measure is installed. Furthermore, the ISDS needs to be properly designed and tested in order to handle the interacting operational functions.

The heavy rotating machinery mounted on deck and the complexity in the operational functions requires that additional classes such as Vibration class and ISDS class are to be considered. Furthermore, it was found that if the gas turbines and their fuel supply systems are to be considered a machinery room of category A, as described in the IGC Code, there are conflicts between the design and the rules. It is, for example, stated that boilers, machinery and such should be segregated from the storage facilities. This poses a problem since the power plant will most probably be mounted on top of the storage tanks. A general solution to this conflict is to perform a thorough risk assessment in order to ensure the same level of safety as required by existing rules and regulations.

The hazard identification done according to IMO's FSA-methodology resulted in risks that are additional in comparison with an FSRU. The requirements and recommendations would be more justified if all the steps of an FSA were performed. For an assessment of that kind to be relevant, however, there should be a customer and a complete concept design. The customer would provide acceptance criteria of hazardous events and a complete design would allow for a more detailed study of the equipment on board.

Finally, the conclusion of this project is that there is a need to gather various rules and design guidelines together with additional requirements in a Classification Note for regasification vessels with power generation.

7. Future work

This section addresses areas that are recommended for further analysis in future projects with a similar objective.

- For more detailed results with, for example, numbers on frequencies of failure modes and acceptance criteria, more experts would have to be involved as well as a customer. This would also be necessary in order to perform all the steps of an FSA, which is suggested.

- In this study, it has been explained how to increase the efficiency and thereby reduce the emission per produced MW of the power generating unit by using a combined cycle process. To further decrease the CO_2-emissions, carbon capture technologies are also suggested for looking into. Some of these technologies are described in Appendix C. There is a potential to further reduce the environmental impact by implementing this type of technology. A study involving this technology will result in an even more complex HAZID and most probable also other hazards that need to be analysed against existing rules and regulations.

- Concerning rules and regulations, it was concluded that there are some gaps and contradictions. This can be further analysed to see if there are more gaps and contradictions or if there are rules applicable to an FSRU GTW-unit which have been missed for giving an even better input for future rule development.

- A closer look at ISO/API standards for cables should also be included in a future study. These standards have only been briefly looked at since they are expensive to gain access to.

- Regarding the most challenging part of an FSRU GTW-unit located offshore, it is crucial to carry out a proper and thorough risk assessment of how the installation of a high-voltage swivel affects the overall safety.

- Future work would finally be to develop a classification note where applicable rules and regulations are described as well as additional ones. This thesis can be used as an input to such a development.

8. References

[1] U.S. Energy Information Administration. *International Energy Outlook 2011*. September 2011. http://www.eia.gov/forecasts/ieo/ (11 May 2012).

[2] R.R. Charpentier. *Natural Gas Resources, Global Distribution of*. United States Geological Survey. Denver, Colorado, United States. June 2004.

[3] Det Norske Veritas. *Floating Liquefied Gas Terminals, Offshore Technical Guidance OTG-02*. March 2011.

[4] Det Norske Veritas. *Classification Notes No. 61.3 Regasification Vessels*. May 2011.

[5] V. Eskola. *New Floating Power for Asia*. Inside Energy. March 2011.

[6] T. Watanabe, H. Inoue, M. Horitsugi, S. Oya. *Gas to Wire System (GTW) for Developing "Small Gas Field" and Exploiting "Associated Gas"*. International Oil & Gas Conference and Exhibition in China. Beijing, China. 5-7 December 2006.

[7] A.A. Olajire, *CO2 capture and separation technologies for end-off-pipe applications - A review*. Energy, Vol. 35, Issue 6, pp. 2610-2628. June 2010.

[8] A.D. Papanikolaou. *Risk-Based Ship Design – Methods, Tools and Applications*. Berlin, Germany: Springer-Verlag. 2009.

[9] H. Hoppe. *Goal-Based Standards – A new approach to the international regulation of ship construction*. Maritime Safety Division, International Maritime Organization.

[10] R. Skjong. *Goal Based Regulations*. Open workshop on Risk-Based approaches in the maritime industry at National Maritime Research Institute. Tokyo, Japan. 22-23 May 2007.

[11] International Maritime Organization. *Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process*. April 2002.

[12] S. Nygård Frangos. *Company for Dr. Bird*. Inside Energy. March 2006.

