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Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του πτυχίου μου».

Η Δηλούσα

Abstract

The aim of this Master thesis is the study of Floating Storage and Regasification Unit (FSRU) in order to supply Natural Gas (NG) to end users.

In this context the structure of the dissertation is as follows. Chapter 1 introduces Floating Storage and Regasification Units (FSRUs) where Liquefied Natural Gas (LNG) is regasified in order to be distributed to end users. We identify the advantages and disadvantages of these units compared to the corresponding liquefied natural gas onshore terminals.

In Chapter 2 we focus on the description and analysis of the processes that take place in FSRUs, from the transfer of liquefied natural gas to the unit, its storage, its regasification and its delivery to the end user.

In Chapter 3 we attempt to outline the basic design of a floating unit with storage and regasification capabilities, designing the process flow diagram, simulating two cases of different delivery pressure of natural gas, analyzing the mass-energy balances, identifying the equipment required and examining the safety issues of the station, staff and environment.

Finally, the most important key advantages of FSRUs are summarized and the current situation for FSRUs in Greece is presented.

Keywords
LNG, NG, FSRU

Περίληψη

Ο στόχος αυτής της μεταπτυχιακής εργασίας είναι η μελέτη του Πλωτού Σταθμού Επαναεριοποίησης και Αποθήκευσης Υγροποιημένου Φυσικού Αερίου με σκοπό την παροχή Φυσικού Αερίου (ΦΑ) στον τελικό χρήστη.

Στο πλαίσιο αυτό, η διάρθρωση της διπλωματικής διατριβής είναι η ακόλουθη. Στο Κεφάλαιο 1 γίνεται μια εισαγωγή αναφορικά με τους πλωτούς σταθμούς επαναεριοποίησης και αποθήκευσης υγροποιημένου φυσικού αερίου, όπου το Υγροποιημένο Φυσικό Αέριο (ΥΦΑ) υφίσταται επαναεριοποίηση προκειμένου να διανεμηθεί στους τελικούς χρήστες. Εντοπίζουμε τα πλεονεκτήματα και τα μειονεκτήματα των μονάδων αυτών σε σύγκριση με τους αντίστοιχους χερσαίους σταθμούς επαναεριοποίησης και αποθήκευσης υγροποιημένου φυσικού αερίου.

Στο Κεφάλαιο 2 επικεντρωνόμαστε στην περιγραφή και ανάλυση των διεργασιών που λαμβάνουν χώρα στους πλωτούς σταθμούς επαναεριοποίησης και αποθήκευσης υγροποιημένου φυσικού αερίου, από την μεταφορά του υγροποιημένου φυσικού αερίου στον σταθμό, την αποθήκευση, την επαναεριοποίηση και την παράδοση του στον τελικό χρήστη.

Στο Κεφάλαιο 3 επιχειρούμε να δώσουμε το περίγραμμα του βασικού σχεδιασμού μιας πλωτής μονάδας με ικανότητα αποθήκευσης και επαναεριοποίησης, σχεδιάζοντας το διάγραμμα ροής των διεργασιών, προσομοιώνοντας δύο περιπτώσεις διαφορετικής πίεσης παροχής φυσικού αερίου, αναλύοντας τα ισοζύγια μάζας-ενέργειας, εντοπίζοντας τον απαιτούμενο εξοπλισμό και εξετάζοντας τα θέματα ασφάλειας του σταθμού, του προσωπικού και του περιβάλλοντος. Τέλος, συνοψίζονται τα σπουδαιότερα βασικά πλεονεκτήματα των πλωτών σταθμών αποθήκευσης και επαναεριοποίησης ΥΦΑ και παρουσιάζεται η τρέχουσα κατάσταση των σταθμών αυτών στην Ελλάδα.

Λέξεις- κλειδιά
ΥΦΑ, ΦΑ, Πλωτός Σταθμός Επαναεριοποίησης και Αποθήκευσης ΥΦΑ

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Glossary of terms and acronyms

AAV – Ambient Air Vaporizer

BOG – Boil-Off Gas

BOR – Boil-Off Rate

CAPEX – Capital Expenditure

DFDE – Dual-Fuel Diesel Electric

EPC – Engineering, Procurement and Construction

ESD – Emergency Shutdown System

ETA – Event Tree Analysis

FEED – Front End Engineering Design

FSRU – Floating Storage and Regasification Unit

FSU – Floating Storage Unit

GCV – Gross Calorific Value

HP – High Pressure

IFV – Intermediate Fluid Vaporizer

IGU – International Gas Union

IMA – International Maritime Associates

IMO – International Maritime Organization

LNG – Liquefied Natural Gas

LNGC – Liquefied Natural Gas Carrier

LP – Low Pressure

MTPA – Million Tonnes Per Annum

NPSHR – Net Positive Suction Head Required

NIMBY – Not in My Back Yard

NG – Natural Gas

OPEX – Operating Expenditure

ORV – Open Rack Vaporizer

PCHE – Printed Circuit Heat Exchanger

PLEM – Pipeline End Manifold

PPE – Personal Protective Equipment

RAE – Regulatory Authority for Energy

SCV – Submerged Combustion Vaporizer

STS – Ship to Ship (Transfer)

TEG – Triethylene Glycol

TFDE – Tri-Fuel Diesel Electric

$ – US Dollar

$/mmbtu – US Dollars per million btus

m^3 – cubic metres

m^3/h – cubic metres per hour

kW – Kilowatt

MW – Megawatt

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Chapter 1: Introduction to LNG & the Floating Storage and Regasification Unit

In this Chapter LNG properties, LNG supply chain, general description of FSRU, FSRU global market up to the end of 2019 and key drivers and limitations of these units are presented.

1.1 Liquefied Natural Gas

When Natural Gas (NG) is being cooled at -162ºC and pressured slightly above atmospheric pressure (1 atm), it is liquefied to a state called Liquefied Natural Gas (LNG). This leads to volume reduction six hundred (600) times. This is the reason why LNG is preferred for shipment and storage purposes.

LNG is a cryogenic, liquid substance which consists, depending upon its origin, of a mixture of light hydrocarbons, mainly Methane CH_4 (87% - 98%), Ethane C_2H_6 (1.4% - 9.5%), Propane C_3H_8 (0.4% - 2.5%), Butane C_4H_{10} (0.1% - 0.5%), Pentane C_5H_{12} and Nitrogen N_2 as inert (0.1% - 1%) [2].

The classification of LNG could be made based on chemical composition (methane and nitrogen amount), density, heating value, Wobbe index but usually we refer to light, medium or heavy LNG due to its density.

LNG is colourless, odorless, non-toxic, non-corrosive, non-flammable, not carcinogenic but it could be asphyxiant in a vapour cloud formation. The flash point is around -188ºC and the boiling point -160ºC [1, p. 68].

Composition of LNG, classification in Light, Medium, and Heavy LNG by densities and Gross Calorific Value are given in Table 1.

Composition (%)	**LNG Light**	**LNG Medium**	**LNG Heavy**
Methane	98.000	92.000	87.000
Ethane	1.400	6.000	9.500
Propane	0.400	1.000	2.500
Butane	0.100	0.000	0.500
Nitrogen	0.100	1.000	0.500

Properties	**LNG Light**	**LNG Medium**	**LNG Heavy**
Gross Calorific Value [kWh/Nm^3]	11.290	11.650	12.340
Density [kg/Nm^3]	427.742	445.694	464.831
Density variation (%)	-	4.2	8.7

Table 1: Composition (%) of LNG and classification in Light, Medium, Heavy LNG by densities [2]

Nitrogen concentration on LNG can play a dual role, since the higher it is, the smaller the Gross Calorific Value of LNG but it is also the first component to boil off (the most volatile component) during the transportation leaving behind more valuable components such as methane [3].

LNG quality plays a significant role in the LNG business due to LNG pricing is based on its heating or calorific value, which depends on the source of gas that is used and the liquefaction process [4]. In Table 2, LNG quality specifications are given by Hellenic Gas Transmission Operator S.A. DESFA, such as Wobbe Index, Gross Calorific Value (GCV), LNG density, Molecular weight, average temperature, Methane, Butane, Pentane, Nitrogen, Hydrogen sulfide and Sulphur concentrations.

LNG Quality Specifications

Value	Unit	Specification	Notes
Wobbe Index	KWh/Nm^3	13.066-16.328	
Gross Calorific Value (GCV)	KWh/Nm^3	11.131-12.647	The Operator may consider the possibility of accepting a cargo with GCV in the range 11.011 KWh/Nm^3 to 11.131 KWh/Nm^3 or 12.647 KWh/Nm^3 to 12.986 KWh/Nm^3, if after unloading this cargo and mixing with the stored LNG in terminal tanks, the GCV of the resulting LNG will be within the mentioned range.
LNG Density	Kg/m^3	430-478	The Operator may consider the possibility of accepting a cargo in the range 420.3 Kg/m^3 to 430 Kg/m^{3}or 478 Kg/m^3 to 483.1 Kg/m^3, if after unloading this cargo and mixing with the stored LNG in terminal tanks, the Density of the resulting LNG will be within the mentioned range.
Molecular Weight	Kg/Kmol	16.52 - 18.88	
Methane	% mol	85.0 min 97.0 max	The Operator may consider the possibility of accepting a cargo with Methane concentration in the range 80 to 85 [% mole] or 97 to 99.8 [% mole], if after unloading this cargo and mixing with the stored LNG in terminal tanks, the value of Methane concentration of the resulting LNG will be within the mentioned range.
i-Butane & n- Butane	% mol	4 max	
i- Pentane & n-Pentane	% mol	2 max	
Nitrogen	%mole	1.24 max	
Hydrogen sulfide (H_2S)	mg/Nm^3	5.0 max	
Total sulphur	mg/Nm^3	30.0 max	
Temperature	°C	-158 max	The average temperature of LNG in all tanks of LNG vessel before discharging should not be greater than -158°C. For LNG temperatures higher than -158°C the method KMK, for the calculation of LNG density, is not valid.

**Normal Cubic Meter or Nm^3 shall mean the quantity of Natural Gas, which at conditions of absolute pressure 1.01325 bar and temperature zero (0) degree Celsius, occupies volume of one (1) cubic meter.*

**Gross Calorific Value (GCV): The amount of heat produced by the complete stoichiometric combustion of one (1) normal cubic meter of Natural Gas at a constant absolute pressure of 1,01325 bar when the initial temperature of the fuel mixture and the final temperature of the products of combustion is considered to be twenty-five (25) degrees Celsius and the combustion produced is concentrated in the liquid state. Normal cubic meter means the amount of Natural Gas mass which, under absolute 1.01325 bar conditions and zero (0) degrees Celsius, occupies a volume of one (1) cubic meter.*

Table 2: LNG quality specifications by Hellenic Gas Transmission Operator S.A. DESFA [5]

The LNG Process Flow diagram is presented in Figure 1. A liquefied natural gas plant is mainly divided into the following processes. Pre-treatment where undesired substances are removed from the gas, acid gas removal where Hydrogen Sulfide (H_2S) and Carbon dioxide (CO_2) are absorbed and removed from natural gas, dehydration where water is removed from natural gas, liquefaction (traces of mercury are removed prior to liquefaction) and heavy oil separation where natural gas is cooled to –162°C using the principle of refrigeration [4].

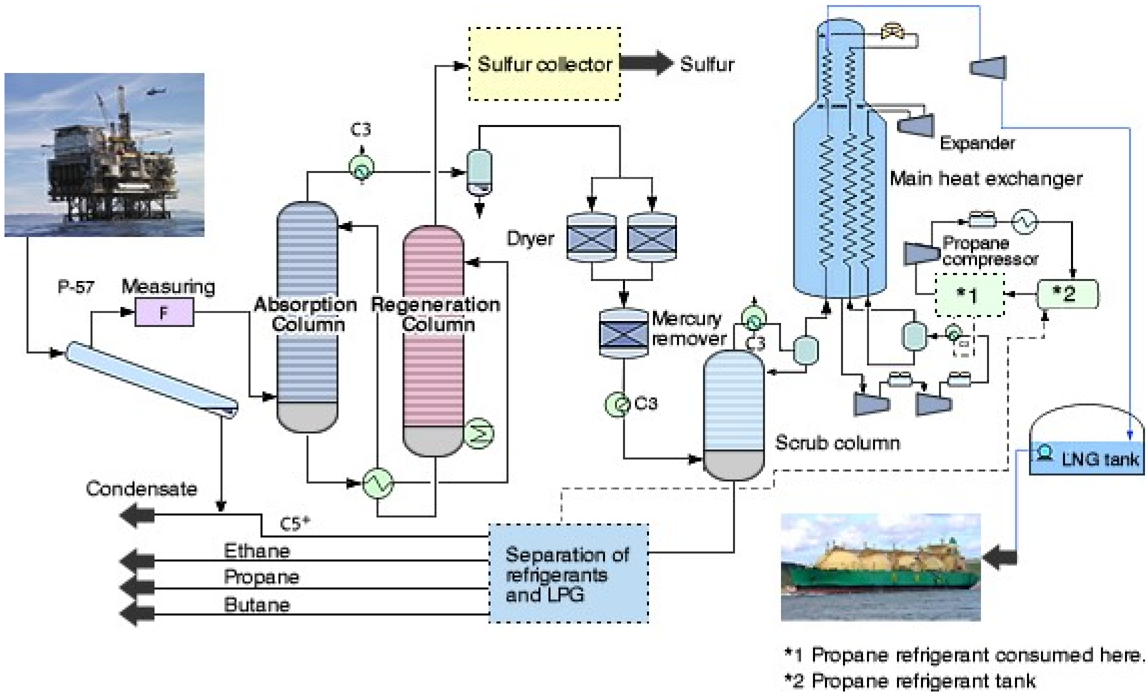


Figure 1: LNG Process Flow diagram [4]

1.2 Liquefied Natural Gas Value Chain

The need for a relatively clean burning fossil fuel as natural gas across the globe, has led to the LNG market in order to be able to transfer and supply NG to end users. The supply chain of LNG is described hereafter, from exploration and production, liquefaction, shipping, storage, regasification and finally NG distribution to market.

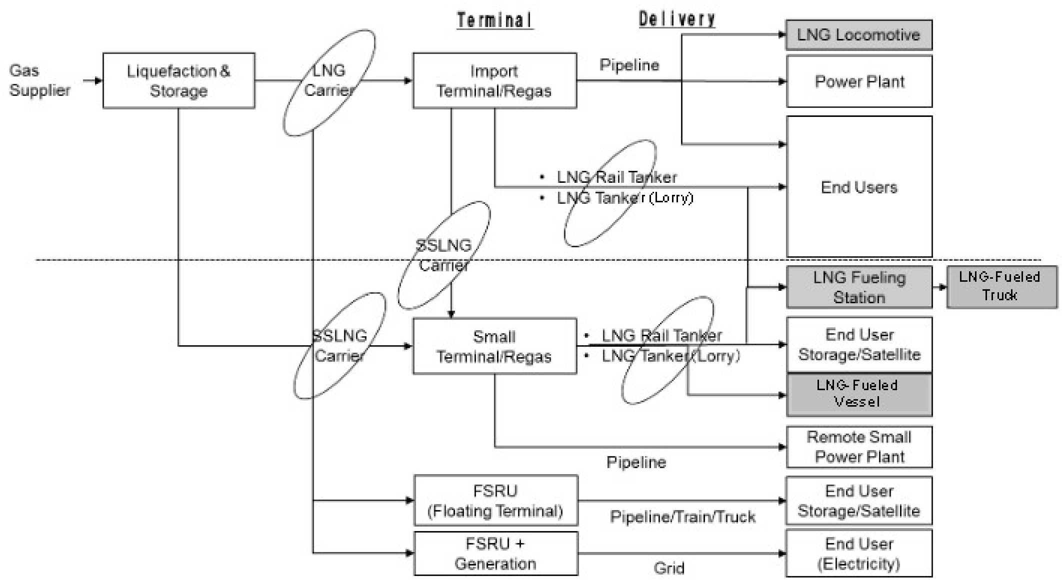


Figure 2: Configuration of the LNG Value Chain [6]

Exploration & production: The upstream part of the NG supply chain includes the detection of natural gas reserves, the extraction from the deposits and the transportation to the liquefaction plant.

Liquefaction: Prior to its liquefaction and cooling, NG has to be treated in order to get rid of all the impurities that may transfer along (removal of acid gases such as Carbon dioxide (CO_2) and Hydrogen Sulfide (H_2S)). Cooling NG at -162ºC, its volume shrinks by a factor of approximately 600.

Shipping: After liquefaction LNG is transported mainly by sea in special vessels called LNG Carriers (LNGC) until it reaches the final receiving facility in order to be offloaded, metered and stored.

Storage & regasification: Storage tanks should maintain the LNG cargo in appropriate conditions such as -162ºC at slightly above atmospheric pressure. LNG is regasified in order to return to its initial gaseous state and supply natural gas to end users.

End users: Power producers or natural gas consumers via pipelines.

FSRU could play a vital role in the LNG supply chain by covering the need of storage and regasification of natural gas, as it is mentioned in the key drivers for these units in the following section.

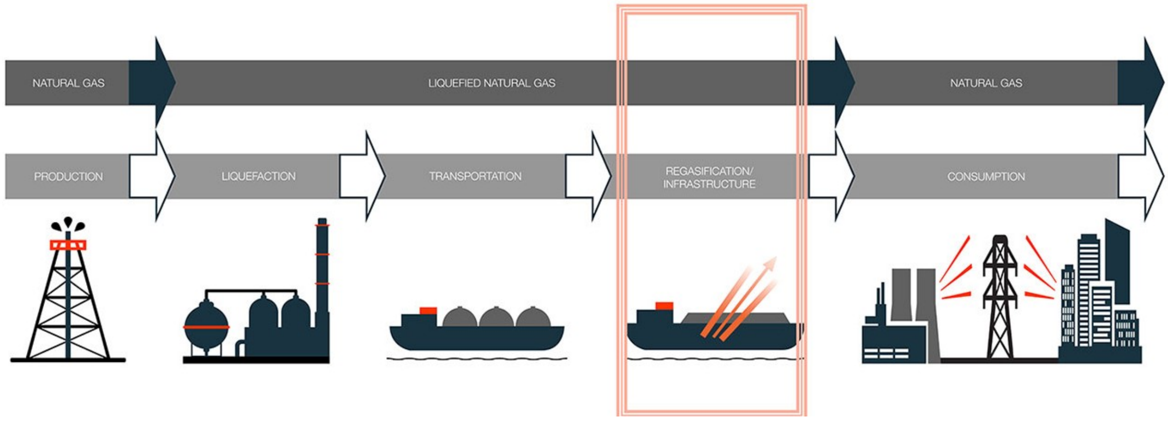


Figure 3: FSRUs, a critical link in the LNG value chain [7]

1.3 Floating Storage Regasification Unit

The concept of Floating Storage and Regasification Unit (FSRU) was introduced globally in 2005 in the US Gulf of Mexico by Excelerate Energy, building the first FSRU vessel with capacity of 138,000 m^3 and decommissioned in 2012 due to shale gas spread in the United States [8]. Since then there has been a major interest for this technology due to the rise in demand for LNG, the cleanest fossil fuel around the world. Therefore, FSRU could be already characterized as a mature technology.

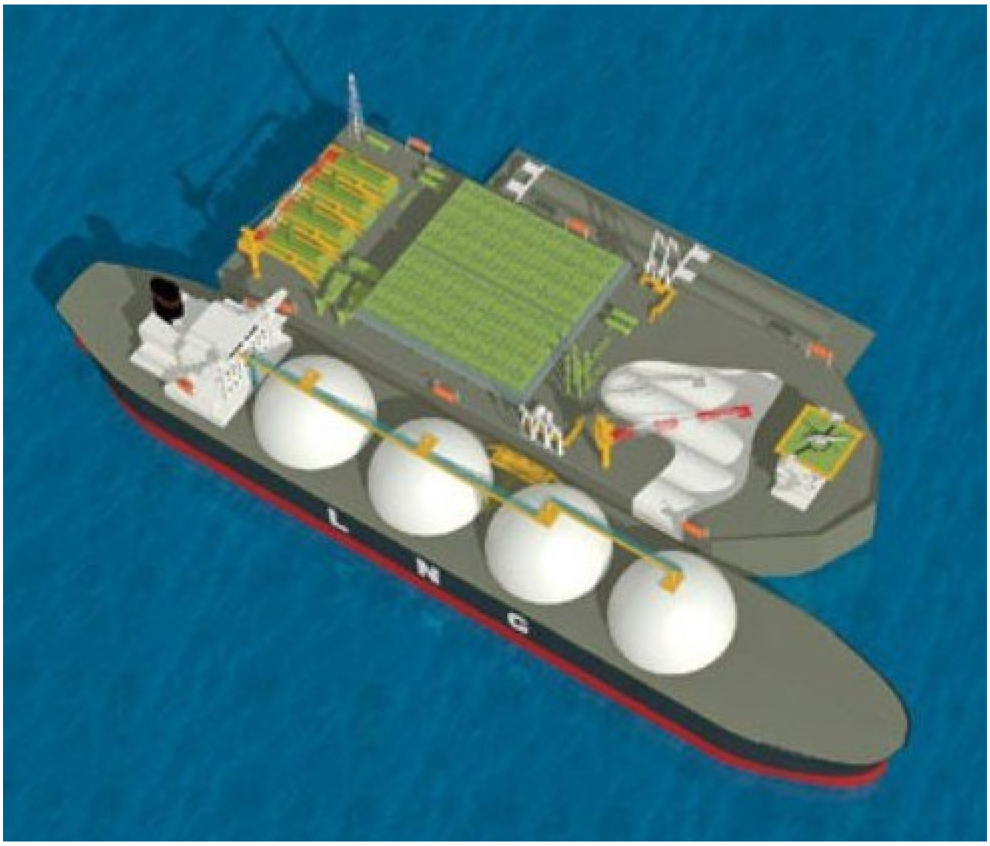


Figure 4: FSRU [9]

As it is mentioned by International Gas Union (IGU) in the 2020 World LNG report and it is depicted in Figure 5, there are currently 34 FSRUs around the globe (see Table 3), constituting 6.3% of the global fleet [10, p. 32].

