Novel technical perspectives for alternative commercial use of old LNG carriers

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Novel Technical Perspectives for Alternative Commercial Use of Old LNG Carriers

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Abstract

Natural gas has been widely recognized as the most promising fuel alternative to oil combining both high efficiency and environmental friendliness. To this end, significant investments have been concentrated on ships transporting large quantities of Liquefied Natural Gas, also known as LNG carriers (LNGC). Even more recently, a portion of the LNGC fleet is candidate for conversion or has already been converted to Floating Storage and Regasification Units (FSRU) to service emerging markets. Insular territories are part of those markets, requiring energy production with reduced emissions, especially those not interconnected with the mainland power grid. A rather established concept for such instances is the integration of an FSRU feeding natural gas to the power plant, thus forming a so called “gas-to-power system”. An even more innovative approach is presented in the current study, proposing the conversion of an LNGC to a floating power plant, combing storage, regasification and power generation functions onboard. To this end, a study is carried out that identifies the optimal technical solutions for the conversion of old LNG carriers with steam turbine and Dual and Tri Fuel Diesel Electric propulsion systems, extending their economic life further, taking into consideration the additional lifecycle costs created from the conversion of the old LNG carriers and making them attractive chartering options. The methodology followed comprises of various steps, namely the identification of candidate vessels; identification of feasible conversion solutions; decision on the equipment and the optimum installation location onboard; and finally economic evaluation of all the alternatives. The results of the research could act as guide for investors to assess alternative options for old LNG carriers thus extending their useful life and optimising their lifecycle cost.

Keywords: LNG, LNG carrier, FSRU, Floating power generation, Lifecycle cost, SHIPLYS.

1 INTRODUCTION

Liquefied Natural Gas (LNG) has been widely recognized as the most promising alternative fuel combining both high efficiency and environmental friendliness. To this end, significant investments have been concentrated first on ships carrying large amounts of LNG (LNG Carriers - LNGCs) and second to storing large amounts of LNG in onshore and offshore terminals or floating storage units. The latter can be either an LNGC operating as a Floating Storage Unit (FSU) or a Floating Storage Regasification Unit (FSRU). On the other hand the expansion of requirements for clean/green energy production even in the islands, in particular those that are not interconnected with the mainland grid, has risen several challenges which can be faced by novel concepts like, for instance, small scale FSRUs and even Floating Power Generation Plants (FPGPs).

Moreover, it is well known that new and more efficient LNG vessels are being built (especially referring to minimized Boil-Off Gas (BOG), thus making a portion of the existing fleet, especially older vessels obsolete. Those older LNGCs are fitted with Steam Turbine and Dual/Tri Fuel Diesel Electric (D/TFDE) propulsion systems as presented in Fig. 1. This fact is concealed in the present phase of the shipping cycle of the LNG market, as the demand for tonnage is high and spot charter rates for older ships follow this trend [1].

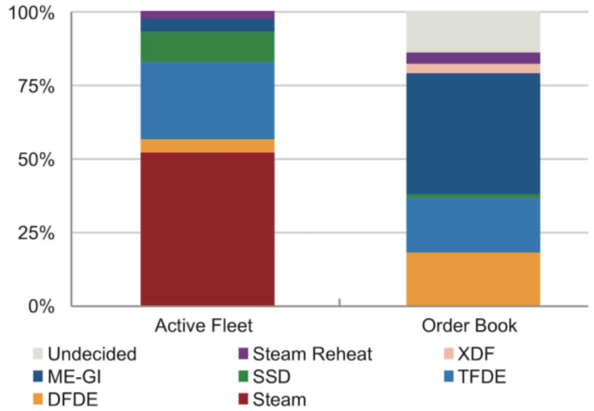

Figure 1. LNGC fleet by type of propulsion system by the end of 2016 ([2])

However, as new tonnage will enter the market in the following years, scrapping or second hand market should not be the only options for shipowners. Older LNGCs may seek alternative options for commercial exploitation offering unattractive chartering options. The conversion to an FSRU is an established choice in a growing niche market, as it provides with a quick to build, short term option for natural gas import. Another, even more inclusive concept proposed in the past is the integration of the LNG carrier to a gas-to-power system, either as an FSRU feeding an onshore power plant or as a FPGP. The latter is the technical option that this paper elaborates further on, with reference to non-interconnected islands utilising natural gas as a fuel for power generation.