[13] Det Norske Veritas. *Offshore Standard DNV-OS-E301 Position Mooring*. October 2010.

[14] D.M. Larruskain, Zamora, A.J. Mazón, O. Abarrategui, J. Monasterio. *Transmission and Distribution Networks: AC versus DC*. Department of Electrical Engineering University of the Basque Country. Bilbao, Spain. 2005.

[15] International Maritime Organization. *International Code for The Construction and Equipment of Ships Carrying Liquefied Gases in Bulk*. 2nd Edition. London: International Maritime Organization. 1993.

[16] Central Commission for the Navigation of the Rhine (CCNR), Oil Companies International Marine Forum (OCIMF). *International Safety Guide for Inland Navigation Tank-barges and Terminals*. Strasbourg Cedex, France: Central Commission for the Navigation of the Rhine. 2010.

[17] M. Hayashi. *Thermal fatigue strength of type 304 stainless steel in simulated BWR environment*. Mechanical Engineering Research Laboratory, Hitachi, Ltd. Ibaraki, Japan. 23 September 1997.

[18] Siemens Energy website. http://www.energy.siemens.com/hq/en/power-generation/gas-turbines/sgt5-8000h.htm#content=Technical%20Data (31 May 2012).

[19] Wärtsilä Engines website. http://www.wartsila.com/en/engines/medium-speed-engines/wartsila50DF (31 May 2012).

[20] R. Kehlhofer. *Combined-Cycle Gas & Steam Turbine Power Plants*. London: Prentice-Hall, Inc. 1991.

[21] Engineer Live website. http://www.engineerlive.com/media/images/large/large_GE_6BHeavyDutyGasTurbineIllustration.jpg (31 May 2012).

[22] M.P. Boyce. *Gas Turbine Engineering Handbook*. 4th Edition. Oxford, UK: Elsevier Inc. 2012.

[23] H.I.H. Saravanamuttoo, G. Frederick, C. Rogers, H. Cohen. *Gas Turbine Theory*. 5th Edition. Harlow, England: Pearson Education Limited. 2001.

[24] M. Ishikawa, M. Terauchi, T. Komori, J. Yasuraoka. *Development of High Efficiency Gas Turbine Combined Cycle Power Plant*. Technical Review, Vol. 45, No. 1. Mitsubishi Heavy Industries, Ltd. March 2008.

[25] Det Norske Veritas. *OPERA – Offshore Power hub for the new ERA*. DNV report no: / 13UVY3F-6. Hövik, Norway. 2012. [For internal use only. Contact DNV for distribution].

[26] SBM Offshore presentation. *The import/export of electrical power from/to FPSO's.* June 2010. http://www.tekna.no/ikbViewer/Content/798897/09%20-%20SBM%20-Poldervart.pdf (31 May 2012).

[27] Det Norske Veritas. *Offshore Standard DNV-RP-F401 Electrical Power Cables in Subsea Applications.* February 2012.

[28] Aker Solutions website. http://www.akersolutions.com/Documents/Subsea/Brochures/Umbilical%20broshure_low%20res.pdf (31 May 2012).

[29] Det Norske Veritas. *Offshore Standard DNV-RP-D201 Integrated Software Dependent Systems*. October 2009.

Appendix A. The FSA methodology

In this appendix a thorough description of the FSA methodology is presented as well as an example of how it can be used on a risk assessment of a swivel installation.

"FSA is a rational and systematic process for assessing the risks relating to maritime safety and the protection of the marine environment and for evaluating the costs and benefits of IMO's options for reducing these risks." (IMO, 2002, p.1, [11])

The FSA methodology [11] may be used as a tool in the IMO rule-making process and can be used in the evaluation process of new regulations that concerns the maritime safety and the marine environment. But it also considers the technical and operational aspects as well as human influence and costs as issues.

The FSA process can be divided into five different steps. The steps are as follows:

(1) Identification of hazards.
(2) Risk analysis.
(3) Risk control options.
(4) Cost-benefit assessment.
(5) Recommendations for decision-making.

The steps are further explained in the following sections. Before step 1 in the process begins, the problem has to be defined and relevant boundary conditions and constraints are set. The definition of the problem should be defined in relation to the regulations that will be developed or reviewed by the project.