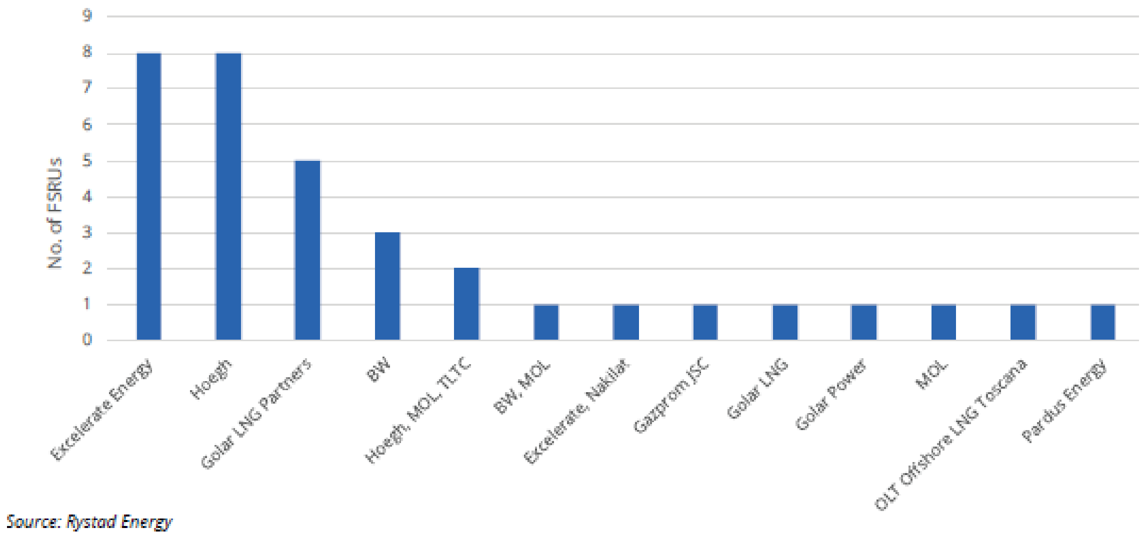


Figure 5: Current FSRU fleets by Shipowner companies [10]

"The key players in the global FSRU market are Excelerate Energy (U.S), Hoegh LNG (Bermuda), Golar LNG (Bermuda), BW gas (Norway), Gazprom FLEX LNG (U.K), Exmar (Belgium), Maran Gas Maritime Inc. (Greece), Offshore LNG Toscana SpA (Italy), Mitsui O.S.K. Lines (Japan) Bumi Armada (Malaysia), Teekay Lng Partners, L.P. (Bermuda)" [11].

The Middle East Region is a key player in the FSRU market by possessing the maximum number of these units and moreover with its LNG reserves, that can meet the demand for LNG across the world [11]. It is estimated that the global FSRU market will increase from 85 Million Tonnes Per Annum (MTPA) in 2018 to 230 MTPA in 2023 at a compound annual growth rate of approximately 13.88% due to the globally increasing NG demand [11].

Global Floating Storage and Regasification Unit (FSRU) market can be segmented based on storage i.e. large, medium and small, construction i.e. newly built and converted, end users i.e. power generation, industrial, others and region i.e. North America, Europe, Asia Pacific, Middle East, and Latin America [12].

The global active LNG/FSRU fleet by the end of 2019 is given in Table 3, presenting the vessel's name, the shipowner company, the shipbuilder company, the capacity of the vessel, the cargo type i.e. storage options, membrane or spherical, the propulsion type and the year of delivery.

As we can observe in Table 3, a typical storage capacity of an FSRU is approximately 170,000 m^3 of LNG, equivalent to 100 million cubic meters of natural gas. The smallest storage capacity of these units is 125,000 m^3 which is often due to conversion of an LNG carrier.

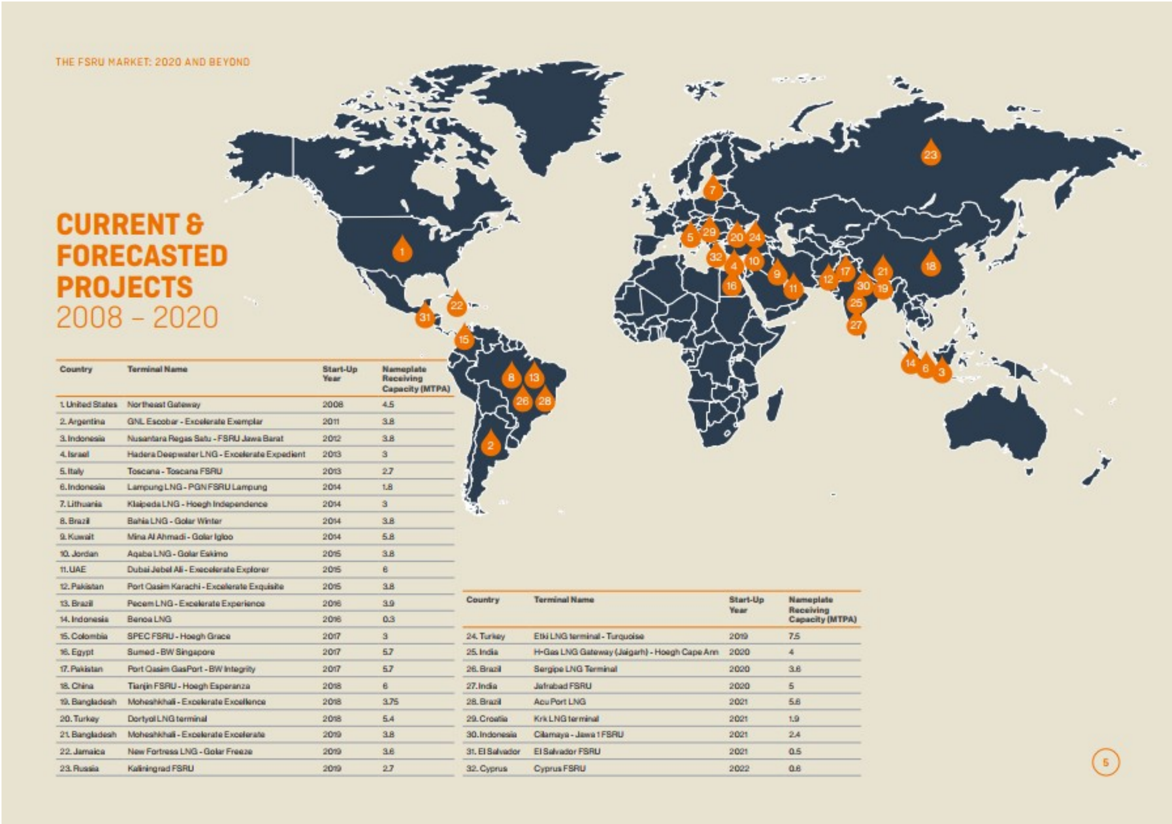
Vessel Name	Shipowner	Shipbuilder	Capacity (m^3)	Cargo Type	Propulsion Type	Delivery Year
BW Integrity	BW, MOL	Samsung	173,500	Membrane	TFDE	2017
BW Magna	BW	Daewoo	173,400	Membrane	TFDE	2019
BW Paris (Converted FSRU)	BW	Daewoo	162,400	Membrane	TFDE	2009
BW Singapore	BW	Samsung	170,200	Membrane	TFDE	2015
Cape Ann	Hoegh, MOL, TLTC	Samsung	145,000	Membrane	TFDE	2010
Excellence	Excelerate Energy	Daewoo	138,000	Membrane	Steam	2005
Excelsior	Excelerate Energy	Daewoo	138,000	Membrane	Steam	2005
Exemplar	Excelerate Energy	Daewoo	150,900	Membrane	Steam	2010
Expedient	Excelerate Energy	Daewoo	150,900	Membrane	Steam	2010
Experience	Excelerate Energy	Daewoo	173,400	Membrane	TFDE	2014
Explorer	Excelerate Energy	Daewoo	150,900	Membrane	Steam	2008
Express	Excelerate Energy	Daewoo	150,900	Membrane	Steam	2009
Exquisite	Excelerate Energy	Daewoo	150,900	Membrane	Steam	2009
FSRU Toscana (Converted FSRU)	OLT Offshore LNG Toscana	Hyundai	137,100	Spherical	-	2004
Golar Eskimo	Golar LNG Partners	Samsung	160,000	Membrane	TFDE	2014

Vessel Name	Shipowner	Shipbuilder	Capacity (m^3)	Cargo Type	Propulsion Type	Delivery Year
Golar Freeze (Converted FSRU)	Golar LNG Partners	HDW	125,000	Spherical	Steam	1977
Golar Igloo	Golar LNG Partners	Samsung	170,000	Membrane	TFDE	2014
Golar Nanook	Golar Power	Samsung	170,000	Membrane	TFDE	2018
Golar Tundra	Golar LNG	Samsung	170,000	Membrane	TFDE	2015
Golar Winter (Converted FSRU)	Golar LNG Partners	Daewoo	138,000	Membrane	Steam	2004
Hoegh Esperanza	Hoegh	Hyundai	170,000	Membrane	DFDE	2018
Hoegh Gallant	Hoegh	Hyundai	170,100	Membrane	DFDE	2014
Hoegh Galleon	Hoegh	Samsung	170,000	Membrane	TFDE	2019
Hoegh Gannet	Hoegh	Hyundai	170,000	Membrane	DFDE	2018
Hoegh Giant	Hoegh	Hyundai	170,000	Membrane	DFDE	2017
Hoegh Grace	Hoegh	Hyundai	170,000	Membrane	DFDE	2016
Independence	Hoegh	Hyundai	170,100	Membrane	DFDE	2014
Marshal Vasilevskiy	Gazprom JSC	Hyundai	174,000	Membrane	TFDE	2018
MOL FSRU Challenger	MOL	Daewoo	263,000	Membrane	TFDE	2017

Vessel Name	Shipowner	Shipbuilder	Capacity (m^3)	Cargo Type	Propulsion Type	Delivery Year
Neptune	Hoegh, MOL, TLTC	Samsung	145,000	Membrane	DFDE	2009
Nusantara Regas Satu (Converted FSRU)	Golar LNG Partners	Rosenberg Verft	125,003	Spherical	Steam	1977
PGN FSRU Lampung	Hoegh	Hyundai	170,132	Membrane	DFDE	2014
Summit LNG	Excelerate Energy	Daewoo	138,000	Membrane	Steam	2006
Turquoise P	Pardus Energy	Hyundai	170,000	Membrane	DFDE	2019

Table 3: Global Active LNG/FSRU Fleet, Year-End 2019 (Source: Rystad Energy Research and Analysis) [10]

The FSRU global market spots (current and forecasted) are depicted in Figure 6, which consists of 32 FSRUs since 2008 with the nameplate receiving capacity in Million Tonnes Per Annum (MTPA) of each one.



Country	Terminal Name	Start-Up Year	Nameplate Receiving Capacity (MTPA)
1. United States	Northeast Gateway	2008	4.5
2. Argentina	GNL Escobar - Excelerate Exemplar	2011	3.8
3. Indonesia	Nusantara Regas Satu - FSRU Jawa Barat	2012	3.8
4. Israel	Hadera Deepwater LNG - Excelerate Expedient	2013	3
5. Italy	Toscana - Toscana FSRU	2013	2.7
6. Indonesia	Lampung LNG - PGN FSRU Lampung	2014	1.8
7. Lithuania	Klaipeda LNG - Hoegh Independence	2014	3
8. Brazil	Bahia LNG - Golar Winter	2014	3.8
9. Kuwait	Mina Al Ahmadi - Golar Igloo	2014	5.8
10. Jordan	Aqaba LNG - Golar Eskimo	2015	3.8
11. UAE	Dubai Jebel Ali - Execelerate Explorer	2015	6
12. Pakistan	Port Qasim Karachi - Excelerate Exquisite	2015	3.8
13. Brazil	Pecem LNG - Excelerate Experience	2016	3.9
14. Indonesia	Benoa LNG	2016	0.3
15. Colombia	SPEC FSRU - Hoegh Grace	2017	3
16. Egypt	Sumed - BW Singapore	2017	5.7
17. Pakistan	Port Qasim GasPort - BW Integrity	2017	5.7
18. China	Tianjin FSRU - Hoegh Esperanza	2018	6
19. Bangladesh	Moheshkhali - Excelerate Excellence	2018	3.75
20. Turkey	Dortyol LNG terminal	2018	5.4
21. Bangladesh	Moheshkhali - Excelerate Excelerate	2019	3.8
22. Jamaica	New Fortress LNG - Golar Freeze	2019	3.6
23. Russia	Kaliningrad FSRU	2019	2.7

Country	Terminal Name	Start-Up Year	Nameplate Receiving Capacity (MTPA)
24. Turkey	Etki LNG terminal - Turquoise	2019	7.5
25. India	H-Gas LNG Gateway (Jaigarh) - Hoegh Cape Ann	2020	4
26. Brazil	Sergipe LNG Terminal	2020	3.6
27. India	Jafrabad FSRU	2020	5
28. Brazil	Acu Port LNG	2021	5.6
29. Croatia	Krk LNG terminal	2021	1.9
30. Indonesia	Cilamaya - Jawa 1 FSRU	2021	2.4
31. El Salvador	El Salvador FSRU	2021	0.5
32. Cyprus	Cyprus FSRU	2022	0.6

Figure 6: Current and Forecasted projects 2008-2020 and beyond [13]

The floating regasification since its beginning starts to gain ground gradually over the onshore permanent regasification facilities as it is exhibited in Figure 7 and Figure 8 [14].

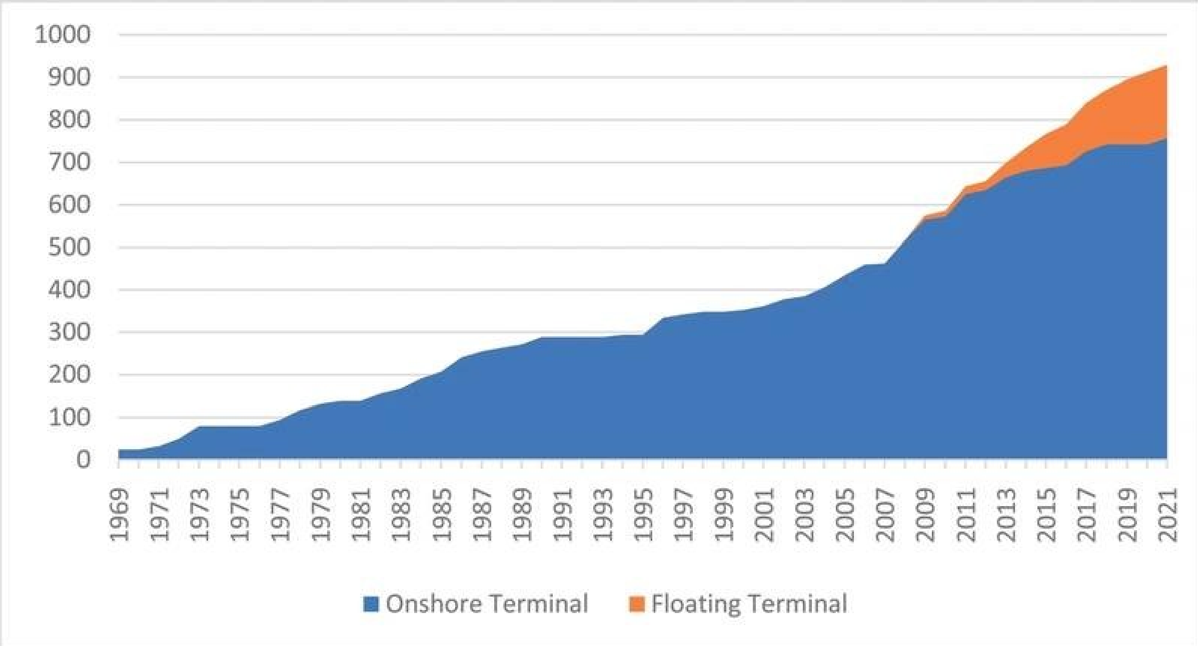


Figure 7: Cumulative Growth in LNG Regasification Capacity (Includes terminals under construction) (Source: IMA/WER database, International Gas Union, GIIGNL, company records) [15]

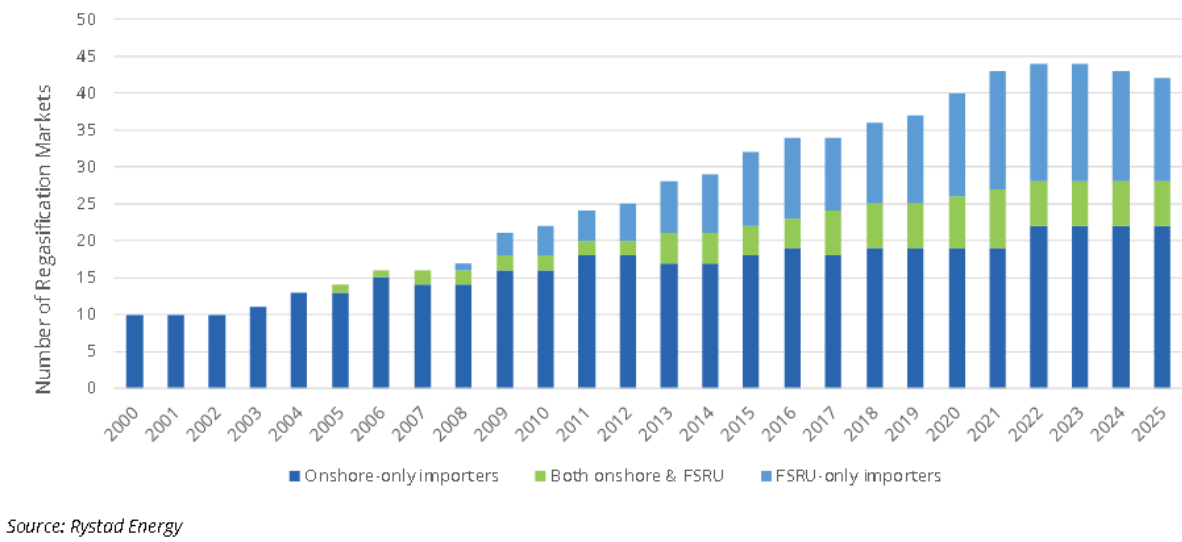


Figure 8: Number of Regasification Markets by Type, 2000-2025 [10, p. 43]

Liquefied Natural Gas (LNG) cargoes could be received and processed through the floating regasification process which is a more flexible, profitable solution and is often proposed to cover energy seasonal demand for global markets [14].

Floating regasification could be implemented through FSRUs, which are a type of vessel providing the option for covering transportation, storage and regasification of LNG onboard.

FSRUs could be either new purpose-built vessels or refurbished, converted gas carriers i.e. LNG vessels with the suitable adjustments, such as regasification module, in order to meet all the processes which take place in an LNG terminal and they can be classified either as ships or as offshore installations [17].

The key specifications of an FSRU are its length, its breadth moulded, its depth, the cargo tank capacity, the gas send-out rate and the send-out pressure. FSRU as LNG import terminals, can be placed either offshore if shore access is not available or be moored against a jetty, a berth or a purpose-built dolphin. LNG Carriers (LNGC) moor alongside the FSRU and LNG is being transferred through cryogenic flexible hoses or hard loading arms to the storage units.

There are predominantly two types of tanks on the FSRU vessel, either spherical Moss type (independent tanks) or membrane (integral tanks) for storing LNG at cryogenic temperatures and keeping it insulated from the hull structure [16]. The classification of LNG vessels is given by the International Maritime Organization (IMO) in Figure 9.