The case of these islands require the evaluation of alternative configurations for the import of LNG, as well as the mode of implementation of the required infrastructure. To this end, a study is carried out that identifies the optimal technical solutions based on a converted LNG carrier, thus servicing the islands and extending its economic life further for the benefit of the shipowner. The study comprises various steps, such identification of candidate vessels, identification of feasible conversion solutions, decision on the equipment and the optimum installation location onboard, and finally economic evaluation of all the alternatives.

2 THE OLD GENERATION OF LNG CARRIERS

2.1 Steam Turbine

An LNGC with a Steam Turbine propulsion system usually has two boilers installed on board capable to burn the Boil-Off Gas (BOG) and produce superheated steam (60 bar, >525 ˚C). This steam is then fed in two grade steam turbines, one of high (HP) and one of low pressure (LP) to provide the shafts with mechanical power ending to one reduction gear and finally transmitting the power to the propeller shaft as depicted in Fig. 2. Another stream of superheated steam is also fed to the steam generators, which produce the required electric power for the vessel.

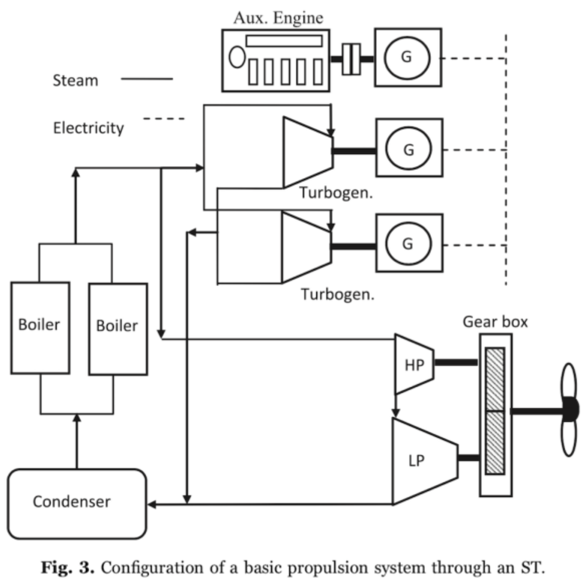

Figure 2.Typical steam turbine propulsion arrangement [3]

Up to approximately 2003 the above mentioned configuration was the dominant option for the energy and propulsion needs of an LNGC due to the capability of the system to burn LNG (in the form of BOG) in combination with HFO and MDO. The boilers of a steam turbine LNGC can operate in three modes: only BOG, only HFO/MDO or a dual fuel mode burning at the same time both fuels in adjusted ratio. In any mode all BOG is burned in the boilers, thus making the use of a Gas Combustion Unit (GCU) unnecessary.

The reliability of such a propulsion system is extremely high, a fact that translates into lower cost due to impairments. Additionally, the acquisition and maintenance cost of a steam turbine LNGC are quite low [3].

A distinct disadvantage is the low thermal efficiency ratio translating into higher fuel costs of the transportation of cargo. Indicatively, an steam turbine LNGC has 175 tons/day fuel consumption compared to newer systems that consume 110-140 tons of fuel daily [2].

In terms of cargo capacity steam turbine LNGCs are usually equipped with moss spherical tanks with the total capacity in the range of 125,000 to 145,000 m^3. A concept drawing of the moss containment system is displayed in Fig 3.