A.1. Identification of hazards

At this stage the various hazards and associated scenarios are identified and which of these that can contribute to accidents. The approach should, according to IMO [11], comprise one creative part and one part that is based on previously identified hazards. The creative part will be particularly interesting in this project since the FSRU GTW-concept has not been tried. The purpose of this part is to find any new hazards associated with this technology.

The identified hazards should go through a course analysis to identify the possible causes and consequences that can occur. Based on the FSA method [11], this can be managed in several ways, for example an event and fault tree and the "what if" method, etc.

The hazards identified and their associated scenarios should be ranked in order to prioritize them and to discard scenarios of minor significance. To be able to prioritize them, a risk level is to be associated with each hazard using a combination of available data and judgement. The ranking is preferably visualized in a risk matrix as in Table 2 with probability and consequence as categories. When it has been concluded what the consequence and probability of a failure mode is, it can be put in the right place in the risk matrix in order to decide which failure modes need more attention, which are unacceptable and which are acceptable with no further work needed. This can be summarized as follows:

Low risk: Conclusion based on a qualitative assessment
Medium risk: Investigate further
High risk: Generally unacceptable, investigate further

Table 2. Risk matrix.

Risk matrix						
	Probability					
Consequence	Very remote	Remote	Low	Possible	Probable	Frequent
Negligible	Low	Low	Low	Low	Low	Low
Slight	Low	Low	Low	Low	Low	Medium
Minor	Low	Low	Low	Low	Medium	Medium
Significant	Low	Low	Low	Medium	Medium	High
Major	Low	Low	Medium	Medium	High	High
Catastrophic	Low	Medium	Medium	High	High	High

A.2. Risk analysis

After all possible hazardous scenarios that are unacceptable or tolerable under certain circumstances have been identified, a more detailed investigation of the causes and consequences is performed.

Methods described by IMO [11] that can be used for this are among others the following:

- Fault Tree Analysis.
- Event Tree Analysis.
- Failure Mode and Effect Analysis (FMEA).
- Hazard and Operability Studies (HAZOP).
- What If Analysis Technique.
- Risk Contribution Tree (RCT).

The result of this step comprises an identification of the high-risk areas, which need to be addressed.

A.3. Risk Control Options

This step aims at creating risk control options for existing risks and for new risks arising from the use of new technology or from new methods of operation and management. The hazards have been identified in the preceding risk analysis and also in which areas effort should be focused. To determine risk control, four key aspects are to be taken into consideration:

- Risk levels.
- Probability.
- Severity.
- Confidence, where the risk models have uncertainties concerning either risk, severity or probability.

The hazards still under consideration are those that are in the yellow or red areas in the risk matrix. The yellow field in Table 2 denoted as medium risk is also often called the ALARP zone, which means As Low As Reasonably Practicable. It might be possible to create a risk control option for failure modes that fall into this zone, but the cost for this might exceed the benefits and gains. On an LNG carrier, for example, there are signs saying that it is not allowed to smoke on board. This is a typical risk control option that would make the intolerable risk that personnel ignite a gas leak because of smoking to become ALARP. Another example from IMO [11] is when a passenger is travelling with a ferry the risk of doing so can never be "intolerable", but neither can it be so safe that the risk is "negligible" and no precautions need to be made. Therefore, the risk should be made "ALARP".

A.3.1. RCMs

If risks are not sufficiently controlled by existing measures, new risk control measures (RCMs) need to be identified, according to IMO [11]. To do this, risk attributes and causal chains can be included in the measures. Risk attributes relate to how a measure might control a risk, and causal chains relate to where, in the chain of events leading to fatalities, risk control can be introduced. The RCMs should primarily aim at reducing the frequency, mitigating the effect of failures, alleviating the circumstances in which failures may occur and mitigating the consequences of possible accidents.

A.4. Cost-benefit assessment

At this stage, an analysis of the benefit versus cost for implementing the RCMs, created in the previous step, is made. The analysis can be carried out by several different methods and techniques. Methods defined by IMO [11] that can be used are, for example, Gross Cost of Averting a Fatality (Gross CAF) and Net Cost of Averting a Fatality (Net CAF). The aim is to be able to rank the RCMs from a cost-beneficial way to make the recommendation process in the next step easier.

A.5. Recommendations for decision-making

The recommendation should, according to IMO [11], be based on the results from the ranked and analysed hazards. The risk control options that have been analysed with regard to both benefits and costs will also affect the recommendations.