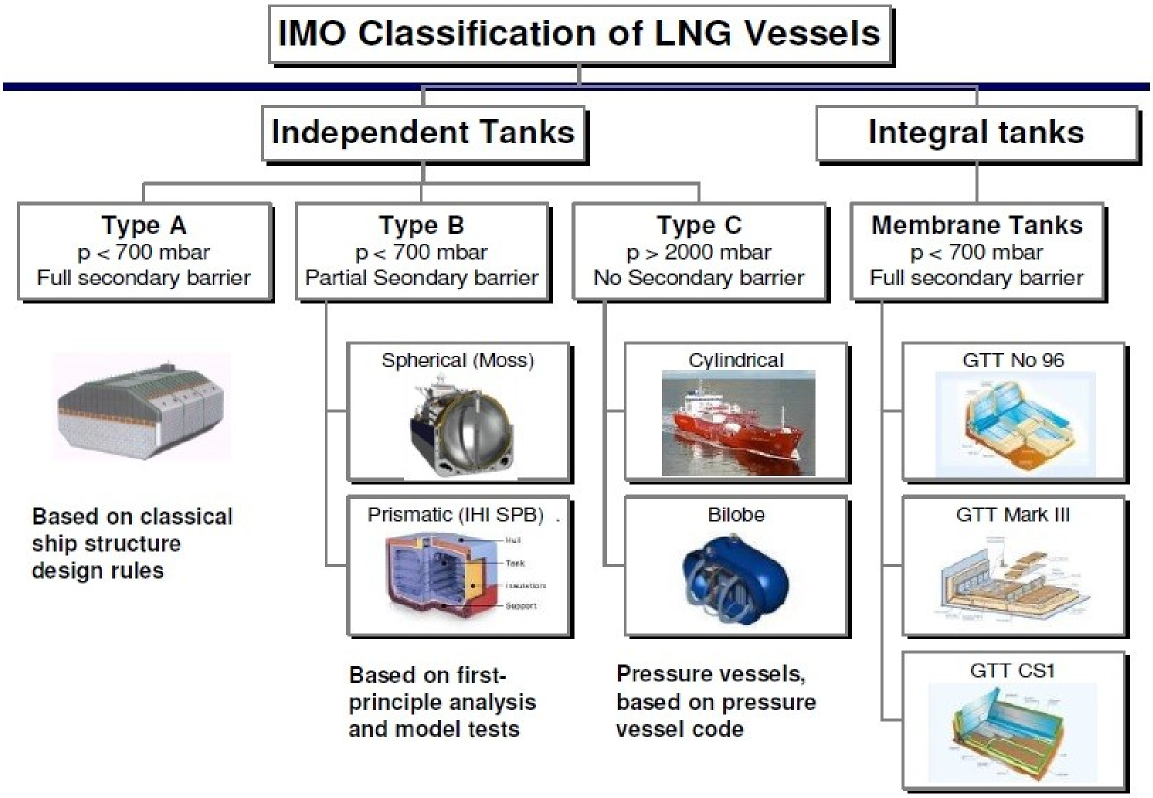


Figure 9: IMO classification of LNG vessels [16]

On Moss type tanks (see Picture 2) the regasification unit could be placed either between the tanks or on the bow. One of the advantages of the membrane concept is the better storage capacity between same size vessels, i.e. generally smaller gross tonnage. Membrane tanks (see Picture 1) could also provide unrestricted navigation visibility compared to Moss type tanks.

Picture 1: Membrane Tanks with regasification facilities on the deck Source: Courtesy Excelerate Energy [17]

Picture 2: FSRU Toscana with Moss type tanks [18]

Brief description is given by Songhurst in "The Outlook for Floating Storage and Regasification Units" regarding a typical FSRU flow scheme and is depicted in Figure 10: *"LNG is received via unloading arms or hoses, metered and stored in the tanks. The low pressure pumps located in the storage tanks send the LNG to the recondenser where it is contacted with compressed boil off gas from the storage tanks and the BOG is condensed back into LNG before entering the high pressure pumps. Some BOG is used as FSRU fuel and topped up if required by vaporised LNG. The fuel used is metered. The high pressure pumps raise the pressure of the LNG from typically 5 bar g to the export pressure required by the customer (e.g. typically 50 bar g for a power generation plant or 100 bar g for a gas network). The LNG is then vaporised at the export pressure, metered and exported via the gas export arm(s) or hoses to the export pipeline and the customer"* [17].

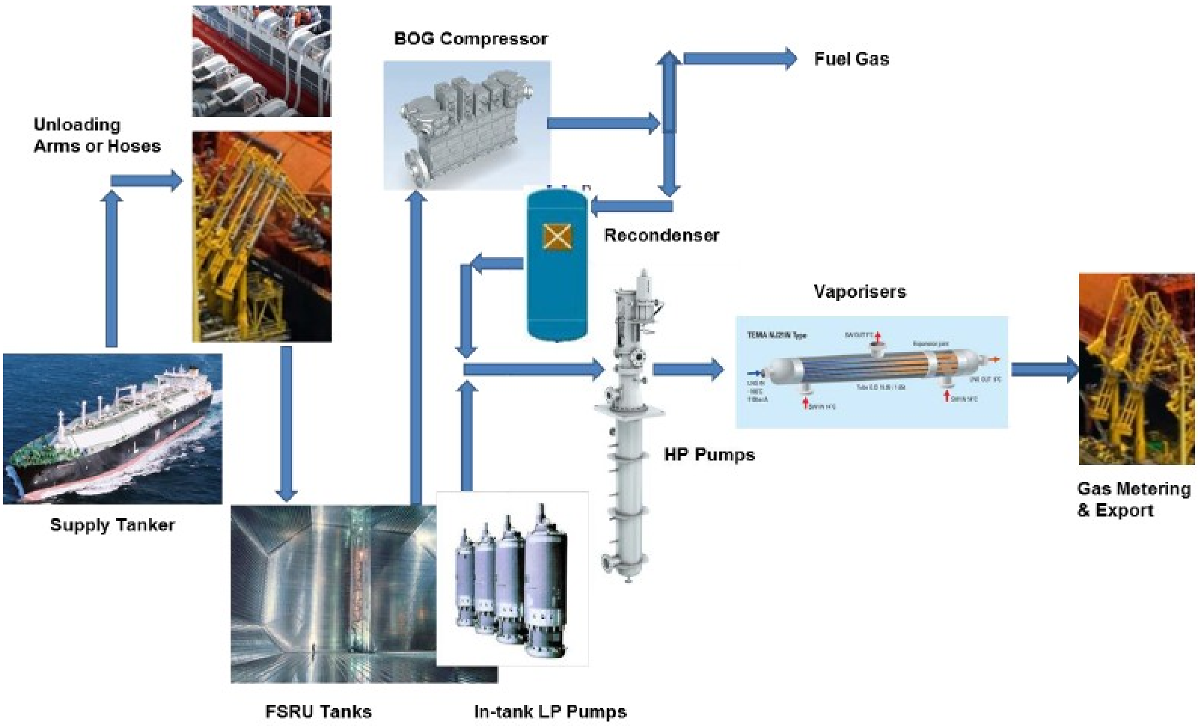


Figure 10: Typical FSRU Flow Scheme [17]

In the following pictures are depicted several processes that take place on an FSRU such as mooring arrangements, Ship to Ship (STS) transfer of LNG, regasification and high pressure NG delivery to the shore.

Picture 3: Permanently moored FSRU [7]

Picture 4: New cargo is ready to be transferred to FSRU through the LNG carrier [7]

Picture 5: LNG transfer from carrier to FSRU [7]

Picture 6: Continuous regasification process on FSRU and sending high-pressure NG to the shore [7]

FSRU mooring systems are presented below, which cover a wide range of solutions depending upon each project restrictions and provide FSRU stability to remain in the exact position and safe LNG transfer. Sea bed conditions, bathymetry, water depth, wind, current and wave conditions, port arrangements act as an input for designing the mooring system of a project. Jetty-type mooring system is suggested for exposed locations, consists of four breasting dolphins and four mooring dolphins and with this configuration is designed to withstand forces [19].

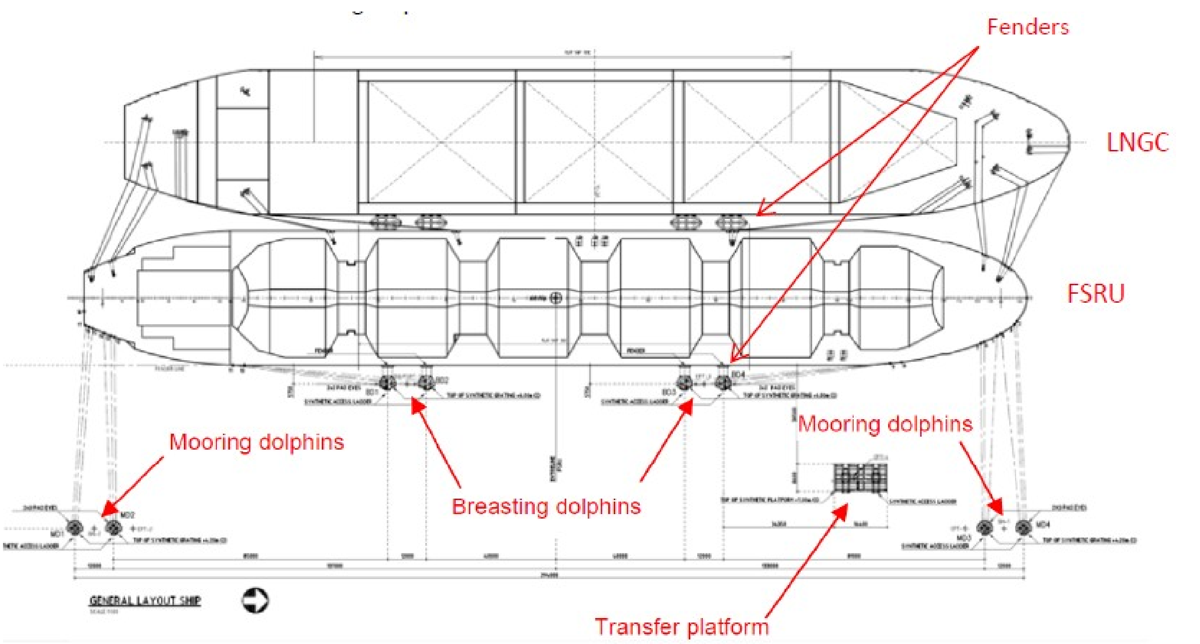
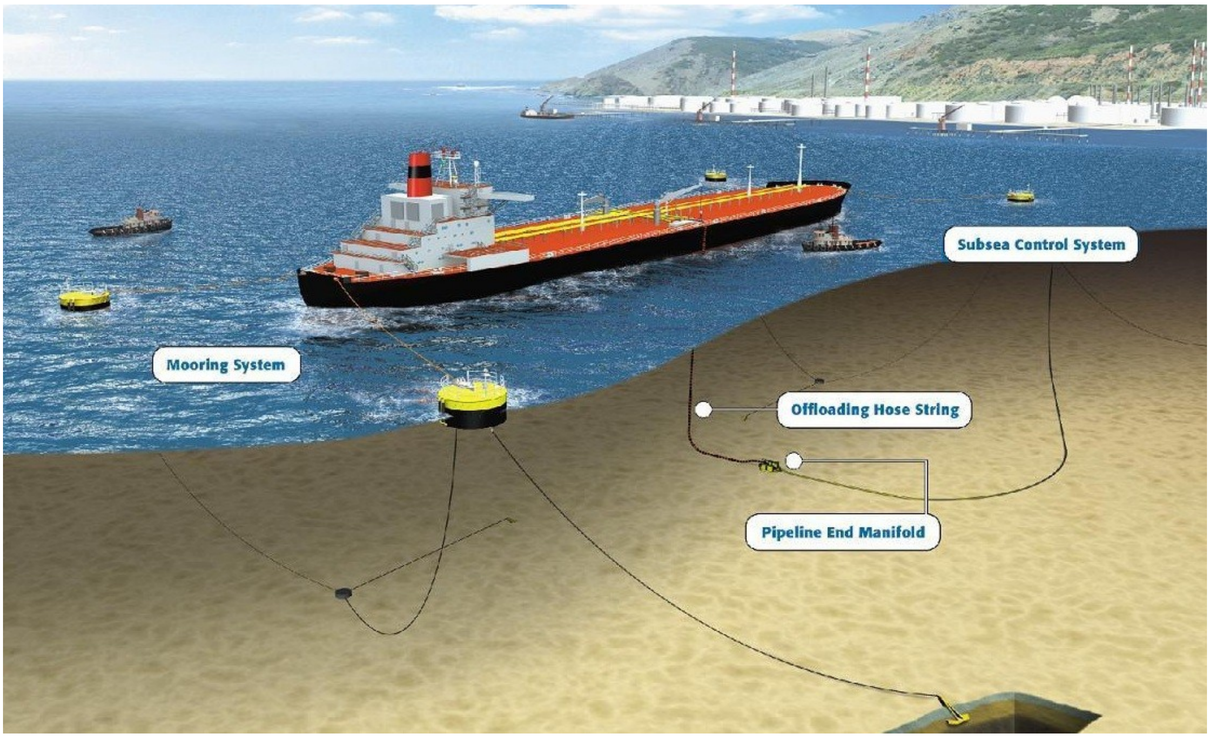


Figure 11: Jetty-type mooring system, side-by-side mooring configuration between FSRU and LNGC [19]

Tower yoke mooring system consists of a tower fixed at the seabed and a yoke connected both to tower and the unit and it is proposed for shallow water environments [20].

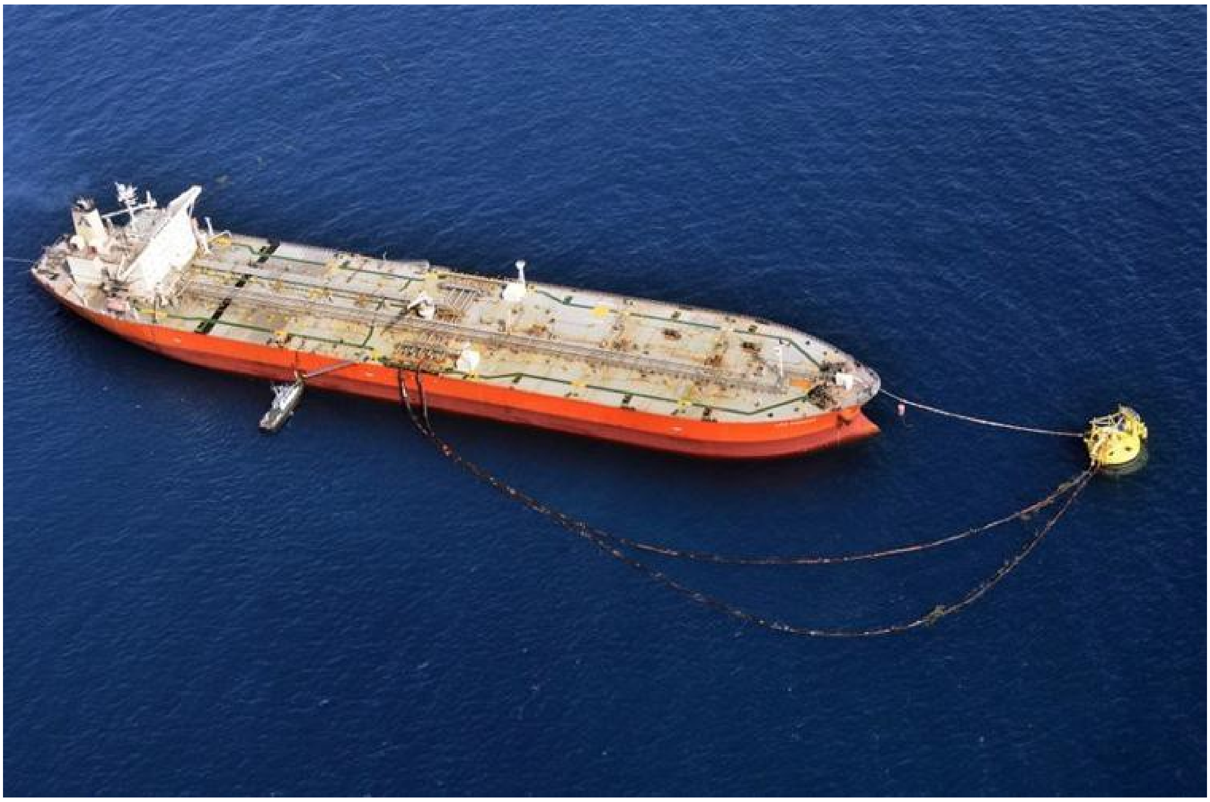
Picture 7: Tower Yoke Mooring System [19]

The Conventional Buoy mooring system consists of multiple buoys that are fixed to the seabed and it is typically designed for nearshore applications and ideally swallow waters (up to 30m depth) [22].



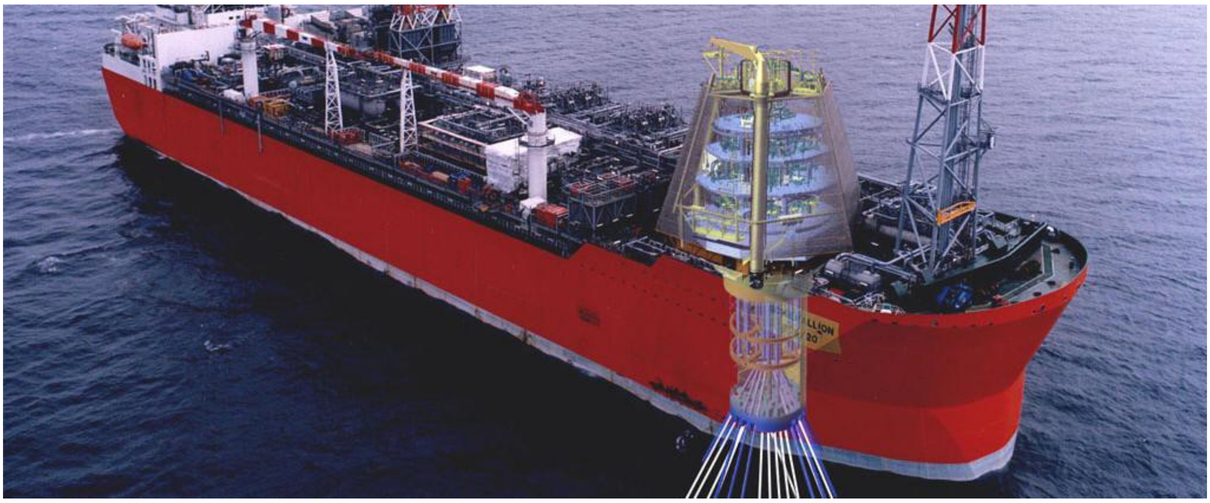
Picture 8: Conventional Buoy Mooring system [21]

Single point mooring buoy system consists of a single buoy that is fixed to the seabed. This mooring configuration is proposed for harsher environments by allowing the unit to weathervane [19].



Picture 9: Single Point Mooring System [19]

On the Turret Mooring System, the unit is anchored at the seabed via the Turret by means of mooring legs and anchor points and it could be internal (harsh environments) or external (mild to medium environments) depending on the environmental conditions [22].



Picture 10: Turret Mooring System [19]

1.4 Key drivers for FSRU

The choice between onshore terminals and FSRUs has to meet several criteria taking into consideration specific market requirements, conditions and constraints. Onshore import and regasification terminals operate successfully in countries with economical, political and energy demand stability, offer a long-term solution for energy supply and fulfill national strategic storage demand [23, p. 19]. Moreover LNG onshore facilities are flexible in case of a future storage and regasification capacity expansion, with the assumption that land area will be available, in order to cover a greater need for LNG supply, despite the fact that they are already offering greater gas on-site storage and send out rates, i.e. annual supply volumes than the offshore facilities. At a permanent onshore installation the Operating Expenditures (OPEX) are also lower than FSRU. Atmospheric and marine phenomena do not have any impact on land based LNG terminals in the contrary to the FSRUs that are subject to specific wind and wave conditions for their operation stability [10]. Maintenance, inspection and operation of an onshore terminal are considered less complex than the corresponding procedures at an FSRU. In case of dry docking of the ship in order to perform inspection and maintenance, that could last a significant amount of time, depending on the location of the docking facility [24].

On the other hand FSRU projects, depending on the location, have to face fewer environmental impacts and licensing restrictions than the enormous land areas that onshore terminals need. They are also facing fewer social opposition in comparison to the development of an onshore facility, which tend to provoke severe 'Not In My Back Yard (NIMBY)' reactions from the local community [17]. FSRUs can cover short term gas market needs, they are proposed as a fast track solution and in many cases they are reusable assets, since they can be moved to supply natural gas to another market around the globe. Furthermore, FSRUs as is depicted in Table 5 require lower Capital Expenditures (CAPEX) due to the common practice of chartering FSRUs from third parties. In addition the Engineering, Procurement and Construction (EPC) period is significantly shorter and this is a good reason for covering the need for LNG supply sooner in a new market. Finally, on environmental scope FSRUs contribute to a lighter environmental footprint.