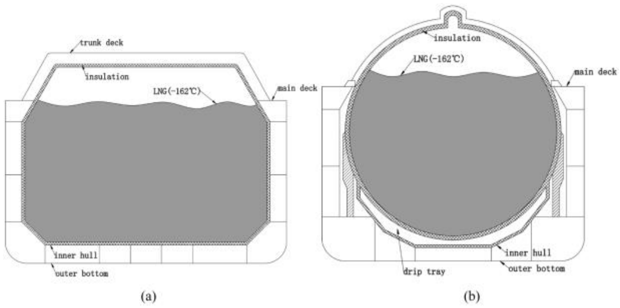

Figure 3. Typical conceptual drawing of membrane (a) and MOSS (b) containment systems [4]

Although moss tanks do not fully utilise the hull of the ship to increase the cargo capacity, they do have a distinct operational advantage over membrane tanks. Due to their geometry, no sloshing issues apply to them and consequently there are no restrictions in their operation caused by adverse weather conditions.

2.2 D/TFDE

After decades during which steam turbine propulsion had been the preferred option for LNGCs, D/TFDE systems were introduced early in 2000s. The dual or tri fuel propulsion introduced an approximately 30% increase in performance compared to the steam turbine, utilizing the Otto cycle.

A typical arrangement of a D/TFDE propulsion system is shown in Fig. 4 and consists of the equipment listed below.

4 Main generator prime movers operating with dual fuel (GAS-HFO/MDO)
4 Generators
2 Electric Propulsion Motors
2 Frequency Converters
2 Propulsion Transformers

2 High Voltage Switchboards
1 or 2 Reduction Gears
1 or 2 Propellers

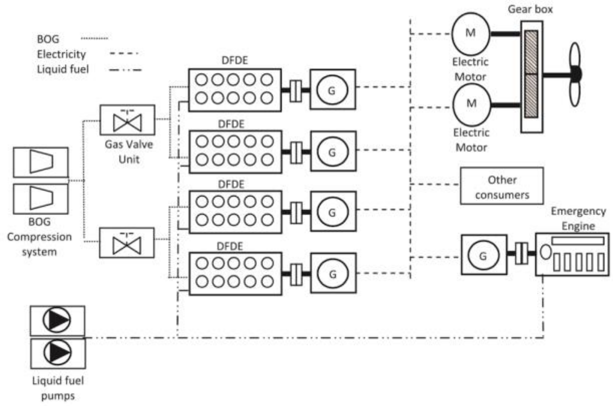

Fig. 14. Configuration of diesel-electric propulsion using DF engines (4S).

Figure 4. Typical D/TFDE propulsion arrangement [3]

Analysing the energy flow of such vessel, LNG is pumped from the cargo tanks and vaporized into BOG either naturally or in a forced process to increase fuel inflow. BOG then flows through a low duty compressor and is preheated up to 80ºC with the use of gas heaters. Then it is combusted in the main generator prime movers, which produce Alternate Current (AC) at medium voltage, commonly 6.600 V. The electric energy is distributed through the high voltage switchboards to the propulsion system and any other electrical needs of the vessel such as hotel loads, engine auxiliaries, deck auxiliaries etc.

Regarding the propulsion system, a three winding transformer decreases the voltage to 3.000V and then a frequency converter (one for each motor) is adjusting the rounds of the propulsion motors by alternating the current frequency. Those two propulsion motors are either connected to one reduction gear (single propeller ship) or to two reduction gears in case of double propeller ships. In case there is excess BOG which cannot be burned in the dual fuel engines, it can be either reliquefied back to the cargo tank or burned in a GCU without producing any power. Notwithstanding the necessity for the operation of a GCU in order to manage BOG consumption, its installation contributes to the LNGC Capital Expenditure (CAPEX), as well as to the cost and complexity of its maintenance.

The advancements in the field of LNGC propulsion coincided with the introduction of another type of cargo containment system. The newest containment system is the membrane-type, that is depicted in Fig. 2. This technology has the advantage of additional storage compared to the moss type tanks, as it is built in the shape of the LNGC hull. It is also capable of achieving savings in terms or BOG, as it can have a boil-off rate as low as 0.07%. Currently, the LNGCs with membrane tanks dominate the market as presented in Fig. 5.