A.6. Example

In this section, an example of a full FSA of a swivel installation is presented.

Identification of hazards

The following table presents the possible hazards found for a swivel installation.

Table 3. Hazard identification of a swivel installation.

Hazard	Cause	Consequence
Flame arc or short circuit	Contamination of insulating oil. Mechanical breakdown that leads to contact between slip rings.	Insulation oil evaporate Internal pressure increase
Oil leak	Damage of swivel equipment	Oil spill or/and fire

A. Flame arc or short circuit.
B. Oil leak.

The hazards are ranked with the use of a risk matrix, see Table 4, where each one of the hazards are allocated a probability and consequence estimation. The product of the variables is defined as the risk.

Risk = f(probability × consequence)

The areas in the risk matrix represent the following;

Green → Low risk
Yellow → Medium risk (ALARP)
Red → High risk

Table 4. Risk matrix presenting the risk level of the hazards.

Risk matrix						
	Probability					
Consequence	Very remote	Remote	Low	Possible	Probable	Frequent
Negligible						
Slight						
Minor						
Significant	B					
Major						
Catastrophic					A	

According to the risk matrix the hazards are ranked as follows;

(1) Flame arc/short circuit.
(2) Oil leak.

Due to the negligible risk of oil leakage it needs no further evaluation. Hazard A needs to be further evaluated.

Risk analysis

A dangerous flame arc can occur within the swivel as a consequence of contaminated insulation oil or by a mechanical breakdown leading to contact between slip rings. If the flame arc occurs because of contamination of the insulating oil it will probably be longer. However, if it is caused by a mechanical breakdown, for example a brush loosening, and comes closer to, or into contact with a slip ring, the energy in the shorter flame arc is likely to cause fragments of the brush and slip ring to loosen and contaminate the oil, reducing its insulating capacity.

Therefore, even a shorter flame arc caused by mechanical breakdown could lead to a larger one, with more energy, between two slip rings.

What can be seen in Table 5 is that the frequency of fatalities due to the swivel installation is approximately 0.31% per ship year. If this is larger than the acceptance criteria set by the customer, control options need to be analysed before considering an installation of this equipment.

Table 5. Event tree of short circuit or flame arc.

Flame arc or Short circuit	Evaporation of insulation oil	Internal pressure increase	Explosion	Fire	Probability of fatalities	Fatality among crew	Frequency	Consequence	Risk
0,03	1	0,99	1	0,94	1	0,1	0,027918	0,1	0,0027918
				0,06	1	0,15	0,001782	0,15	0,0002673
			0	0	0		0	0	0
				1	0		0	0	0
		0,01	1	0,94	1	0,1	0,000282	0,1	0,0000282
				0,06	1	0,15	0,000018	0,15	0,0000027
			0	0	0		0	0	0
				1	0		0	0	0
	0	0	0	0	0		0	0	0
				1	0		0	0	0
			1	0	0		0	0	0
				1	0		0	0	0
		1	0	0	0		0	0	0
				1	0		0	0	0
			1	0	0		0	0	0
				1	0		0	0	0
						Total risk	0,309	Percent fatalities per ship year	

Risk control options

As described in the previous section, the risk of flame arc can be unacceptable and therefore a risk control option is recommended. Since the pressure build up is so rapid, if a flame arc occurs, the safeguard of cutting the power is not quick enough. The pressure might have exceeded the design limit before the power is cut off.

The IS-limiter and transformer installation will not lower the frequency of the event but the consequence will be less severe since the power is shut off more quickly and the voltage will stay unchanged. The transformer will also reduce the energy in a potential short circuit and consequently the oil evaporation rate.

Even though the frequency of the flame arc event is unchanged, the frequency of an explosion due to a flame arc is reduced. This is because the frequencies of flame arc and IS-limiter failure are multiplied to get the frequency of an explosion. With the IS-limiter installed the frequency of the event of an explosion due to flame arc is reduced to approximately 0,00006 %, which, hopefully, is below the acceptance criteria set. This can be seen in Table 6.

Table 6. Event tree of short circuit or flame arc with IS-limiter.