	Onshore LNG Terminal	FSRU
Engineering, Procurement and Construction (EPC) Period	5-7+ years (EPC, Environment Assessment and Approval)	3 years (new built) 1 year (LNG ship remodelled)
Environmental Impacts and Regulations	Large environmental impacts Stringent regulations	Small environmental impacts Depending on location fewer regulations
Atmospheric and Marine Phenomena	N.A. (not applicable)	Calm atmospheric and marine conditions are required (impacts of waves are large)
Removal	Permanent usage is considered and offers long term supply security	Moving and removal are easy and allows for quicker fuel switching or complementing domestic production
Expansion	Flexible but also greater gas storage capacity	Incremental by adding ships
CAPEX/OPEX	Requires lower Operating Expenditures (OPEX)	Requires lower Capital Expenditures (CAPEX)

Table 4: Comparison of Onshore LNG Terminal and FSRU [25, p. 4][10, p. 43]

The capital cost of a new FSRU can typically represent about 60% of an onshore terminal with the same capacity as it is exhibited in Table 5 [17].

	3mtpa, 180,000m^3 storage	
Component	**Onshore (m$)**	**FSRU (m$)**
Jetty including piping	80	80
Unloading lines	100	N/A
Tanks 1 * 180,000m^3	180	in FSRU
FSRU Vessel	N/A	250
Process Plant	100	in FSRU
Utilities	60	in FSRU
Onshore interface/infrastructure	N/A	30
CAPEX	**$520m**	**$360m**
Contigency 30% Onshore, 10% FSRU	156	36
Owner's costs	74	54
Total CAPEX	**$750m**	**$450m**

Table 5: CAPEX Comparison for Onshore Terminal and FSRU [17]

A feasibility study is crucial for every project in order to examine all the aspects prior to making a decision whether FSRU or onshore facility is the optimal solution as an import terminal. Songhurst in the "The Outlook for Floating Storage and Regasification Units", attempts to outline the key considerations that guide us to evaluate each installation facility, which are given briefly in Table 6 [17].

Feature	FSRU	Onshore	Comments
Send-out < 6 mtpa	✓		Some FSRUs are capable of peak send-out > 6 mtpa but not guaranteed. 8 mtpa may be possible with newer vessels. Option for 2 FSRUs.
Additional capacity required in future		✓	Expanding FSRU capacity not realistic – space on onshore site allows additional vaporisers to be easily added
Storage > 170,000 m^3		✓	Max vessel size 170,000 m3. Qmax option is available at 266,000 m3 but this would be bespoke. Could add FSU.
Additional storage required in future		✓	Expanding FSRU capacity is not realistic – space on onshore sites allows for further tanks. Could consider adding FSU.
Strategic storage required		✓	FSRU is a flexible (removable) option
No existing harbour available	✓		Offshore FSRU with pipeline to shore best option as harbour/breakwater construction expensive
Water depth < 14 m at harbour entrance	✓		Dredging expensive and ongoing OPEX. Offshore FSRU with pipeline to shore possible best low cost option
Onshore permitting difficult - NIMBY	✓		Onshore terminals are major construction projects involving major earth moving and heavy construction materials
Short term gas market need	✓		Possibly while longer term onshore terminal planned or just to meet seasonal needs
Fast track need for gas market	✓		Onshore terminals typically take 4 years to construct. Recent Ain Sokhna 2 terminal operational in just 5 months
Financing difficult and lack of capital	✓		FSRU can be leased but still need to finance harbour works and pipeline connection to customers/grid
No land available for onshore terminal	✓		Land reclamation may be possible but is an expensive option
High local content needed		✓	Limited local content with FSRU likely built in Far East shipyard albeit some local work likely for harbour and infrastructure

Table 6: Preliminary Guide - Decision factors regarding the choice of FSRU and Onshore LNG plant installation [17]

Chapter 2: FSRU Process Description

In this Chapter the main processes that take place in an FSRU will be presented.

Each project design consists of the following stages: Conceptual design, Feasibility Study, Front End Engineering (FEED), Basic Design, Detailed Design, Procurement & Construction, Start-Up and Operation. For each FSRU project several environmental factors should be considered, which are subjected to the location's selection for FSRU deployment. For this reason prior to the installation of the unit, measurements should be taken for an adequate time period, through suitable equipment such as meteorological buoys in order to monitor the site's conditions. These buoys are equipped with sensors for measuring wind speed and prevailing direction, ocean wave height and direction, ocean current profiles from the surface to the seabed (motion analysis), ambient air temperature, humidity and seawater temperature [26]. All these environmental and meteorological data shall be examined thoroughly prior to the design stage, guiding engineers to the optimal choices. For example the sea water temperature and the air temperature guide us to determine the appropriate vaporization method.

Picture 11: Fugro's SEAWATCH Wavescan buoy with met mast [26]

Different types of Conceptual design studies are depicted in Figure 12 and Figure 13.

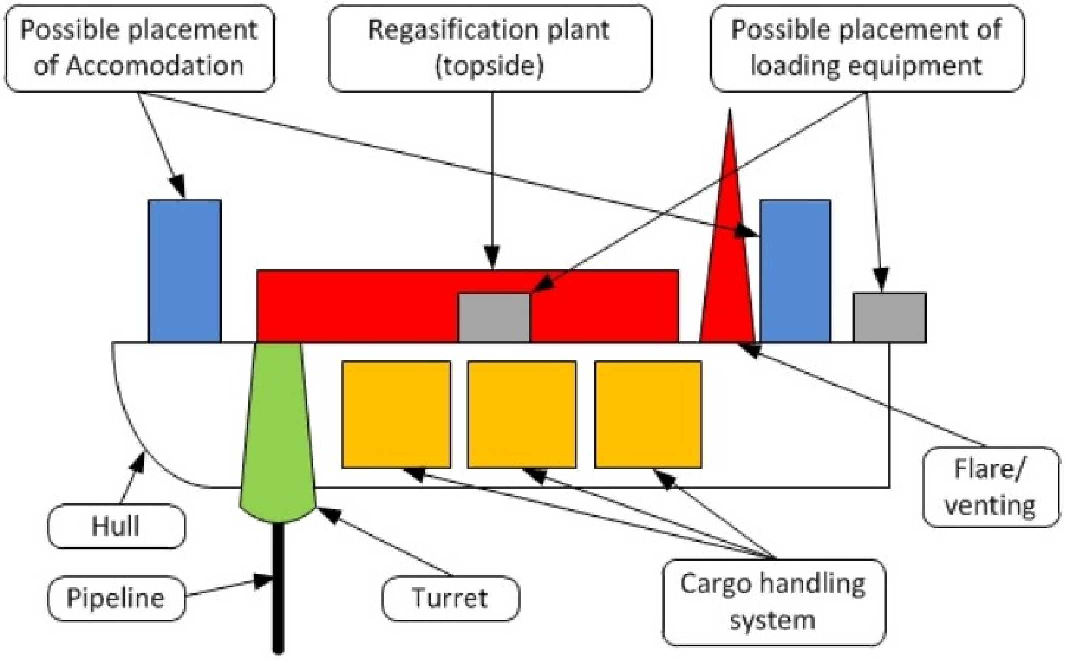


Figure 12: Conceptual layout of an FSRU [27, p. 17]

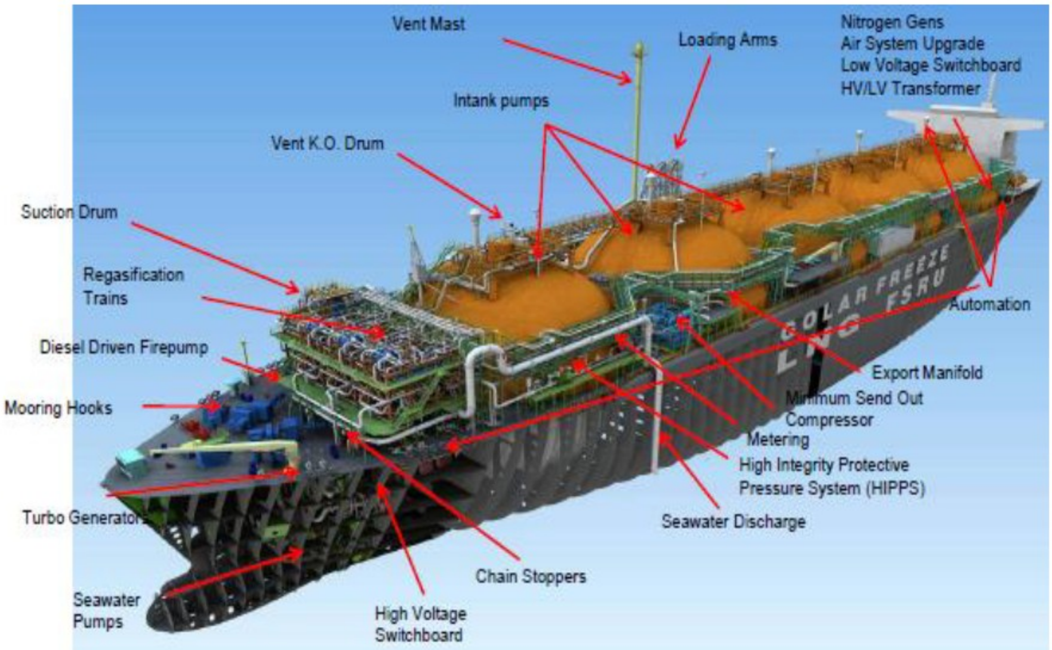


Figure 13: Example of a conceptual design [28]

2.1 FSRU Process Flow

The Process Flow of a typical LNG Terminal is presented in Figure 14.

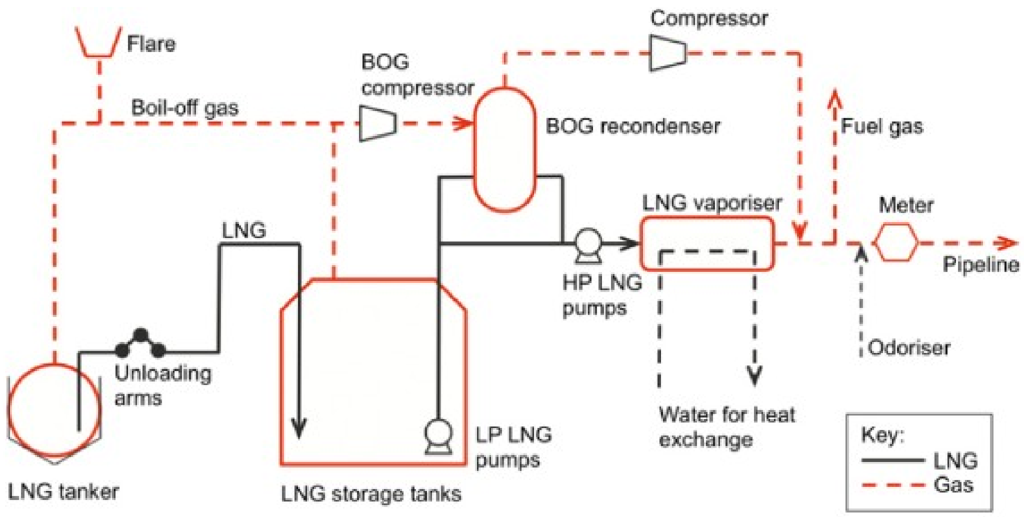


Figure 14: Process Flow of a typical LNG receiving and regasification terminal [29, p. 17]

Adopting this approach in FSRU, the process flow steps are presented in the sections hereafter.

2.2 LNG transfer to FSRU Vessel

Ship-to-Ship LNG transfer operation can be either side by side, through a jetty, or in tandem and either be through hard loading arms or flexible cryogenic hoses. Flexible cryogenic hoses are the most affordable solution but they are responsible for generating more Boil-Off Gas (BOG) and the offloading procedure takes longer to complete [17]. Hard loading arms fitted on the FSRU tend to be the most frequent option for transferring LNG [17]. It is known that a certain amount of LNG is vaporized when LNG is being transferred between the carrier and the FSRU, due to the heat exchange with the storage system. For this reason the boil-off redirection process has to take place in order to prevent overpressure in the storage tank of the FSRU and pressure drop in the LNG storage tank carrier. The undesirable scenario of overpressure may lead to gas release into the atmosphere through the relief valves or the collapse of the structure [30, p. 5].

2.2.1 Ship to jetty to FSRU

The transfer of LNG from an LNG Carrier (LNGC) takes place through a jetty to the FSRU. The jetty is equipped with fixed loading arms in order to connect in both vessels and allow the offloading - loading procedure.

Picture 12: Ship to jetty to FSRU transfer, jetty is equipped with regasification plant [31, p. 20]

2.2.2 Side by side using flexible hoses

Flexible cryogenic hoses are used to discharge LNG as an alternative to more expensive mechanical arms and take place through double-banking between the LNGC and the FSRU.

Picture 13: LNG transfer side by side using flexible hoses [31]

2.2.3 Side by side through loading arms

The discharging of LNG could also utilize fixed loading arms, designed to allow the structure to absorb mechanical stresses and it is often selected when the mooring system is either a Turret system or a mooring dolphin and a breasting dolphin [31].

Picture 14: LNG transfer side by side through loading arms [31]

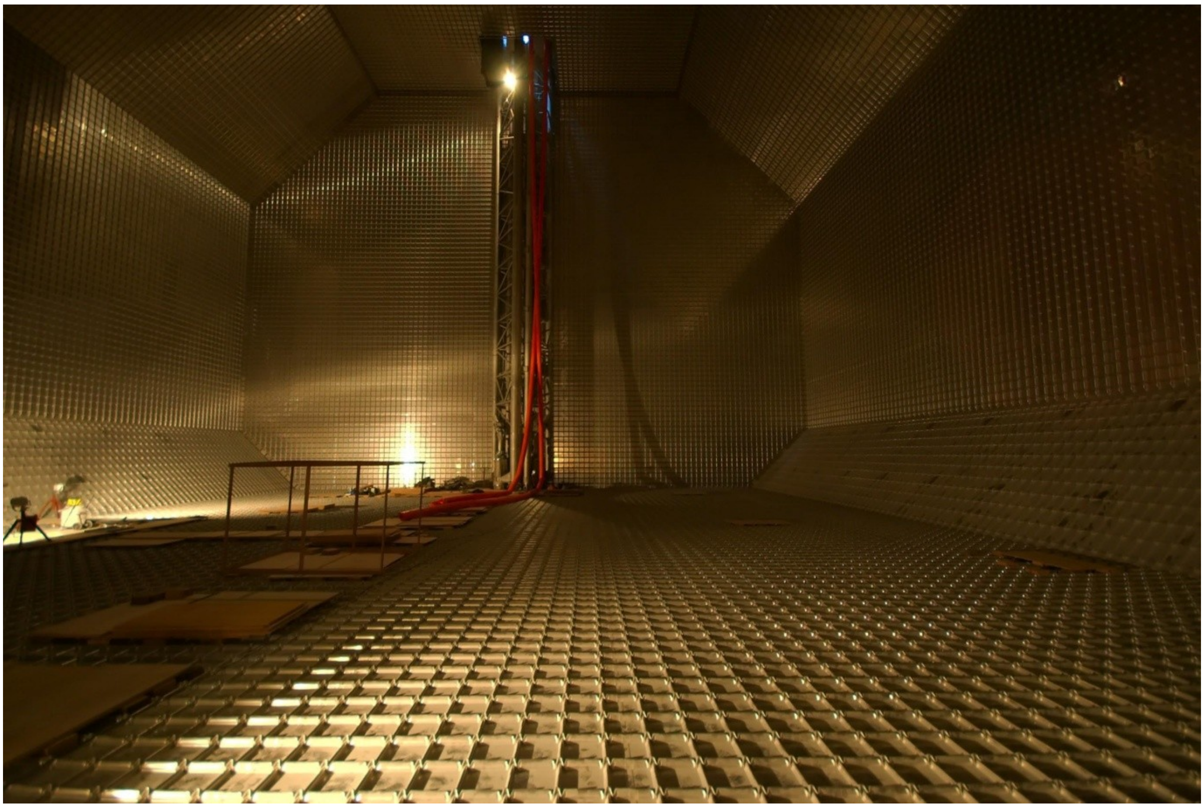
A “water curtain” is applied during the Ship to Ship LNG transfer, in order to ensure that the metal of the ship will not be affected by any sudden change in temperature caused by an LNG spill [32].

Picture 15: Water curtain during STS transfer [32] Wärtsilä, 2014

2.3 LNG Storage

The operation/handling of storing LNG at -162℃ is one of the most vital and energy demanding parts of FSRUs, hence one of the most expensive procedures. The LNG cargo shall be stored onboard at FSRUs either on membrane systems or in independent tanks.

In a membrane system, the storage conditions of LNG are: temperature approximately -162℃ for cargo density of 0.470 to 0.500 tonnes per cubic meter and in atmospheric conditions, pressure approximately 0.7 bar [31, p. 18]. The goal, except from containing the LNG at a temperature of -162°C, is to seal it with a totally impermeable layer between the liquid cargo and the vessel’s hull, while also limiting cargo loss through BOG. The primary membrane shall be Stainless steel 304L - 1.2 mm, Fe-36%Ni alloy and the secondary shall be composite materials or Fe-36%Ni alloy. Manufacturing companies of membrane systems have to guarantee an indicative Boil-Off Rate (BOR) but it is also project dependent due to vessel size, tank arrangement and reinforcements [33]. Membrane tanks by GTT (Gaztransport & Technigaz) such as No.96 tanks and Mark III tanks with their characteristics (material of construction, insulation) are presented in Picture 16, Figure 15, Figure 16.



Picture 16: Interior of a non-spherical, Technigaz Mark III stainless steel membrane, LNG tank [34]

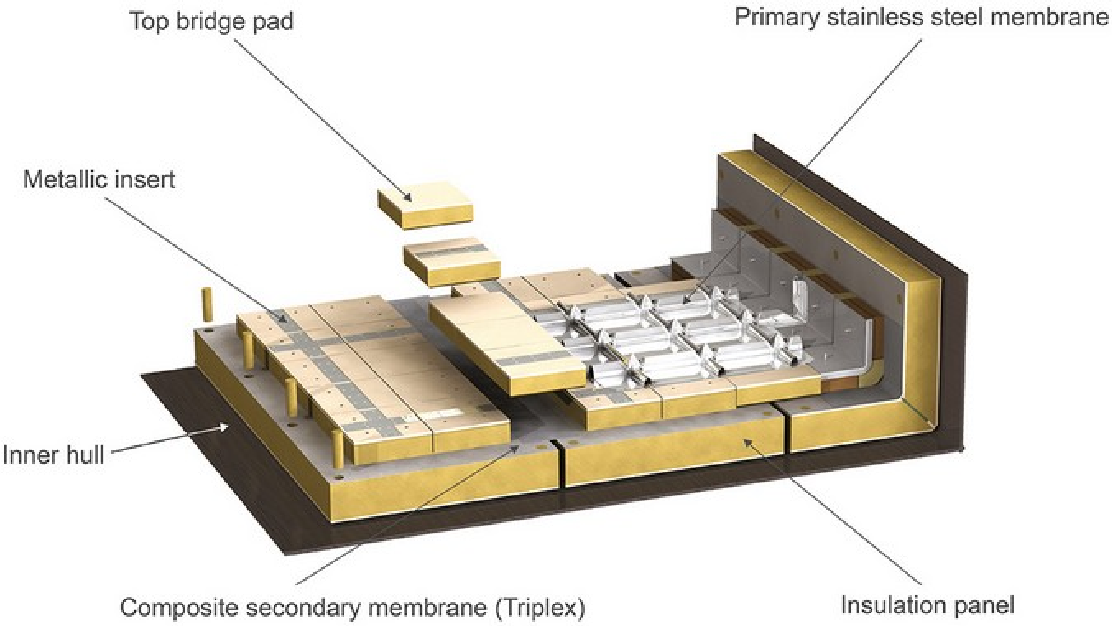


Figure 15: GTT Mark III membrane system [35]

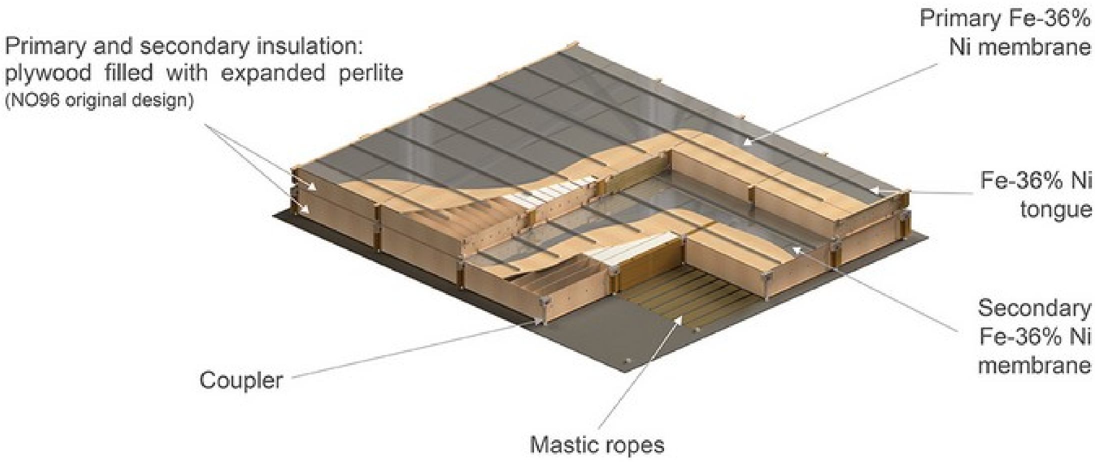


Figure 16: GTT NO96 concept [36]

Among the independent tanks (type A, type B, type C) as exhibited in Figure 9, IMO classification of LNG vessels, type B-Spherical Moss systems are primarily preferred in FSRUs, which are constructed of either aluminum or 9% nickel steel.