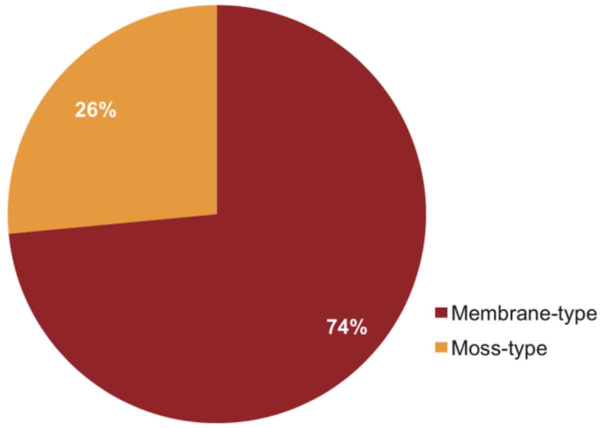

Figure 5. Existing fleet by type of containment system by the end of 2017 [2]

3 THE POWER SUPPLY PROBLEM IN ISLANDS

3.1 Current State

The power generation system of insular regions is a complex issue. Such regions include multiple islands or multiple sources of power demand, which are secluded from the main power grid of a country and in most occasion are interconnected with each other. Even when the power generation takes place, the required fuel in most cases is oil, meaning harmful emissions are released and burden the local environment. The islands in the Aegean Archipelago of Greece is a characteristic case of such a system. Currently, all power is supplied in most islands through local small power plants operating on each of them.

Greece being a member state of the European Union must comply with certain environmental regulations, thus contributing to the complexity of the problem of power supply. According to European Directives 2010/75/EC and 2015/2193/EC, a medium combustion plant has a rated thermal output between 50 and 300 MW and small combustion plants between 1 and 50 MW. Those Directives are in force and impose strict limits for the emissions of small combustion plant, which can be found in the aforementioned islands. Those limits concern practically all power plants of non-interconnected islands and according to the estimations of Public Power Corporation, all units will confront operational restriction from 2025 for new plants that started operation from 2018 onwards and from 2030 for existing units.

3.2 Alternative scenarios

Alternative solutions to address the issue on time may include either the interconnection of the islands to the mainland grid or the technological upgrade of the existing plants to meet environmental conditions by introducing an appropriate fuel such as Natural Gas (NG), the use of which complies with the environmental regulations. A number of solutions and a methodology to examine their feasibility is explored in the work of Lyridis et al. [5].

For NG to become available as a fuel to the power plants, a feasible supply chain must be first established.

The NG supply is cost effective for the quantities required if it is in the form of LNG, as an island-to-mainland pipeline interconnection is much more costly than the corresponding electric interconnection. LNG will be transported in an LNGC in volumes proportional to the periodical fuel demand of the islands. The import point for the cargo may be onshore facilities close to the existing or planned power plants or offshore units, where LNG can be stored, regasified and distributed locally.

Offshore facilities are the focus of the present study and more specifically FPGPs, which are floating units that combine LNG storage, regasification and power generation onboard (Fig. 6).

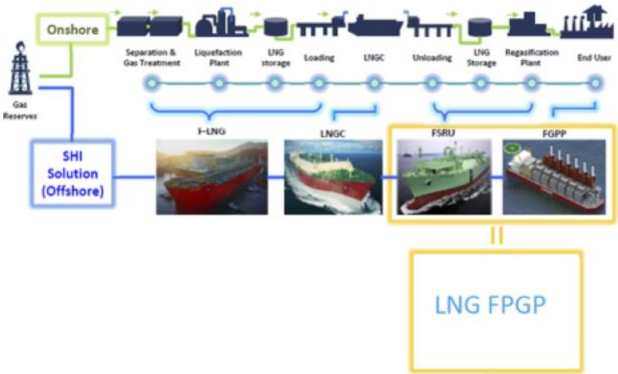

Figure 6. The FPGP in the natural gas supply chain

Several design of such units exist in the market as referenced by Hutchinson and Dobson [6], which can be categorized into self-propelled power ships and not self-propelled power barges. The majority of operational projects run on HFO, MDO and fewer are capable of burning NG if available onshore. A major operational constraint for the units using NG is the small inventory they can hold, thus requiring frequent cargo transfers of LNG if there is no NG pipeline nearby.