Flame arc or Short circuit	Failure of Is-limiter	Evaporation of insulation oil	Internal pressure increase	Explosion	Fire	Probability of fatalities	Fatality among crew	Frequency	Consequence	Risk
0,03	0,0002	1	0,99	1	0,94	1	0,1	5,5836E-06	0,1	5,5836E-07
					0,06	1	0,15	3,564E-07	0,15	5,346E-08
				0	0	0		0	0	0
					1	0		0	0	0
			0,01	1	0,94	1	0,1	5,64E-08	0,1	5,64E-09
					0,06	1	0,15	3,6E-09	0,15	5,4E-10
				0	0	0		0	0	0
					1	0		0	0	0
		0	0	0	0	0		0	0	0
					1	0		0	0	0
				1	0	0		0	0	0
					1	0		0	0	0
			1	0	0	0		0	0	0
					1	0		0	0	0
				1	0	0		0	0	0
					1	0		0	0	0
							Total risk	0,0000618	Percent fatalities per ship year	

Recommendations

As can be seen in the previous section the installation of a transformer and an IS-limiter will have a significant risk-reducing effect. Introducing this equipment leads to a negligible increase in overall risk and should therefore definitely be considered for installation.

Appendix B. Hazard identification

This appendix contains five different tables showing all the identified hazards with their associated cause and consequence. Table 7 shows the hazards related to the FSRU GTW-unit in general. The other four tables, Tables 8, 9, 10 and 11, present the hazards associated with each subsystem, respectively.

Each table consists of three columns where the first column presents the identified hazards. The second column explains why this hazard might occur and the third column presents possible consequences of a certain hazard.

The additional hazards presented in Section 4 have been distinguished from the hazards presented in this appendix.

Table 7. Hazard identification of an FSRU GTW-unit in general.

Hazards	**Cause**	**Consequence**
Failure in storage and transfer systems	See Table 8	See Table 8
Failure in regasification system	See Table 9	See Table 9
Stability issues	Decreased GM due to installed weight above CG. Sloshing Green water Incorrect loading operation Water ingress because of structural damage	Increased consequence of initial instability. Can cause roll, pitch and list of the unit. Can cause structural damage to the equipment place on deck due to significant heel.
Collision	Drifting vessel Bad weather	Structural damage
Grounding	Bad weather Navigation system malfunctioning	Damage to hull Water ingress Ship sinks
Fire/explosion	A combination of ignition and fuel in an uncontrolled manner	Fire escalation
Failure in power plant	See Table 10	See Table 10
Failure in electrical export system	See Table 11	See Table 11
Terrorism	Terrorists Pirates	Fire/explosion Personnel injuries and fatalities Economical loses
Loss of mooring	Bad weather Mooring system is damaged by other means	Cryogenic leakage if a loading operation is on-going Power cable damage
Navigation systems of 3rd party vessels and shuttle tankers are disturbed by excessive magnetic fields	Large transformer installations and large high voltage direct current cables	Collision between FSRU GTW-unit and the disturbed shuttle tanker.

Table 8. Hazard identification transferring and storage systems.

Hazard	Cause	Consequence
Breakdown of headers, pumps and valves	Dropped objects Insufficient maintenance	No inert gas Overfilling
Sloshing	Significant wave height over design limit in addition with a filling level between 70% and 10% for membrane tanks	Might lead to structural failure of tank, which can lead to cracks and leakage
Roll over	Long-term storage can lead to stratification of LNG in tank. Shift in density between the layers because of heating of high-density layer. Loading of different qualities may cause stratification	Very high boil off rate, which can cause over pressure explosion
Fire/explosion	Gas leak in combination with ignition source. Ignition can be caused by potential difference between FSRU GTW-unit and shuttle tanker, engines, machinery and/or human errors. Explosions can be caused by rapid heating of LNG due to spill in water, also called rapid phase transition.	Structural damage, which can lead to leakage. Injuries and fatalities
LNG leakage	Loading arm failure Cracks in tanks or pipes. Failure of export, loading, inert gas, blanking, pump and valve systems	Cryogenic effects on structure Injuries and fatalities Pool of LNG Rapid phase transition
Gas leakage	Cracks in tanks or pipes. Failure of export, inert gas, blanking, pump and valve systems	Explosion/fire Injuries and fatalities
Oxygen in storage tank in combination with natural gas	Inert gas system failure	Explosion/fire
Structural failure of piping	Dropped object	Gas or LNG leakage
Excessive boil off gas rate	Temperature too high in storage tanks	Environmental pollution
Failure of loading equipment	Collision Rolling Dropped objects on loading equipment Loss of mooring between the vessels	LNG leakage

Table 9. Hazard identification of regasification system.