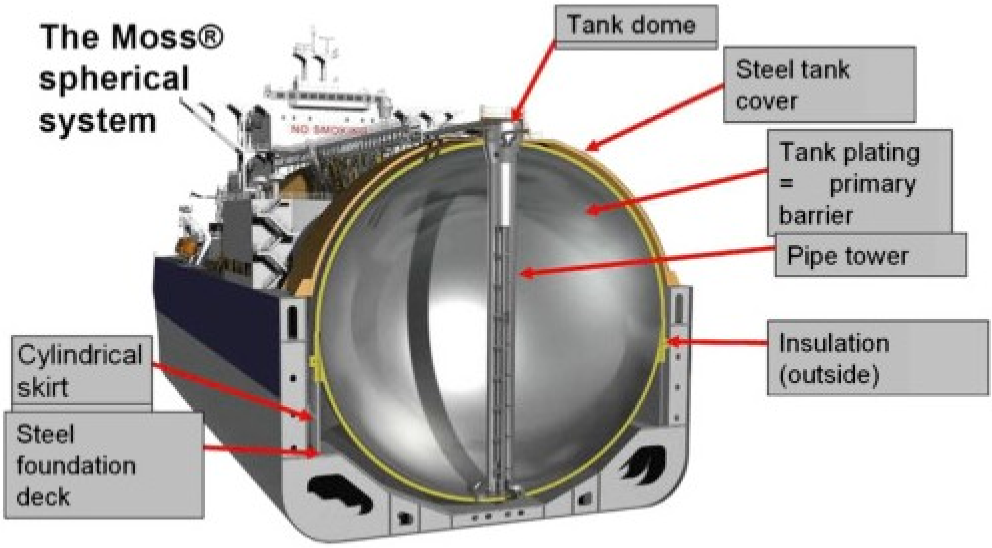


Figure 17: Moss tank [37]

Moss is owned by Norwegian Company Moss Maritime. They are insulated with polyurethane foam which is purged with nitrogen (N_2). Normal operating pressure of Moss Tanks is around 220 mbar (22kPa) [38].

Figure 18: Moss Tank concept [39]

As we have already mentioned, LNG is a multi-component mixture of hydrocarbons and nitrogen, which is being stored at a gauge pressure of some 0.10 to 0.24 bar and temperature of approximately -162°C in suitable tanks. Despite storage tanks insulation, a certain amount of heat from the environment is being transferred eventually inside the tanks causes the evaporation of the most volatile components (lowest boiling points) such as nitrogen and methane, producing vapor (BOG), changing the initial LNG's composition and properties and leading to a mechanism known as "weathering" or "ageing". As a consequence the composition of stored LNG is altered through a time period affecting in fact cargo's density and forming separate layers within a storage tank, i.e. stratification takes place, leading to a phenomenon known as "rollover", which has safety and environmental issues associated with it. Stratification will also occur when loading or unloading a storage tank with for example a "light" and a "heavy" LNG due to different densities and then it is most likely for rollover phenomenon to appear [40, p. 8].

2.4 LNG Pumping

LNG is stored as we have already mentioned at pressures near atmospheric but the gas delivery from the FSRU has to comply with gas operator's requirements, which indicate NG delivery at elevated pressures. Pumping a liquid than compressing a gas is easier and more cost- and energy-effective, thus LNG is pumped to the required send-out pressure prior to its regasification [41, p. 16].

Usually two stages of pumping are taking place, one inside the storage tanks (in-tank pump) and the other in the process area, as topside modules or as hull-integrated system. The first stage of pumps (Low Pressure pumps, LP) supply LNG with discharge pressure around 7-8 bar. The send-out gas needs usually to be delivered onshore in elevated pressures of approximately 80 to 100 bar, in case for example it is injected in the gas distribution system. To achieve these pressures booster pumps (High Pressure pumps, HP) are required in order to take LNG from the first stage pump and increase the pressure prior to the vaporizers at the required pressure [42]. The right pressure of HP pumps should be set taking into consideration the send-out pressure and the inevitable pressure drop from the regasification process which is usually around 1-2 bar [43, p. 52]. It is advised to use inducers in the pump inlet when liquefied gases are pumped (often near to their boiling point) in order to ensure that adequate Net Positive Suction Head Required (NPSHR) is provided to the main centrifugal impellers [44].

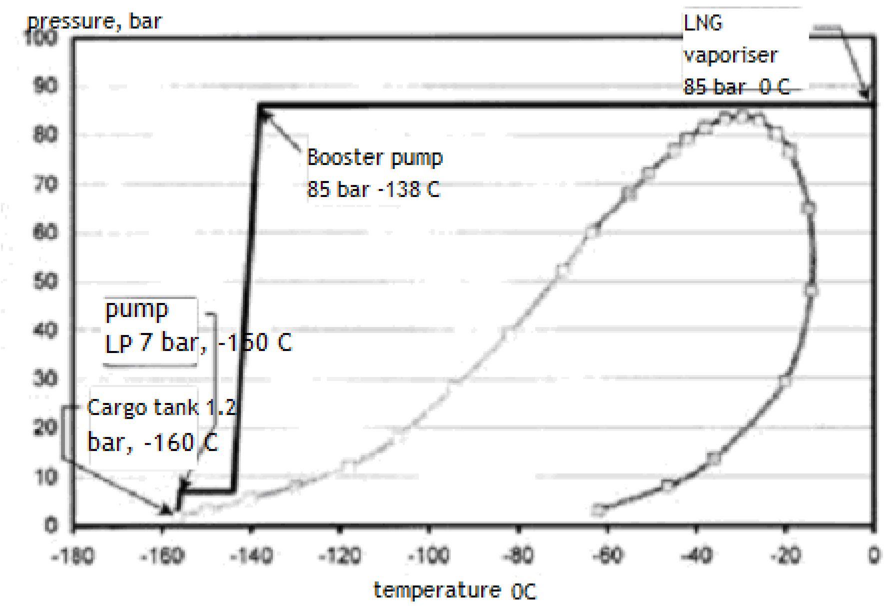


Figure 19: Pressure - Temperature LNG diagram [45]

2.5 LNG Evaporation/Regasification

Regasification or evaporation of LNG is a process that is being executed onboard by FSRU's regasification plant, in order to convert LNG back to its gaseous phase as NG. Regasification of LNG can be implemented in either open loop mode, closed loop mode, or combined loop mode. *"The optimum process depends on various factors including plant site location, climatic conditions, throughput capacities, energy efficiency, emissions and regulatory approvals"* [46].

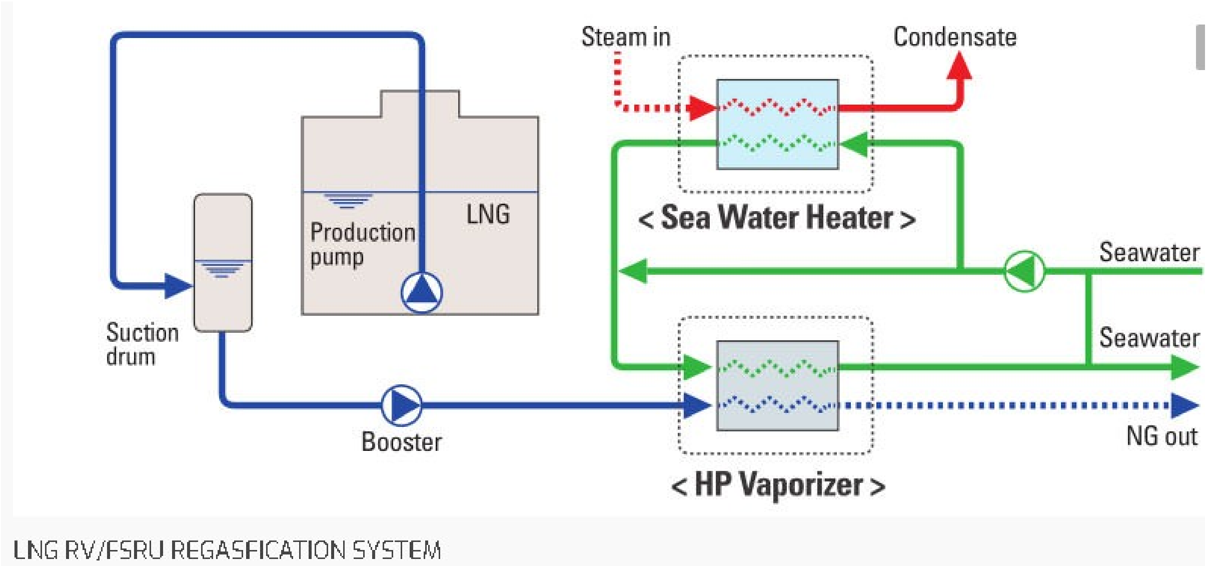


Figure 20: Combined open/closed loop with seawater and steam heating [47]

In an open loop regasification system, seawater is used for heating the LNG, which is continuously provided to the FSRU for the heat exchange process, circulated through the heat exchangers and subsequently is dumped overboard [46]. Heat exchange process could be implemented either between seawater (as the heating source) and an intermediate fluid (propane), or between propane and LNG [46]. Open loop regasification is a preferred technology worldwide, it is simpler compared to the close loop and offers lower greenhouse gas generation emissions [46]. Closed loop regasification is implemented by using gas-fired steam boilers in order to heat circulating water within the FSRU. Replenishment of water is typically made annually for maintenance purposes or if the system is switched to open loop mode [46]. Compared to open loop, it offers a better regasification performance for seawater temperatures below 15ºC and has lower intake and discharge needs for seawater. The disadvantages of this technology for regasification are the higher capital investment cost due to the provision of boilers and the higher operating costs [46]. Similar to the open loop regasification is also the combined loop with continuous provision of seawater but in this mode the seawater is now heated via steam from gas-fired boilers prior to reaching the regasification system on the FSRU [46].

In Picture 17 we observe the construction of a regasification system at FSRU Toscana by Saipem SA that was built in 2003 and is sailing under the flag of Italy.

Picture 17: Construction of regasification section by Saipem SA at FSRU Toscana [48, p. 53]

In particular there are four main categories of regasification systems on FSRUs:

In “Closed-loop propane with seawater as heating medium” liquid propane is initially used to warm LNG up to -10℃ and it is pumped around the refrigeration loop. Natural gas delivery temperature is achieved at 5℃ to 7℃ [31].

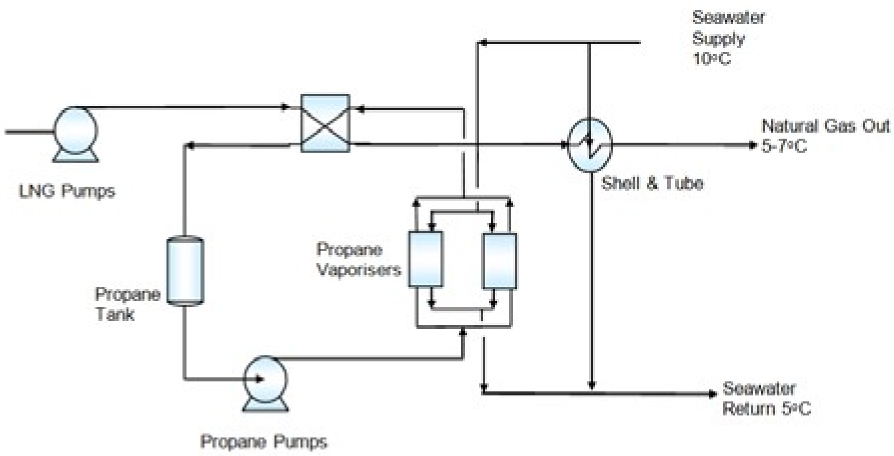


Figure 21: Closed-loop propane with seawater as heating medium [31]

In "Direct seawater vaporizers" fully welded shell and tube heat exchangers with seawater as the heating medium are used for the regasification process. The seawater is raised to the required pressure by a set of seawater pumps and used as the heat sink for the LNG at -162°C. Afterwards, the seawater is discharged back to the sea (open-loop) [31].

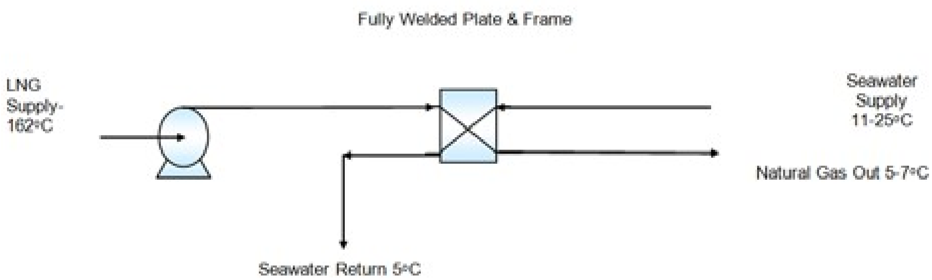


Figure 22: Direct seawater vaporizers [31]

In "Closed-loop TEG/water and steam", a mixture of triethylene glycol (TEG) and fresh water is the heating medium for LNG. TEG - fresh water mixture has to be rewarmed by steam in shell and tube heat exchangers and pump around the system. Printed Circuit Heat Exchanger (PCHE) is the main heat exchanger for warming the LNG [31].

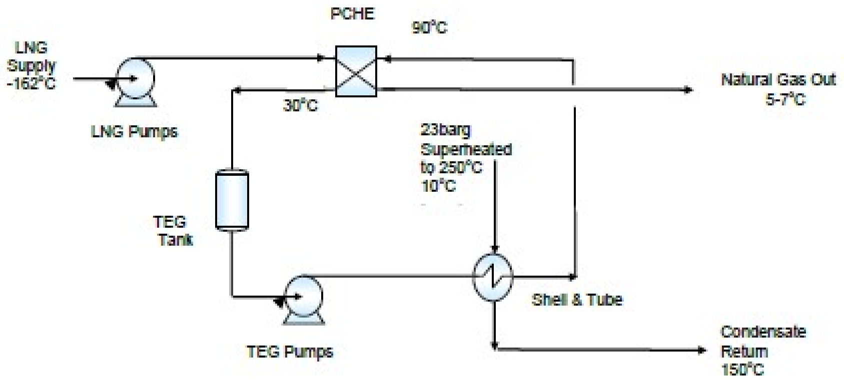


Figure 23: Closed-loop TEG/water and steam [31]

In a "closed-loop TEG/water and seawater system", LNG reaches the required temperature by a mixture of TEG and fresh water which is warmed by seawater. PCHE is also present in this system heating up the LNG [31].

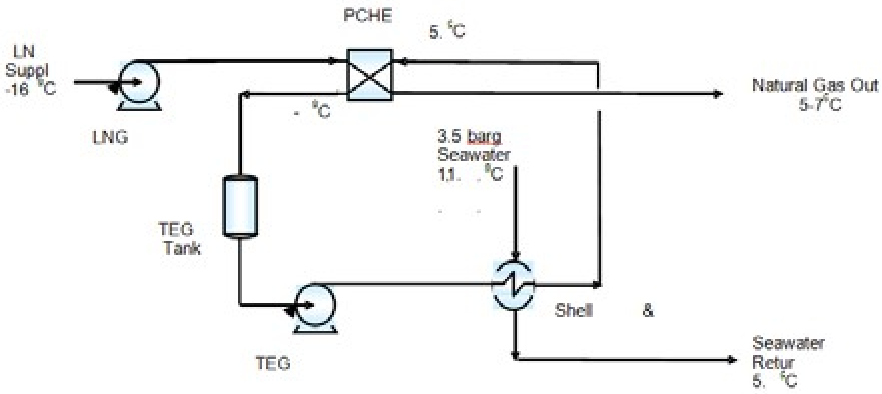


Figure 24: Closed-loop TEG/water and seawater [31]

In Figure 25, we observe a shell and tube heat exchanger with seawater as a heating medium, which heats LNG up to 8ºC in the outlet. In order to prevent corrosion due to seawater, tubes are protected with anti-corrosion material. When direct heating with seawater as the heating medium for regasification is chosen, it is advised that shell and tube heat exchangers must use 6% molybdenum, a material that can withstand seawater conditions [49]. The need for this durable material should be considered in the feasibility study of the project, since it is four times more expensive than stainless steel [49].

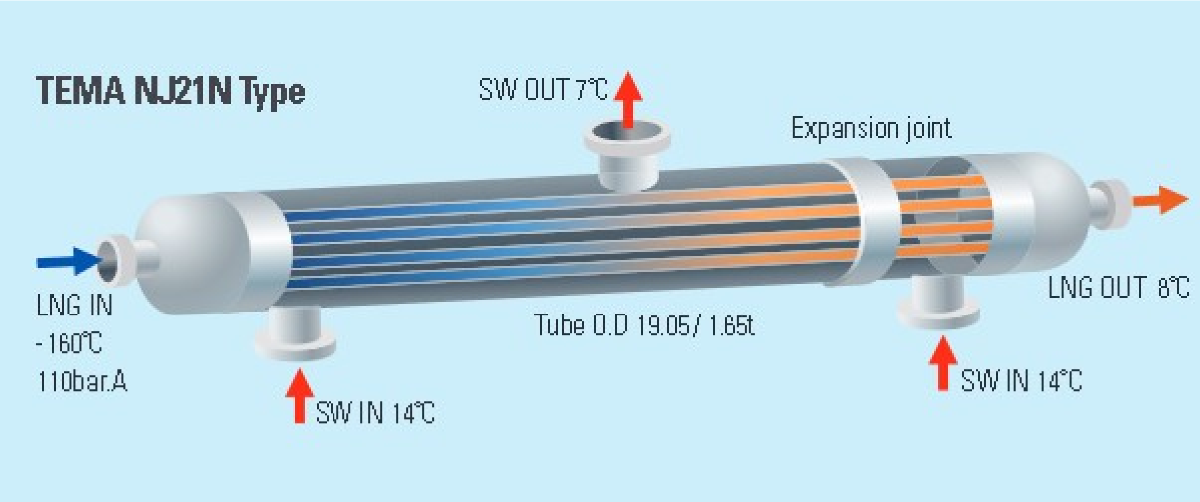


Figure 25: Shell and Tube type heat exchanger [47]

Patel et al. in their study [50] compare six vaporizer options based on different heating mediums in terms of their application, operation and maintenance, utility and chemical requirements, environmental impacts and relative plot sizes and they are presented in Table 7. The six options considered in their study are Open Rack Vaporizer (ORV) uses seawater as heating medium, second option uses propane as the intermediate fluid with seawater as the heating source, third option uses glycol water as the intermediate fluid with air as the heating source, fourth option uses glycol water as the intermediate fluid with seawater as the heating source, fifth option uses Submerged Combustion Vaporizer (SCV) using fuel gas and waste heat from cogeneration plant and sixth option uses Ambient Air Vaporizer (AAV) [50]. The optimum vaporization option was examined by the ambient locations, for warm ambient locations where the site ambient temperature is above 18°C and the most desirable is Option 3 (IFV (GW/Air)) and cold ambient locations where ambient temperature drops below 18°C and the most desirable option is a combination of seawater heating and SCV [50].