The basis for the proposed FPGP unit is an LNGC, which constitutes a significant differentiation compared to the designs reviewed above. In this way, LNG can be stored in larger quantities compared to the existing barges and, if combined with either a BOG reliquefaction system or batteries to store excess production of electrical power from BOG, then it could reduce the total cost of the supply chain. The two older types of LNGCs described in Section 2 are identified as candidates for conversion to FPGP according to the methodology analysed below.

To determine the specification for a FPGP and the conversion, a specific methodological approach is followed consisting of the following discrete steps:

- Define energy demand, metocean data etc.
- Define the optimum LNGC (size and power system) for conversion.
- Investigate the required components for the conversion.
- Calculate the total conversion cost for the project and the production cost of electricity.

The total conversion cost is estimated and taken into account for cost calculations based on the Lifecycle Cost methodology developed under the H2020 project named SHIPLYS, The LCC analysis can provide cost estimations over the entire life of a vessel (from the cradle to the grave), in this case the retrofitted LNG carrier.

4 THE FPGP SOLUTION

4.1 Conversion of a steam turbine LNGC to FPGP

The first option explored is the conversion of a steam turbine LNGC to a FPGP with the capability of producing up to 100MW at 6,600V AC and 60 Hz. A typical candidate vessel of this type has specifications as those in Table 1.

Table 1. Candidate steam turbine LNGC main particulars

Measurement	Value	*Units*
Length L_{BP}	283.06	m
Breadth	43.4	m
Depth	26	m
Draught	11.4	m
Capacity	145,000	m^3
Boil-Off Rate	0.15%	

According to this scenario, further components are added to the power plant in order to raise the power capacity of the power plant to 100MW. Specifically, 2 generators are installed each one producing up to 35 MW at 50 Hz, which will be connected to 2 gas turbines with an efficiency ratio of 42%. The total cost of both generators and gas turbines amounts to 18 million $.

The heat of the exhaust gases from the gas turbines, having a temperature of approximately 466 °C, is utilised to produce steam at 525°C, thus raising the efficiency of the whole power plant. This is achieved with the preheat of the water fed to the main boiler to 285,8 °C and of the air to 300 °C utilising the appropriate equipment.

Further components to be installed in the power plant candidate vessel are 2 type D main boilers, 1 steam turbine unit consisting of the HP turbine and the LP turbine coupled via a reduction gear, 2 steam turbine with generators), 2 Low Duty (LD) compressors and 2 High Duty (HD) compressors for the NG. The relevant specifications are described in Tables 2-6.

Table 2. Main boiler characteristics

Measurement	Value	*Units*
Max evaporation	65,000	kg/h
Normal evaporation	52,000	kg/h
Feed water temperature	145	deg
SH outlet temperature	525	deg
SH outlet pressure	59	bar
FG consumption MCR	3,990	kg/h

Table 3. Main turbine and generator characteristics

Measurement	Value	*Units*
Inlet steam pressure	57.5	bar
Inlet steam temperature	520	°C
Power	29,455.1	kW
HP turbine speed at MCR	5,075	rpm
LP turbine speed at MCR	3,350	rpm
Generator voltage	6,600	VAC
Generator frequency	60	Hz

Table 4. Auxiliary turbine and generator characteristics

Measurement	Value	*Units*
Inlet steam pressure	57.4	bar
Inlet steam temperature	520	°C
Power	3,450	kW
HP turbine speed at MCR	1,800	rpm
LP turbine speed at MCR	57.4	rpm
Generator voltage	6,600	VAC
Generator frequency	60	Hz