Hazard	Cause	Consequence
Fire/explosion	Gas leak in combination with ignition source.	Personnel injuries Fatalities Structural damage
High pressure leakage	Break down of send out pump.	Fire/explosion Personnel injuries Fatalities
LNG leakage	Cracks in pipes and flanges	Release of LNG Fire/explosion Cryogenic effects on structure Personnel injuries
Ice in thermal loop	Not enough flow of warming medium	Clogging
Release of cold seawater	Open-loop water-based regasification system	Eco-system disturbance
Excessive thermal gradients	Improper cool-down procedure	Cracks Leaks Flange failures
Thermal fatigue	Thermal stresses	Structural failure

Table 10. Hazard identification of power generating system.

Hazard	**Cause**	**Consequence**
Fire/explosion	Leakage of gas fuel in an amount that will reach the lower explosion limit	Fatalities and major material damage
High pressure gas leak	Rupture of fuel gas pipes	Explosion/fire Injuries and fatalities
Turbine blades failure	Due to particles in the combustion air or other impurities fatigue cracks can occur.	Can cause vibration in structure Can cause an uneven flow through the turbine
Fuel gas supply failure	Failure in valves and pumps Failure in regasification system or earlier in the flow chain	The power plant will not generate any electricity
Excessive vibrations	Unbalanced turbine setup Can escalate if the rotors are damaged in the turbine	Fatigue in the ship structure. Fatigue in process structure Working environment is affected by vibrations
Incomplete combustion	Wrong proportions of combustion air and gas fuel.	Will release methane through exhaust system, which is a dangerous green gas. The methane can ignite because of the heat in the exhaust system. Possible fire in HRSG Loss of production
Boiler explosion	Overpressure in steam boiler	Explosion/fire Injuries and fatalities
Leak of CO2 into combustion chamber	Caused by excessive exhaust gas leak	Incomplete or no combustion. Loss of production.
Over speed in steam turbine	Boiler in HRSG too hot	Rotor failure in steam turbine

Table 11. Hazard identification of power export systems.

Hazard	**Cause**	**Consequence**
Flame arc/short circuit	Contamination of insulating oil. Mechanical breakdown that leads to contact between slip rings.	Insulation oil evaporate Internal pressure increase
Cable failure	Too high current in the export cable	Production failure Environmental impact and 3rd party impact.
Transformer explosion	Vapourization of cooling and insulating oil	Injuries of personnel and structural damage

Appendix C. Carbon-capture technologies

Capturing carbon dioxide, CO_2, is an essential parameter for limiting the environmental impact that the combustion of hydrocarbons induces. According to Olajire [7], CO_2 emissions can be reduced for power generation by three capture technologies: post-combustion, pre-combustion decarborization and oxyfuel combustion. Some important factors in selecting capturing systems are the CO_2-concentrations in the gas stream, the pressure in the gas stream and the fuel type. Below is a description of the first two mentioned which could be examples of how it is possible to further reduce the environmental impact of an FSRU GTW-unit.

Post-combustion

The post-combustion technology involves separating CO_2 from the flue gas produced by fuel combustion. Post-combustion is, according to Olajire [7], a downstream process, which in combination with a typically low concentration of CO_2 in power plant flue gas means that a large volume of gas has to be handled. This results in large equipment sizes and high capital cost. Significant design challenges are the low partial pressure of the CO_2 in the flue gas and the high temperature. Furthermore, the low CO_2 concentration needs powerful chemical solvents to be used and releasing the CO_2 will require a large amount of energy. Some of the separation technologies that exist within this category are chemical absorption, gas-separation membranes and low temperature distillation.

Pre-combustion carbon capture

When using natural gas as fuel, several methods for carbon capture such as steam reforming, partial oxidation and autothermal reforming are used. The steam reforming method converts CH_4 and water vapour into CO and H_2, the process needs temperatures from 700 °C to 850 °C. As explained by Olajire [7], partial oxidation uses exothermic reaction of oxygen and methane, while autothermal reforming is a combination of both methods. After the shift reaction, an acid gas removal solvent separates the CO_2. Since both the CO_2 concentration and the pressure are higher in pre-combustion capture than in post-combustion capture the equipment is much smaller and different solvents can be used, with lower penalties for regeneration.