HEATING MEDIUM	Option 1 Seawater (SW)	Option 2 Propane (C3) / Seawater (SW)	Option 3 Glycol-water (GW) / Air	Option 4 Glycol-water (GW) / Seawater	Option 5 Hot Water (HW) Fuel Gas (FG)) / Waste Heat (WH)	Option 6 Air
FEATURE	Direct LNG vaporization using sea water	Indirect LNG vaporization by condensing propane which is heated by seawater	Indirect LNG vaporization by glycol which is heated by air fin exchanger	Indirect LNG vaporization by glycol which is heated by seawater	Indirect LNG vaporization by hot water which is heated by waste heat and SCV	Direct LNG vaporization using air
MAJOR APPLICATION	70% base load plants use ORV	Cold climate application and avoid freezing of seawater	For warm climate application. IFV makes up 5 % of base load plants	Similar to Option 3 except seawater is used as the source of heating	For energy conservation with use of waste heat. SCV is used in 25% of base load plants	For warm climate application, peak shavers and where real estate is not a constraint
OPERATION & MAINTENANCE	Seawater pumps and filtration system Maintenance of vaporizers and cleaning of exchangers	Similar to Option 1 with addition of a glycol loop and propane system	Similar to Option 2 with a glycol loop and use of air as the source of heat	More Complex, requiring coordination with power plant	More complex control. Need to balance waste heat and fuel gas to SCVs. Require coordination with power plant operation	Cyclic operation, requiring adjustment of the defrosting cycle according to ambient changes
UTILITIES REQUIRED	Seawater and electrical power	Seawater and electrical power	Electrical power only	Seawater and electrical power	Fuel gas and electrical power	Electrical power only
CHEMICALS	Chlorination for seawater treatment.	Similar to Seawater but lower chlorination	None	Similar to Seawater but lower chlorination	Neutralization required for pH control and NOx reduction by SCR	None
EMISSION & EFFLUENTS	Impacts on marine life from cold seawater and residual chloride content	Impacts on marine life from cold seawater and residual chloride content	No significant impact on environment except dense fog	Impacts on marine life from cold seawater and residual chloride content	Flue gas (NOx, CO2) emissions and acid water condensate discharge	No significant impact on environment except dense fog
SAFETY	Leakage of HC from ORV to atmosphere at ground level	Leakage of HC to atmosphere at ground level. Operating a propane liquid system is additional safety hazard	Leakage of HC to glycol system which can be vented to safe location via surge vessel	Leakage of HC to glycol system which can be vented to safe location via surge vessel	Leakage of HC to water system which can be vented to safe location via the SCV stack and surge vessel	Leakage of HC from AAV to atmosphere at ground level
PLOT PLAN	Medium Size	Medium Size	Large Size	Medium Size	Small Size	Large Size

Table 7: LNG Vaporization Option Qualitative Comparison [50]

2.6 Boil-Off Gas (BOG) compression

LNG as we have already mentioned is stored in insulated tanks in liquid form at a temperature of -162°C, close to the vaporization temperature and any amount of external heat lead to natural evaporation of LNG, i.e. Boil-Off Gas. The amount of BOG per hour depends mainly on the size of the tanks, the load level of the LNG, the ambient temperature and the quality of the LNG tank insulation. The formation of boil-off gas is unavoidable due to the natural cargo heating and operations (transfer, storage) and has to be removed from the tanks in order to maintain the cargo tank pressure (during ship-to-ship LNG transfer, a certain amount of BOG that has been created due to this process, is redirected through a vapour return valve to LNGC). For this reason boil-off gas needs to be monitored by the BOG handling system. BOG handling system is responsible for either providing BOG as fuel gas, that is compressed by low duty compressor up to the required pressure or by redirecting BOG to the recondenser for recondensation [51, p. 21]. Moreover, due to the regasification process, a certain amount of LNG boils off and creates boil-off gas which is compressed by BOG compressors and is commonly added to the NG send-out [1].

When the amount of BOG exceeds the amount to fill the empty volume in LNG storage tanks, BOG compressor has to gather this boil-off gas and redirect it to BOG recondenser. The most important variable about BOG compressors is discharge pressure and the value is determined for maximum efficiency. BOG production rate in each FSRU project indicates the optimum capacity of the BOG compressor [43]. The BOG recondenser has to handle the excess of BOG that is not used in DFDE-type (dual-fuel diesel electric) for power generation, by recovering and liquefying BOG with sub-cooled LNG.

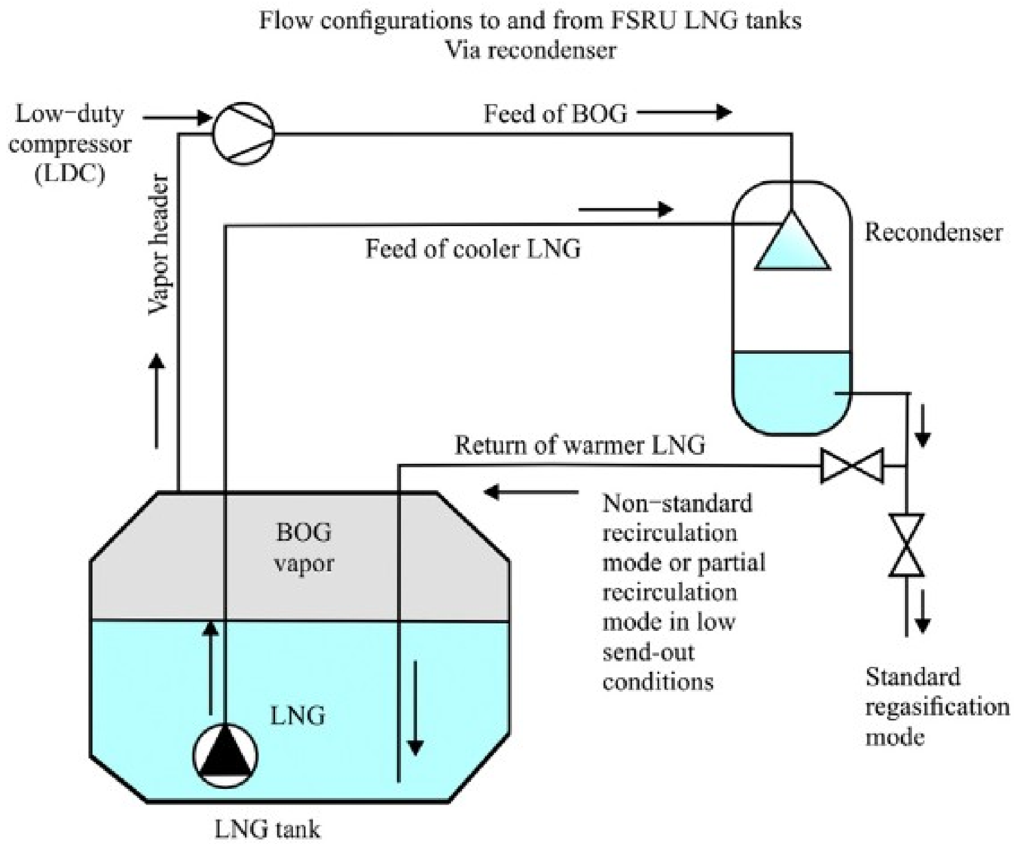
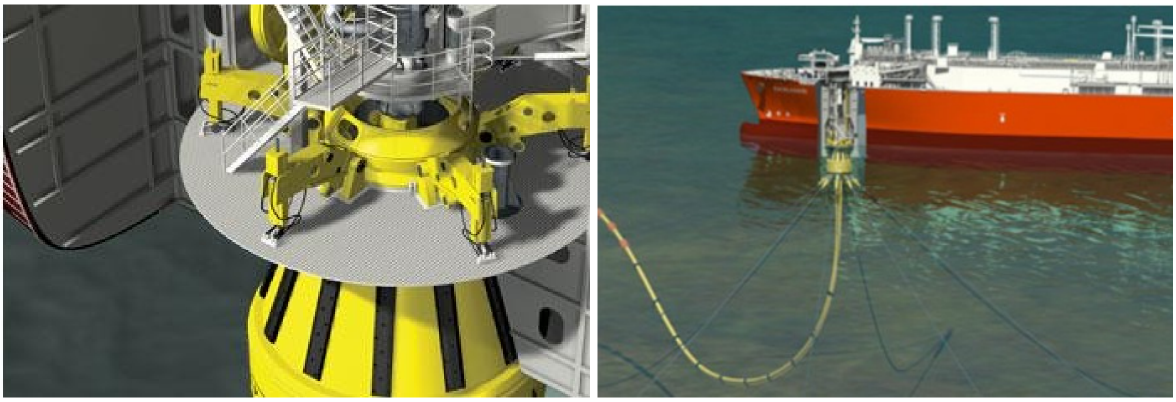


Figure 26: Flow configurations to and from FSRU tanks via recondenser [52]

2.7 Natural Gas delivery to shore

Finally, high-pressure natural gas is delivered to onshore facilities via pipeline, either through high-pressure gas offloading arms or a subsea buoy linked to a subsea pipeline. Prior to its delivery, NG flow rate is measured by an ultrasonic flow meter and the gas is odorized.

Picture 18: Natural gas is discharged via high-pressure gas offloading arm [53]



Picture 19: Natural Gas is discharged through a subsea buoy linked to a subsea pipeline [53]

Chapter 3: FSRU Basic Design

In this Chapter the Basic Design on an FSRU Project will be presented with emphasis on key process parameters of FSRU and connection to delivery system. Two different delivery pressure requirements will be examined: a High Pressure one (at 80 bar) and a Low Pressure one (at 12 bar) in order to show constraints and technologies to be used in each case.

3.1 Basic Design Data

An FSRU installation (as shown in Figure 27) shall consist of:

- a Floating Storage Regasification Unit (FSRU)
- a Mooring system
- a Pipeline system connecting the FSRU to the National Gas Transmission System. FSRU vessel shall be permanently moored and have a high pressure natural gas transfer system, transmitting the gas through flexible risers to the Pipeline End Manifold (PLEM), where the gas transmission pipeline is connected.

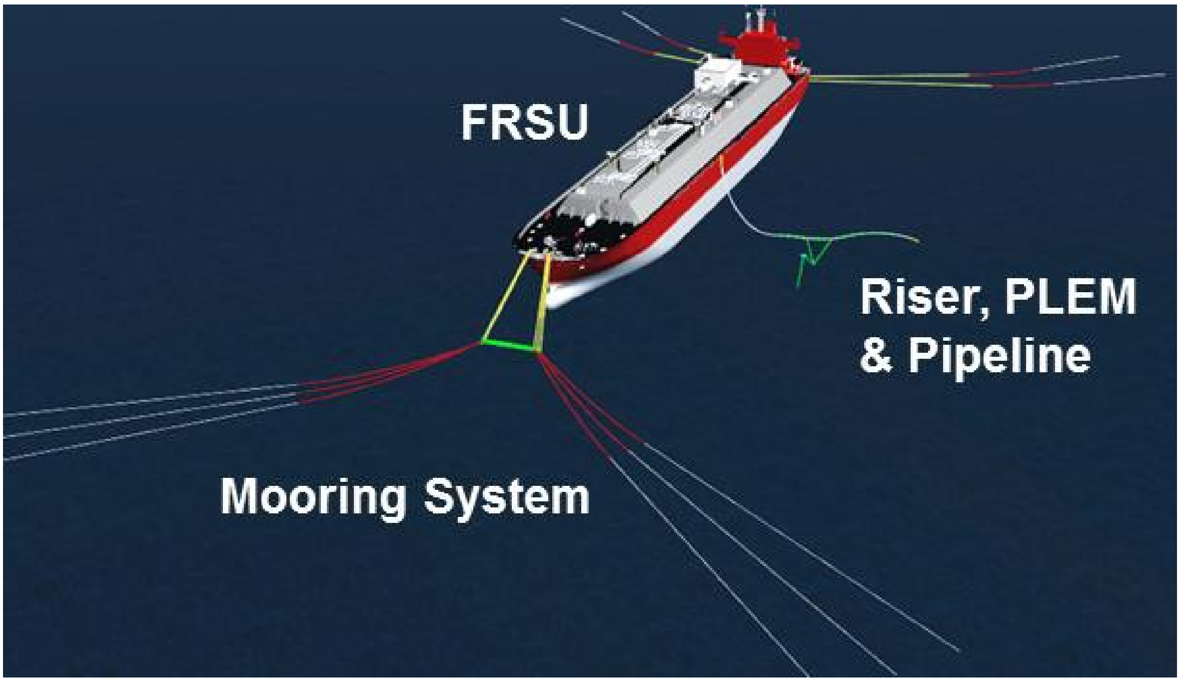


Figure 27: FSRU Installation [32]

The following Basic Design Data for FSRU installation shall be considered.

Typical LNG composition (mole fractions) [43]:

- Methane: 0.9133
- Ethane: 0.0536
- Propane: 0.0214
- Isobutane: 0.0047
- N-butane: 0.0046
- Isopentane: 0.0001
- N-pentane: 0.0001
- Nitrogen: 0.0022

- Terminal Send-out Rate to Pipeline: 4 x 400 m^3/h LNG

  Two delivery systems of LP and HP will be examined:

  HP System:

  - Design Send-out Pressure: 100 bar
  - Operating Send-out Pressure: 80 bar
  - Design Send-out Temperature: 50ºC
  - Operating Send-out Temperature: 5ºC

  LP System:

  - Design Send-out Pressure: 15 bar
  - Operating Send-out Pressure: 12 bar
  - Design Send-out Temperature: 50ºC
  - Operating Send-out Temperature: 5ºC

- Offloading System:
  - Ship: 120,000 m^3
  - Offloading Rate to FSRU: 6,000 m^3/h

- LNG Cargo Tanks:
    - Capacity: 120,000 m^3
    - Design pressure: 250 mbarg
    - Operating pressure: 200 mbarg
    - Design Temperature: -173°C
    - Operating Temperature: -162°C
    - BOR (Boil-Off Rate): 0.075% wt daily
- Cooling Water/Seawater Temperature Difference: 5°C
- Design lifetime: 20 years

3.2 Process Description

An LNGC delivers LNG to FSRU. Following berthing, LNG is pumped via LNGC ship pumps through unloading arms in order to be transferred from LNGC to FSRU storage tanks (stream 1). The transfer rate shall be approximately 6,000 m^3/h. LNG shall be stored in insulated type B-Spherical Moss System Tanks of a total capacity 120,000 m^3. LNG boil-off gas is formed during transfer and storage due to heat losses to ambient and volume displacement. This BOG shall be sent either via BOG compressor directly to pipeline or recondensed in recondenser before delivery pipeline. Recondensing shall be done via mixing of the gas with LNG before transfer via HP pumps for vaporization. The operation of BOG compressors shall ensure that the BOG produced is sent to pipeline or used as fuel, otherwise it should be flared to a safe location. Depending on the maximum required send-out rate, high pressure pumps have to satisfy this rate in order to provide LNG at required discharge pressure. LNG shall be pumped with high pressure pumps up to delivery pressure prior to the regasification process in vaporizers (stream 2, 4, 6, 8). After regasification, natural gas at required pressure and temperature shall be sent to the valve right before the pipeline (stream 3, 5, 7, 9). Streams 13, 14 indicate cooling water/seawater requirements for the regasification process. At every stage, NG shall be measured in order to estimate the losses. A vent mast shall be present in order to ensure safe disposal of hydrocarbon vapors which may occur in the regasification process and in the BOG handling system at abnormal operation.

Operating Modes of the FSRU terminal shall be:

- FSRU Loading with Send-out
- Send-out without FSRU Loading
- Holding (zero Send-out/no Loading)

A typical process flow diagram for an FSRU is shown in Figure 28 with LNG and NG Streams.

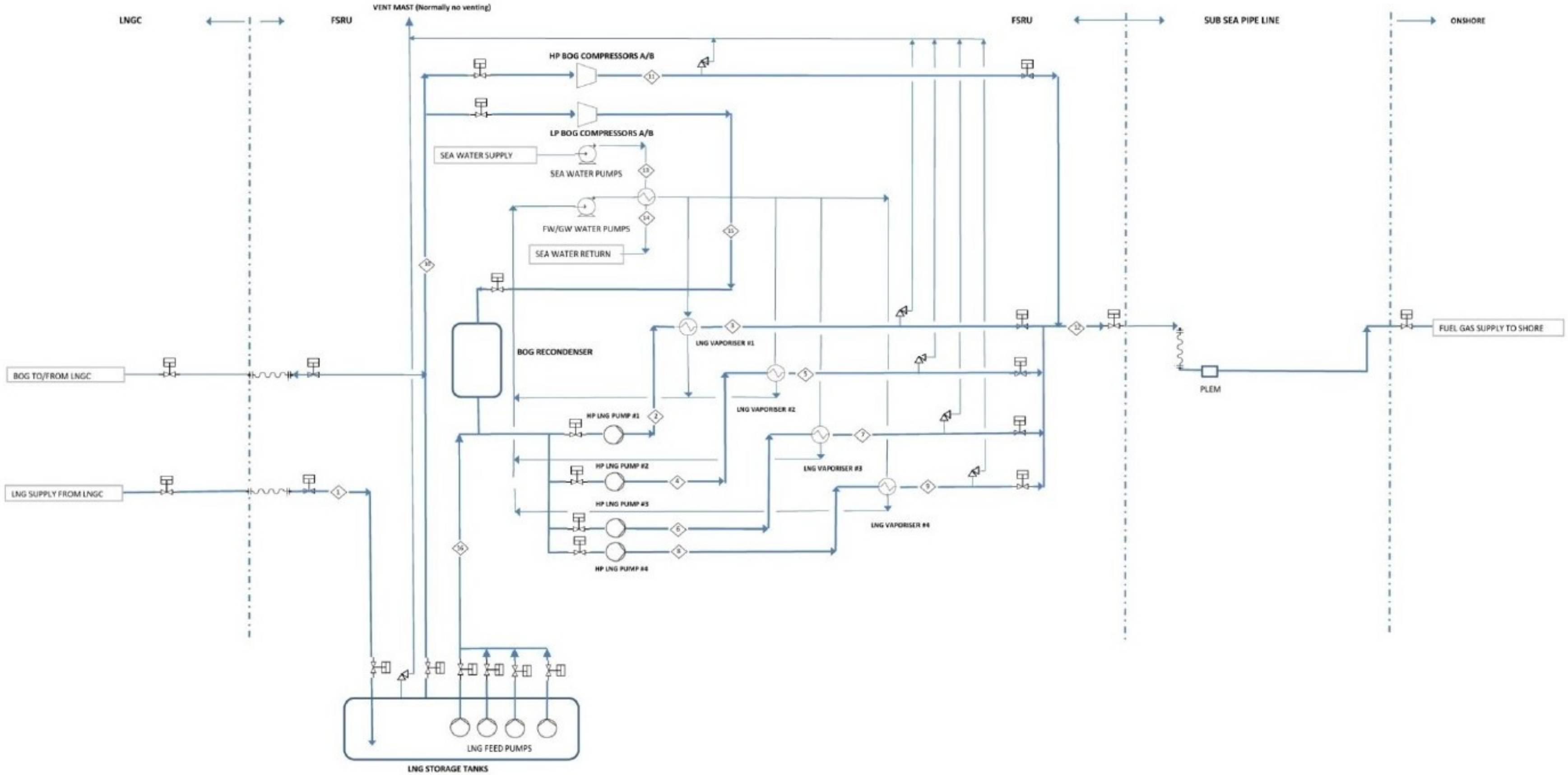


Figure 28: FSRU Installation Schematic [32]

3.3 Process Simulation

The simulation of the above mentioned process has been performed using DWSIM steady state simulator. DWSIM is a chemical process simulator that allows the user to model process plants by using rigorous thermodynamic and unit operations models [54]. For this simulation, the thermodynamic model which is selected is the Peng-Robinson (PR) property package that uses the Peng-Robinson cubic equation of state and is recommended for use with hydrocarbons. In Table 8 the main symbols along with their description used in DWSIM are given.

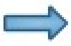
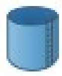
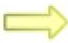
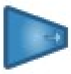
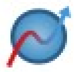
Symbol	Symbol description	Symbol	Symbol description
	Material stream		Tank
	Energy stream		Stream mixer
	Pump		Stream splitter
	Compressor		Heat exchanger
	Cooler		Gas-liquid separator

Table 8: Process flow diagram symbols for simulation in DWSIM [54]

In order to simulate the processes that take place in an FSRU, we formulate in blocks the main processes such as storage of LNG in the FSRU tanks, BOG handling, regasification and natural gas supply to pipeline.

3.3.1 Boil-Off Gas (BOG) Simulation

The Boil-Off Gas (BOG) is composed only of methane and nitrogen, in analogies depending on LNG composition. It is transferred from the FSRU tank via a BOG compressor either to the delivery system or to recondenser for vaporization.

BOG is the gas generated from LNG mainly due to the following factors:

- heat loss to ambient (BOR - Boil-Off Rate) in FSRU tank
- liquid level displacement during the loading mode.

The capacity of the vessel and the loading rate affect the amount of the BOG formation i.e. the larger the vessels and the greater the loading rates, the higher the BOG formation. In order to calculate the BOG amount (stream 10), we simulate the BOG production as it is presented in Figure 29 hereafter. The simulation will result in the maximum BOG production during FSRU Loading Mode to be considered for sizing the BOG Compressor.

First, we have to calculate the heat input in kW from the ambient to the vessel (heat ingress to FSRU tank). We need to define the vessel size (m^3), the vessel's BOR (% wt daily), the methane heat of vaporization (kJ/kg), the methane density at -162°C and 1 atm and pure methane vaporization (kg/h) since the BOG is expressed in terms of pure methane mixture. In particular for a vessel of 120,000 m^3 the calculated heat input is 224.5 kW.