Table 5. LD compressor characteristics

Measurement	Value	*Units*
Volume flow	4,000	m^3/h
Inlet pressure	1.03	barA
Outlet pressure	2.00	barA
Inlet temperature	-120	°C
Discharge temperature	-80	°C
Shaft speed	12,000-24,000	rpm
Motor speed	1,790-3,580	rpm
Rated motor power	280	kW

Table 6. HD compressor characteristics

Measurement	Value	*Units*
Volume flow	26,000	m^3/h
Inlet pressure	1.03	barA
Outlet pressure	2.0	barA
Inlet temperature	-140	°C
Discharge temperature	-111.5	°C
Compressor rotor speed	11,200	rpm
Rated motor power	770	kW

Additionally, a switchboard of 33MVA is required to act as a connection point of the FPGP with an electric cable of 6,600 V power capacity to enable the interconnection with the shore. The arrangement of the powerplant is displayed in Fig. 7, which can be found in Appendix A.

Several advantages can be identified for the proposed conversion scenario. Multiple old LNGC vessels are available in the market and can be retrofitted with the equipment on favourable terms for retrofitting. Although, technology of such ships is long-standing, it can still be deemed very reliable in terms of reliability and operation, leading to a minimum of requirements in terms of maintenance. As a result maintenance cost can be lower up to 40% over the DFDE scenario.

The only major drawbacks of this scenario are the relatively increased CAPEX and complexity of the conversion onboard the LNGC. The total CAPEX amounts to approximately 37.5 million $ including the purchase of the components for the retrofit (20 million $), the mooring (15 million $) along with the works (2.5 million $), excluding the electrical cable for interconnection as its length may vary depending on the FPGP-shore distance. Finally, Operational Expenditures (OPEX) of the FPGP consist of the fuel cost (7 $/MMBTU), plus the regular OPEX of the steam turbine LNGC of approximately 12,000 $/day.

The results for the operation of the FPGP are summarized in Table 7. A small portion of the produced power is consumed for the unit's operation, while the remaining 100MW are delivered to the local system with a production cost of 63 $/MWh if no additional charter fee to the owner is assumed and 80$/MWh if a 40,000$/day charter rate is added. The emissions of the FPGP are also displayed in terms of NOx and CO_2.

Table 7. Operational profile of a 100MW steam turbine FPGP

Measurement	Value	*Units*
Power output	102,982.4	kW
FPGP consumption	2,500	kW
Power to the grid	100,482.4	kW
Plant Efficiency	41.0%	%
Gas consumption	20,062.8	MMBTU/day
FPGP Autonomy	153	days
NOx emissions	0.47	g/kWh
CO_2 emissions	455.43	g/kWh
Production cost excluding hire rate	63	$/MWh
Production cost with hire rate	80	$/MWh

4.2 Conversion of a D/TFDE LNGC to FPGP

Following the same methodology as with the steam turbine vessel, the conversion of a D/TFDE LNGC is examined. The candidate vessel main particulars are presented in Table 8.

Table 8. Candidate D/TFDE LNGC main particulars

Measurement	Value	*Units*
Length L_{BP}	274	m
Breadth	43.4	m
Depth	26	m
Draught	11.5	m
Capacity	154,800	m^3
Boil-Off Rate	0.15%	

In this case the only components required for the conversion is a switchboard for the FPGP-shore interconnection of 30 MW, the electric cable and a modification of the control systems of the vessel. The four generators are already installed in the power plant, generating electrical power at 6,600V and 60Hz. Two generators (11.4MW power each) will operate at 50Hz and will directly feed the shore connection with 18.33 MW of electrical power, while the other two (one of 11.4 and one of 5.7MW) will operate at 60Hz feeding approximately 2 MW to the vessel and the rest to the shore via a frequency converter. A total power of 32.83 MW will be available for consumption by the local shore grid. The arrangement of the powerplant is displayed in Fig. 8, which can be found in Appendix A.