Ship Size (m^3)	**Ship BOR (% wt daily)**	**Methane Heat Of Vaporization (kJ/kg)**	**Methane Density @ -162°C and 1 atm**	**Pure Methane Vaporization (kg/h)**	**Calculated Heat Input (kW)**
120,000	0.075	510.15	422.46	1584.2	224.5

Table 9: Heat input from ambient

This calculated input is introduced in the tank simulation block as heat input that would result into a flash and production of BOG (the composition of the BOG is presented in Figure 29).

Then, an equivalent volume of 6,000 m^3/h of the same BOG quality is introduced to simulate the vapour displacement due to liquid level increase inside the tank.

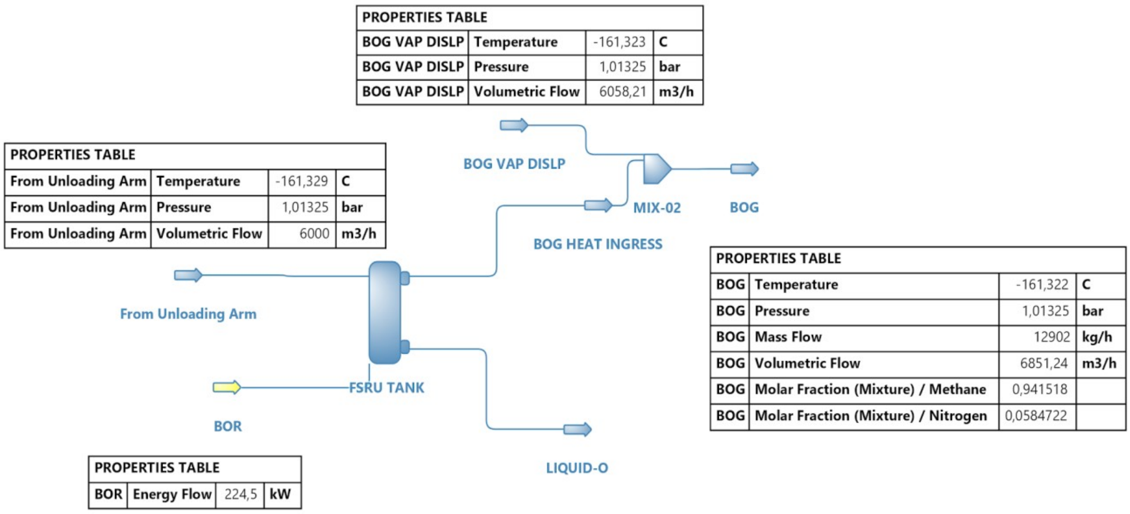


Figure 29: Simulation of BOG production in DWSIM

From the simulation results, it is clear that the amount of BOG produced during FSRU loading is 6,851.24 m^3/h of gas (12,902 kg/h) of the following quality:

- Methane: 94.15%
- Nitrogen: 5.85%

This result will be introduced in the general simulation model of the FSRU.

3.3.2 FSRU Simulation

The most demanding operation of the FSRU, FSRU Loading and Maximum Send-out, is simulated using DWSIM in order to size major pieces of equipment. There is a set of four (4) HP Pumps and four (4) Vaporizers to achieve the Maximum Send-out rate of 4 x 400 = 1,600 m^3/h LNG. A cooling water pump is also present in order to provide seawater to the vaporizers and a BOG Compressor for BOG handling from FSRU Tank.

We examine in FSRU simulation the following cases:

- Low Pressure delivery at 12 bar
- High Pressure delivery at 80 bar

The developed flowsheets for both cases are presented in Figure 30, Figure 33 and the results of the simulation in the form of heat and material balances are shown in Table 10, Table 12 hereafter.

3.3.2.1 FSRU Simulation - Low Pressure Delivery System

For a Low Pressure delivery system at 12 bar, a BOG compressor is added in simulation to transfer the produced BOG generated directly to the delivery system. The compressor is sized for the maximum BOG production case that is the FSRU Loading mode without Send-out. It is the maximum BOG production case since the vapour displacement is maximum in this case.

The BOG compressor is modeled for the following conditions:

- Suction Pressure: almost atmospheric
- Discharge Pressure: 12 bar
- Capacity: 12,902 kg/h as calculated in the previous section
- BOG Quality: Methane: 94.15% mol, Nitrogen: 5.85% mol as calculated in the previous section

- Efficiency: 75% (typical)

The results of the simulation give a compressor machine with the following characteristics:

- Discharge Temperature: -32ºC
- Required Power: 872 kW

The compressor discharge BOG is mixed with the evaporated LNG and sent to the delivery system. Part or all of it could be used for power generation requirements in the FSRU and the remaining gas could be sent to the delivery system instead of flaring it.

For the LNG vaporization, a set of 4 pumps is used to transfer LNG to vaporizers that operate by means of cooling water.

These pumps are located inside the tank and are of type vertical centrifugal pumps. They are designed for the following data:

- Suction Pressure: almost atmospheric with static head depending on tank level
- Discharge Pressure: 13 bar
- Pressure Increase (Head): 12 bar
- Capacity: 400 m^3/h
- Efficiency: 75% (typical)
- Required Power: 177.6 kW

Four (4) vaporizers, one per pump are simulated for the vaporization of the LNG to NG via cooling water. The allowable pressure drop per vaporizer is 1 bar and the cooling water required, for Temperature Difference DT = 5ºC and inlet cooling water temperature of 15ºC, is estimated to 6,425 m^3/h per vaporizer. The vaporizers outlet temperature of the NG is 5ºC, higher than the NG dew point.

The water pump for cooling water purposes are also vertical centrifugal pumps with the following design characteristics:

- Suction Pressure: almost atmospheric

- Discharge Pressure: 3 bar
- Pressure Increase (Head): 2 bar
- Capacity: 25,700 m^3/h
- Efficiency: 75% (typical)
- Required Power: 1,891 kW

The simulation flowsheet and the Heat & Material Balances are shown hereafter.

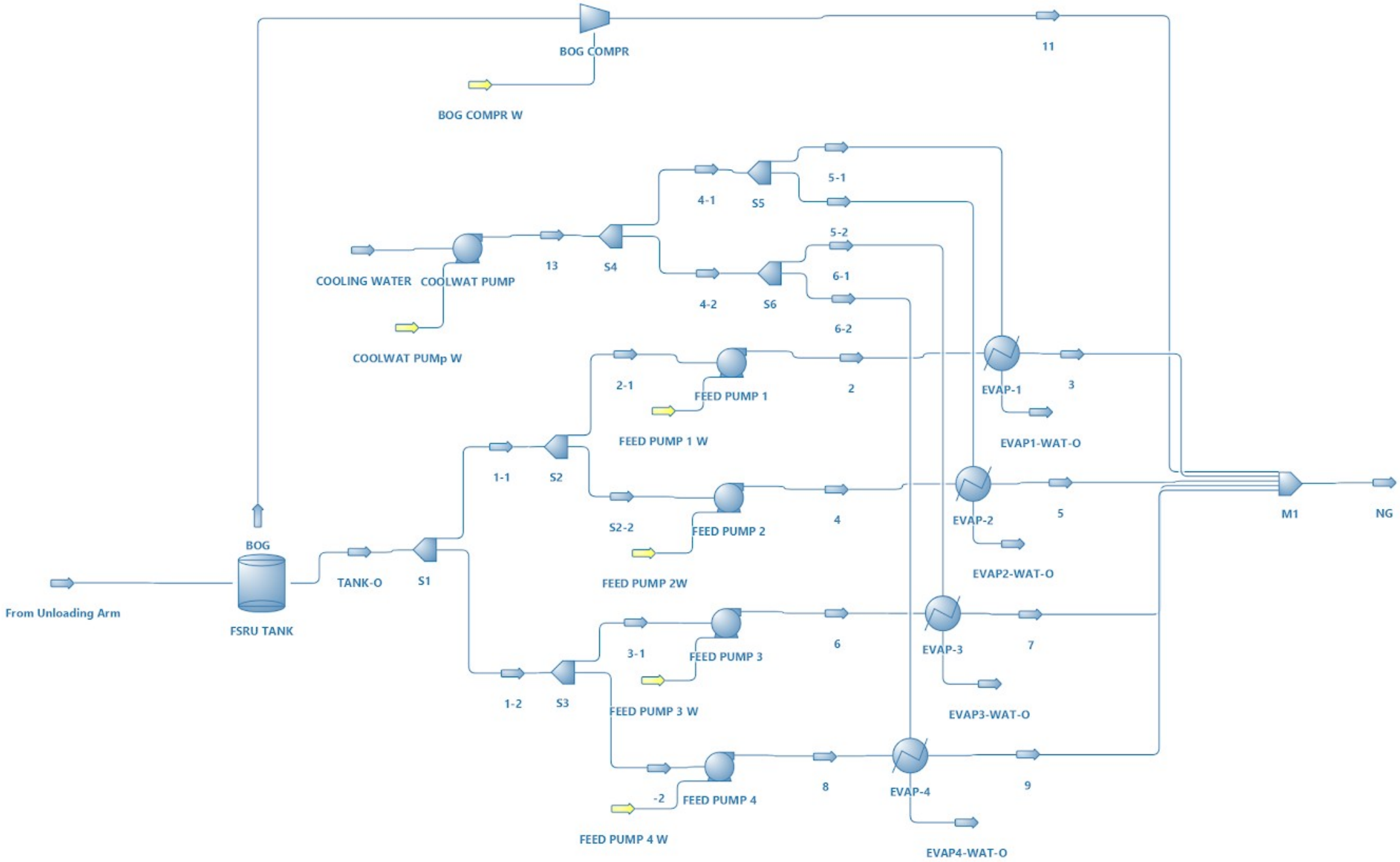


Figure 30: Simulation Flowsheet in DWSIM - Low pressure delivery at 12 bar

Stream	1	2	3	4	5	6	7	8	9	10	11	12		13	14
	LNG from LNGC to FSRU	LNG from Pump 1 to Vaporizer 1	NG from Vaporizer 1 to valve (before pipeline)	LNG from Pump 2 to Vaporizer 2	NG from Vaporizer 2 to valve (before pipeline)	LNG from Pump 3 to Vaporizer 3	NG from Vaporizer 3 to valve (before pipeline)	LNG from Pump 4 to Vaporizer 4	NG from Vaporizer 4 to valve (before pipeline)	BOG from FSRU to compressor	BOG at compressor discharge	Total NG at delivery pipeline	Seawater supply	Inlet Sea water for regasificatio n	Outlet Seawater from regasification
Liquid Flow (m^3/h)	1,600	400	-	400	-	400	-	400	-	-	-	-	25,700	25,700	25,700
Gas Flow (m^3/h)	-	-	18,220	-	18,220	-	18,220	-	18,220	6,851	1,229	74,123	-	-	-
Phase	Liquid	Liquid	Gas	Liquid	Gas	Liquid	Gas	Liquid	Gas	Gas	Gas	Gas	Liquid	Liquid	Liquid
Pressure (bar)	1	13	12	13	12	13	12	13	12	1	12	12	1	3	3
Temperatur e (C)	-162	-161	5	-161	5	-161	5	-161	5	-161	-32	4.3	15	15	10

Table 10: Heat And Material Balances from DWSIM Simulation - Low pressure delivery at 12 bar

Number of items	Equipment description	Equipment type	Materials of construction	Operating Conditions		Design Conditions		Capacity				Insulation data	Remarks
				Temperature (°C)	Discharge Pressure (bar)	Temperature (°C)	Discharge Pressure (bar)	Flow (m^3/hr)	Volume (m^3)	Length (m)	Diameter (mm)		
4	LNG Unloading Arm	-	stainless steel	-162	2-3	-173	5	6,000	-	-	410	urethane foam	2 for LNG unloading, 1 for vapour return, 1 hybrid for spare
6	Type B-Spherical Moss System Storage Tank	vessel	aluminum or stainless steel	-162	200 (mbarg)	-173	250 (mbarg)	-	20,000	-	-	polyurethane foam	-
1	Cooling Water Pump	pump	aluminum bronze	15	3	30	5	25,700	-	-	-	-	-
1	BOG Compressor	compressor	carbon steel	-162/-32	12	-173	15	6,851	-	-	-	-	-
4	High Pressure Pumps	pump	carbon steel	-162	13	-173	15	400	-	-	-	-	-
4	Vaporizers	heat exchanger	stainless steel	5	12	-173/50	15	400	-	-	-	-	-
1	Flare Stack	pipe	-	-	AMB	-	3.5	-	-	65	100-200	-	-

Table 11: List of Equipment Low pressure delivery at 12 bar

3.3.2.2 FSRU Simulation - High Pressure Delivery System

In this simulation we set the delivery pressure of NG at 80 bar. The BOG Compressor has to handle the BOG generation on Loading Mode i.e. 12,902 kg/h at 80 bar delivery pressure. The compressor discharge temperature depends on the polytropic efficiency and the selected pressure difference (inlet, outlet). By specifying the compressor outlet pressure (80 bar) and polytropic efficiency (75%), we manage to deliver the outlet stream of the compressor (Stream 11) at 127°C with 2 MW power required for the compressor's operation. Despite the fact that in simulation a compressor with this required pressure increase could work (see Figure 31), in reality it is unfeasible and such a machine cannot exist.

For this reason, we simulate the case with a set of three compressors and air-cooled intercoolers that sequentially could achieve the required pressure difference as presented in Figure 32. This layout with compressors and intercoolers could be feasible with respect to equipment requirements, but it is an installation that requires a lot of space in order to be arranged and in our case it could not be a feasible solution from the construction point of view and for the space available in a ship. In FSRU installation, the high pressure delivery requires recondensing due to high compressor machine requirements.

Therefore, we examine the case with recondensation as presented in the following section. Recondensation is preferable based on the design heuristic that: better pump a liquid than compress a gas. Indeed the power required for the pressure increase is higher in the gas phase compared to the liquid phase. The recondensation is based on the concept of mixing the BOG with a quantity of LNG to get a liquid mixture that will be further vaporized. The recondenser is a mixing drum of typically 4 m^3. The recondensing will require two levels of pumping. A set of LP Pumps at a pressure that will be also the BOG Compressor delivery pressure and the HP Pumps to bring LNG to the final delivery pressure prior to vaporization.

The LP pumps are of type vertical centrifugal pumps. They are designed for the following data:

- Suction Pressure: almost atmospheric
- Discharge Pressure: 8 bar
- Pressure Increase (Head): 7 bar
- Capacity: 400 m^3/h
- Efficiency: 75% (typical)
- Required Power: 104 kW

The HP pumps are of type vertical centrifugal pumps. They are designed for the following data:

- Suction Pressure: 8 bar
- Discharge Pressure: 81 bar
- Pressure Increase (Head): 73 bar
- Capacity: 413 m^3/h
- Efficiency: 75% (typical)
- Required Power: 1,116 kW

Four (4) vaporizers, one per HP pump are simulated for the vaporization of the LNG to NG via cooling water. The allowable pressure drop per vaporizer is 1 bar and the cooling water required, for Temperature Difference DT = 5°C and inlet cooling water temperature of 15°C, is estimated to 5,462 m^3/h per vaporizer. The vaporizers outlet temperature of the NG is 5°C, higher than the NG dew point.

The water pump for the cooling water purposes are also vertical centrifugal pumps with the following design characteristics:

- Suction Pressure: almost atmospheric
- Discharge Pressure: 3 bar

- Pressure Increase (Head): 2 bar
- Capacity: 21,850 m^3/h
- Efficiency: 75% (typical)
- Required Power: 1,608 kW

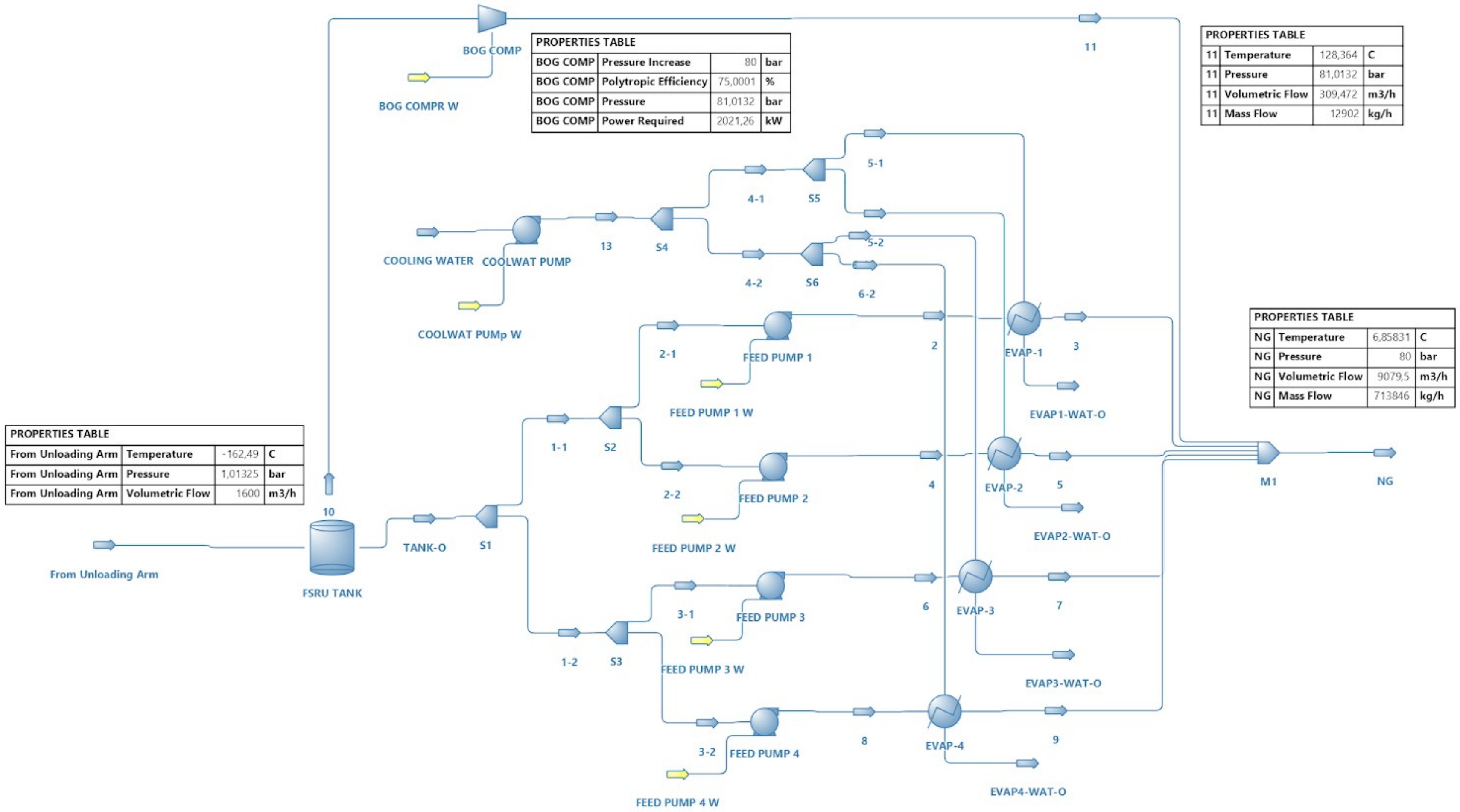
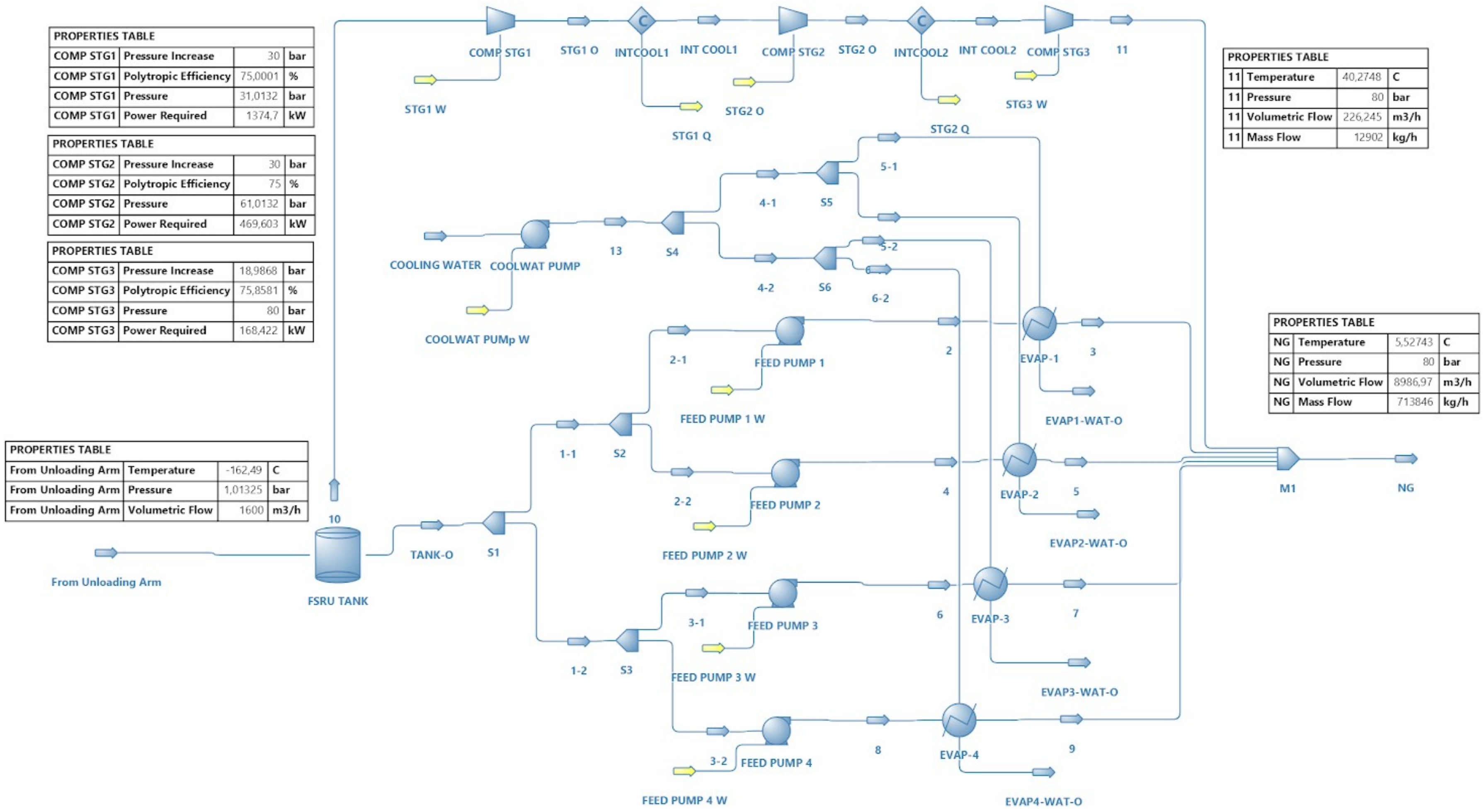


Figure 31: Simulation Flowsheet in DWSIM - High pressure delivery at 80 bar without recondensing - 1 stage Compressor



PROPERTIES TABLE			
COMP STG1	Pressure Increase	30	bar
COMP STG1	Polytropic Efficiency	75,0001	%
COMP STG1	Pressure	31,0132	bar
COMP STG1	Power Required	1374,7	kW

PROPERTIES TABLE			
COMP STG2	Pressure Increase	30	bar
COMP STG2	Polytropic Efficiency	75	%
COMP STG2	Pressure	61,0132	bar
COMP STG2	Power Required	469,603	kW

PROPERTIES TABLE			
COMP STG3	Pressure Increase	18,9868	bar
COMP STG3	Polytropic Efficiency	75,8581	%
COMP STG3	Pressure	80	bar
COMP STG3	Power Required	168,422	kW

PROPERTIES TABLE			
From Unloading Arm	Temperature	-162,49	C
From Unloading Arm	Pressure	1,01325	bar
From Unloading Arm	Volumetric Flow	1600	m3/h

PROPERTIES TABLE			
11	Temperature	40,2748	C
11	Pressure	80	bar
11	Volumetric Flow	226,245	m3/h
11	Mass Flow	12902	kg/h

PROPERTIES TABLE			
NG	Temperature	5,52743	C
NG	Pressure	80	bar
NG	Volumetric Flow	8986,97	m3/h
NG	Mass Flow	713846	kg/h

Figure 32: Simulation Flowsheet in DWSIM - High pressure delivery at 80 bar without recondensing - 3 stages Compressor

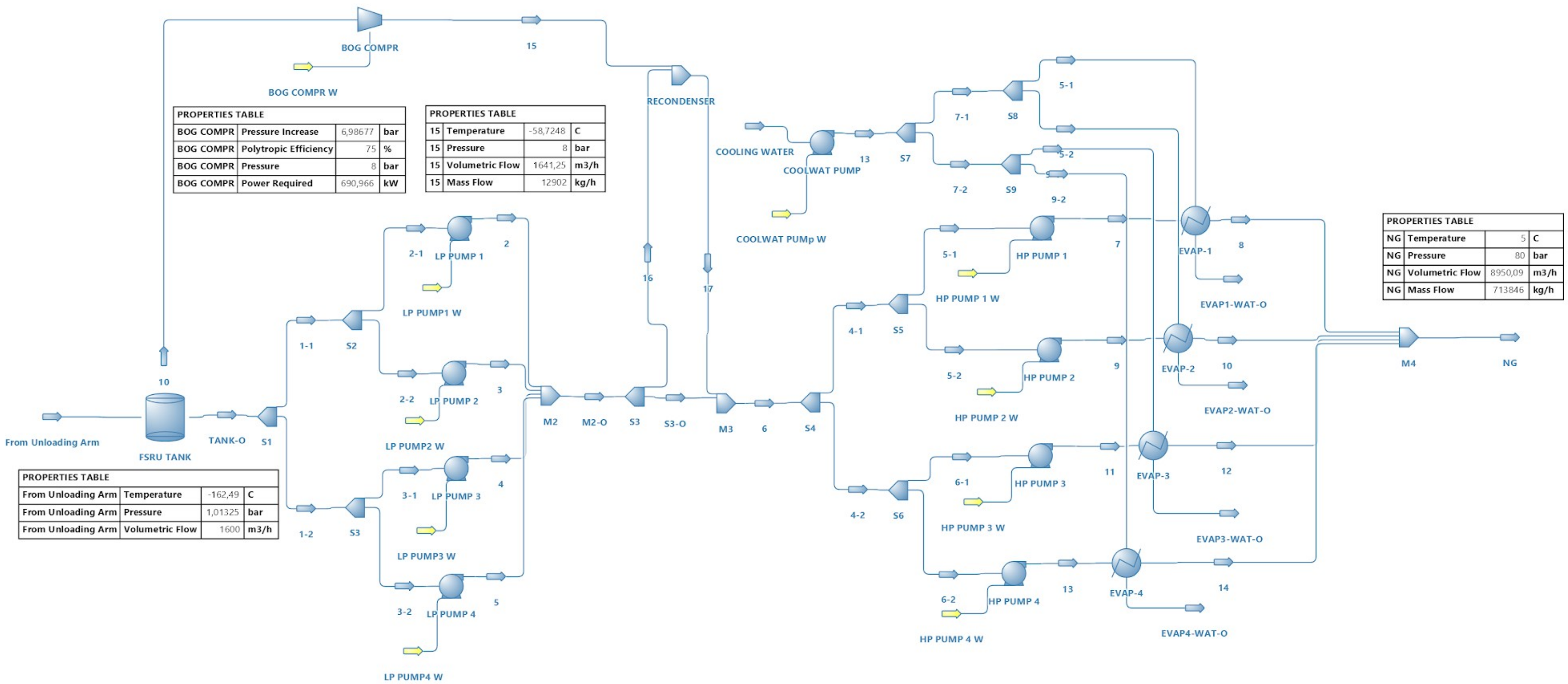


Figure 33: Simulation Flowsheet in DWSIM - High pressure delivery at 80 bar with recondensing

Stream	1	2	8	3	10	4	12	5	14	10	15	17	18		13	
	LNG from LNGC to FSRU	LP Pump 1 Outlet	NG from Vaporizer 1 to valve (before pipeline)	LP Pump 2 Outlet	NG from Vaporizer 2 to valve (before pipeline)	LP Pump 3 Outlet	NG from Vaporizer 3 to valve (before pipeline)	LP Pump 4 Outlet	NG from Vaporizer 4 to valve (before pipeline)	BOG from FSRU Compres-sor	BOG Compressor discharge	LNG + BOG from Recondense r	Total NG at delivery pipeline	Seawater supply	Inlet Sea water for regasifica-tion	Outlet Seawater from regasifica-tion
Liquid Flow (m^3/h)	1,600	400	-	400	-	400	-	400	-	-	-	272		21,850	21,850	21,850
Gas Flow (m^3/h)	-	-	2,238	-	2,238	-	2,238	-	2,238	6,851	1,641	-	8,950	-	-	-
Phase	Liquid	Liquid	Gas	Liquid	Gas	Liquid	Gas	Liquid	Gas	Gas	Gas	Liquid	Gas	Liquid	Liquid	Liquid
Pressure (bar)	1	8	80	8	80	8	80	8	80	1	8	8	80	1	3	3
Temperatur e (C)	-162	-162	5	-162	5	-162	5	-162	5	-161	-59	-129	5	15	15	10

Table 12: Heat And Material Balances from DWSIM Simulation - High pressure delivery at 80 bar with recondensing

Number of items	Equipment description	Equipment type	Materials of construction	Operation Conditions		Design Conditions		Capacity				Insulation data	Remarks
				Temperature (°C)	Discharge Pressure (bar)	Temperature (°C)	Discharge Pressure (bar)	Flow (m^3/hr)	Volume (m^3)	Length (m)	Diameter (mm)		
4	LNG Unloading Arm	-	stainless steel	-162	2-3	-173	5	6,000	-	-	410	urethane foam	(2 for LNG unloading, 1 for vapour return, 1 hybrid for spare)
6	Type B-Spherical Moss System Storage Tank	vessel	stainless steel or aluminum	-162	200 (mbarg)	-173	250 (mbarg)	-	20,000	-	-	polyuretha-ne foam	-
1	Cooling Water Pump	pump	aluminum bronze	15	3	30	5	21,850	-	-	-	-	-
1	BOG Compressor	compres-sor	carbon steel	-59	8	-173	15	6,851	-	-	-	-	-
4	Low Pressure Pumps	pump	carbon steel	-162	8	-173	15	400	-	-	-	-	-
4	High Pressure Pumps	pump	carbon steel	-158	80	-173	100	413	-	-	-	-	-
4	Vaporizers	heat exchanger	stainless steel	5	80	-173/50	100	413	-	-	-	-	-
1	Recondenser	drum	-	-129	8	-173	15	272	4	-	-	-	-
1	Flare Stack	pipe	-	-	AMB	-	3.5	-	-	65	100-200	-	-

Table 13: List of Equipment - High pressure delivery at 80 bar with recondensing

3.4 FSRU Required Utilities

The following utilities are required in order to support and ensure safety for FSRU's processes leading to the proper operation of the unit:

- Emergency Power Generation System: FSRUs have their own power generation systems. Dual fuel type power generators can operate on both boil-off gas as fuel gas, under the normal operation of the unit and diesel oil under start-up or maintenance or under emergency conditions. For this reason a diesel power generator should also be provided on the FSRU Vessel [55].
- Diesel Oil Storage System: storage unit for diesel oil which is used mainly for power generation and other operations onboard [55].
- Lubricating Oil Storage System: storage unit for lube oil which is used for the power generation prime movers and for major rotating equipment [55].
- Nitrogen generators: nitrogen generation for the purpose of inert gas purging (purging the unloading arms of LNG before disconnecting during LNG transfer) [55].
- Cooling medium: seawater for the regasification process [55].
- Instrument Air System: redundant air compressors will be provided to generate the utility and instrument air for the FSRU [55].
- Fire and gas system protection and leak detection system
- Gas detection devices
- Control Room which includes the instrument control panel, flow computers and the SCADA telemetry computer.
- Wobbe Index correction system shall be installed onboard at the FSRU facility in order to provide flexibility for receiving various types of LNG by correcting the LNG characteristics, so the final product would comply with the requirements of each county gas grid operator [56].

- Temporary storages for hazardous waste and waste management systems.

3.5 Venting & Blowdown Philosophy

At normal conditions there is not any need for hydrocarbon's disposal in the atmosphere. A venting mast (flare system) of approximate height 65m and pipe diameter 0.1m - 0.2m, which disposes the excess boil-off gas shall be present in FSRU, ensuring safe disposal of hydrocarbon vapors in abnormal and emergency situations (during start-up, emergency shutdown, maintenance activities, operational upsets). BOG handling needs to be adequate in order to minimize the losses of the fuel which is routed to the venting mast. Blowdown system shall also be present in FSRU in order to mitigate the consequences of equipment and piping failure during emergency conditions, by enabling blowdown valves - emergency depressurization valves and shutdown valves.

3.6 Health & Safety Design considerations

Emergency Shutdown System (ESD) monitors the FSRU's safety system. The ESD system has to provide safety actions and mitigate directly and efficiently the consequences of an accident or major event such as hydrocarbon leakage (LNG) / gas dispersion, fire in case of LNG is ignited, rapid phase transition if large leak of LNG occurs to sea, toxic or flammable chemical leakage (e.g. diesel stored at the FSRU). Moreover, ESD has to respond also in natural hazards such as excessive sea movements due to cyclones, storms, hurricanes creating waves of up to several meters high, seismic activity, tsunami, earthquakes. A risk assessment has to be conducted in the early phase of the design of the FSRU unit including a systematic and thorough identification of potential hazards that could directly or indirectly result in loss of life, fire and explosion, cryogenic release, loss of structural integrity, escape or evacuation [57, p. 28].

The main risks for safety and environment are related to the handling of liquefied natural gas and pressurized natural gas. Personal Protective Equipment (PPE) shall be used by the crew members in order to conduct with adequate safety all the operations in hazardous areas. FSRU shall have emergency procedures in the event of pollution, fire and explosion, gas releases and it is required to have an automatic system of fire and gas detection, escape or evacuation.

Park et al. conduct an Event Tree Analysis (ETA), developing fire and explosion scenarios which may occur by different events in an FSRU and they are listed in Table 14. *"Three sizes of leakage holes (small, ≤10 mm; medium, 10–50 mm; and large, 50–150 mm) are considered in accordance with the International Association of Oil & Gas Producers. The outcomes of the event-tree are categorized into five severities, where IB has the smallest degree of severity and NINB has the largest. Even if isolation and blowdown fail, the presence or absence of detection cause a major or massive effect"* [49].

Event	Description
Release	Leakage of flammable medium from regasification facility
Gas detection	Detection of gas leakage around regasification facility
Immediate ignition (fire)	Immediate ignition of leaking gas, causing a fire
Fire detection	Detection of fire around regasification facility
Isolation	Isolating sections through shutdown valves
Blowdown	Draining flammable medium in isolate sections by blowdown valves
Delayed ignition (explosion)	Ignition of accumulated gas cloud, causing an explosion

Table 14: Fire and explosion accidents for an Event Tree Analysis (ETA) [49]

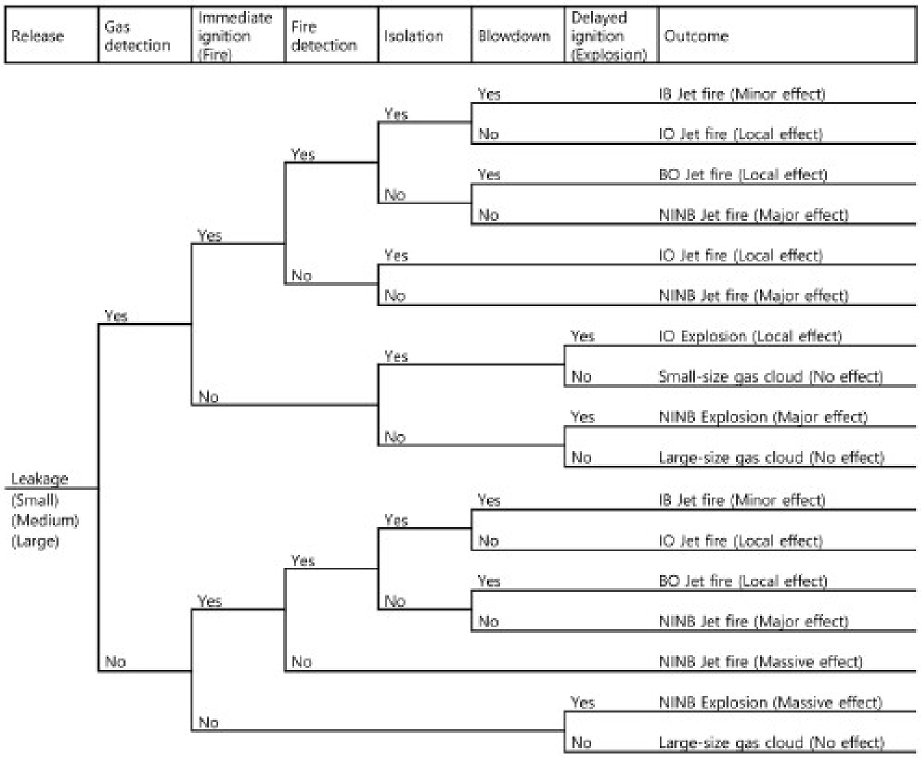


Figure 34: Structure of the Event Tree Analysis (ETA) [49] *Where IB stands for isolation and blowdown success, IO is the isolation-only success, BO is the blowdown-only success and NINB represents no isolation and no blowdown*

Discussion of results

The technology of Floating Storage Regasification Unit for Natural Gas supply has been analyzed in this thesis with a focus on the design process of the unit, mainly with process simulation as a guiding tool. In process simulation of natural gas supply through an FSRU, two delivery systems of Low Pressure at 12 bar and High Pressure at 80 bar have been examined in order to simulate the main processes that take place in an FSRU and size major pieces of equipment. Constraints and restrictions in case of High Pressure delivery have been identified and a solution has been proposed and implemented.

Conclusions

In this thesis, LNG and the role of FSRU as an alternative to an onshore storage and regasification unit for NG supply have been studied.

According to International Maritime Associates (IMA) / World Energy Reports and their 12-month assessment of the floating and regasification market, global demand for natural gas is expected to grow at an annual rate of 1.5% to 2.5%, mainly due to the economic and environmental advantages of natural gas as fuel for heat and power generation [15]. Also the fast transition to the use of renewable energy sources will boost the consumption of natural gas as an intermediate/alternative energy source, instead of other forms of fossil fuels (coal - oil), until this transition will be completed. But even after the transition, natural gas will be used for electricity production, mainly as a stabilization factor to the power grid, considering the daily/seasonal variation of renewable sources.

Since the introduction of the first FSRU in 2005 in the gulf of Mexico, there has been a significant pick up in deployment of the technology leading to optimization of costs and capability and access to new markets all over the globe. Currently the global FSRU fleet consists of more than 30 vessels and many more to be commissioned in next years.

As described in Chapter 1 of this thesis, FSRU offers some key advantages compared to onshore terminals and we are going to focus mainly on:

- Lower capital cost: The capital cost of a new FSRU can typically represent 60% of an onshore terminal but special attention needs to be given in the operation expenditures which have to be considered in a feasibility study of an FSRU investment. Typically OPEX can be between 0.4 to 0.7$/mmbtu depending on commercial terms [58].

- Shorter lead time: Typically FSRUs can be delivered in half time of an onshore terminal, since there is a minimal need of onshore infrastructure development and often fewer permitting issues, which usually drive up the lead time. A new FSRU takes about 2.5 to 3 years to be completed, while a conversion of a LNG vessel to FSRU around 1.5 years. Moreover lead times can be significantly accelerated by utilizing an existing FSRU [58].
- Greater flexibility: The multipurpose use of an FSRU (as floating storage and regasification terminal, floating storage unit or as conventional LNGC) can provide additional options to the investor and add significant value and opportunities to exploit any future opportunity given the right market conditions. FSRU gives the ability to 'retire' and re-use the vessel at relatively low cost, a feature which adds even greater commercial flexibility. Finally FSRU can provide an early gas option to markets which are considering building an onshore facility [58].

FSRUs have matured as a proven technology over the last years, offering the opportunity for new countries to become LNG importers in the last decade. In Greece, Revithoussa LNG Terminal is now the only land-based operating terminal that receives LNG cargoes, stores, regasifies and supplies NG to the National Natural Gas Transmission System. Revithoussa is located on the islet of Revithoussa, in the gulf of Pachi at Megara, 45 km west of Athens and has a storage capacity of 225,000 m^3 LNG and a regasification capacity of 1,250 m^3/h. [59] FSRU terminal is about to be introduced in Greece with the "Alexandroupolis Independent Natural Gas System" with a storage capacity of up to 170,000 m^3 of LNG and a regasification capacity of 1,600 m^3/h and it will be located south-west of Alexandroupolis in the sea of Thrace (Aegean Sea) [60]. The commercial operation date for the project is planned for 2023.

[61] Another FSRU project, Independent Natural Gas System "DIORYGA GAS" has obtained a license from Regulatory Authority for Energy (RAE) in order to be implemented

in Corinth, west of Athens. This project is proposed to have a storage capacity of 170,000 m^3 LNG and a regasification capacity of 300 to 500 m^3/h [62]. The commercial operation estimated date for the project is planned for December 2022 [63].

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