The power capacity of the D/TFDE FPGP is distinctly smaller compared to that of the previous steam turbine unit. This can be explained due to the combination of the complexity of the conversion and to the lack of retrofit options onboard the vessel exploiting the existing power plant. The complexity is underlined if one considers that one propulsion transformer must be disconnected from the input of a frequency converter and connected to the output of the other. Furthermore, there is a significant loss of power due to the operation of generators at different frequencies. Finally, the OPEX increases to 15,000 $/day.

Despite the adversities, the solution has several advantages. First of all, the CAPEX is notably less from the steam turbine FPGP, equal of 16.5 million, of which 1.5 million $ is the equipment and modification cost and 15 million $ relate to the mooring. Moreover, the current configuration enables the virtually full exploitation of the generated electric power. It offers greater reliability, since it operates only one of the two frequency converters, which are the weakest link of the installation. A crucial issue is the commercial flexibility of the specific FPGP, as the ship will be able to re-operate as LNG Carrier contrary to the steam turbine FPGP, which will require further work.

The results for the operation of the FPGP are summarized in Table 9. 32.83 MW are delivered to the local system with a production cost of 63 $/MWh if no additional charter fee to the owner is assumed and 80$/MWh if a 40,000$/day charter rate is added. The emissions of the FPGP are also displayed in terms of NOx and CO_2

Table 9. Operational profile of a 32.83MW D/TFDE FPGP

Measurement	Value	*Units*
Power output	34,833	kW
FPGP consumption	2,000	kW
Power to the grid	32,833	kW
Plant Efficiency	42.8%	%
Gas consumption	6,279.5	MMBTU/day
FPGP Autonomy	537	days
NOx emissions	9.71	g/kWh
CO_2 emissions	423,9	g/kWh
Production cost excluding hire rate	75	$/MWh
Production cost with hire rate	138	$/MWh

4.3 FPGP mooring and grid interconnection

With regards to the mooring arrangement, a FPGP presents no difference to those of a FSRU. The unit can be located at a coastal area with the exact distance from shore depending on the metocean conditions of each specific project such as water depth, wind and current speed and direction, etc. If the FPGP operates near shore then it can be secured with mooring dolphins to a jetty in order for the LNGC to perform a cargo transfer in three different positions: cross jetty, in straight line or ship-to-ship.

On some occasions the FPGP could be forced to operate at a distance from shore for regulatory reasons or in case of heavy marine traffic nearshore. The FPGP will then be moored offshore at a cost of 15 million $ and can utilize a turret system to receive a cargo and/or to host the electric cable, which connects the FPGP with the onshore grid under the sea surface.

5 CONCLUSION AND FURTHER RESEARCH

In this paper an alternative option is considered for the commercial operation of old LNGC, namely with steam turbine and D/TFDE propulsion. The aim is to increase the useful lifespan of such vessels improving their lifecycle cost. The conversion to a FPGP unit is examined for each type of LNGC with the purpose of providing power to coastal areas isolated from mainland electricity grids such as islands.

Not only the proposed technical solution enables the import and use of NG as a fuel for power generation, but also it incorporates power generation onboard the vessel. In that way a quick short term infrastructure is available, thus bypassing the lack of NG-ready onshore power plants, wherever none exist.

The results of the study show that both FPGP types have a satisfactory efficiency ratio (41% for the steam turbine and 42.8% for the D/TFDE) and a power capacity ranging from 32.38 to 100 MW. The steam turbine FPGP can produce up to 100MW making it a suitable option for markets with increased electricity demand, which can compete with existing power ship or power barge in terms of power capacity and cost. The power output is achieved while economies of scale occur with regards to the electricity production cost. On the other hand, the D/TFDE FPGP is more costly in terms of production cost, but it can be more commercially flexible for the ship-owner of the LNGC, as it requires a relatively small CAPEX and can be redeployed as a LNGC in short notice. It has larger operational autonomy (537 days) due to its lower fuel consumption. However, its lower power output means it is more appropriate to cover seasonal electricity demand in some regions.

Further research on the subject should explore regulatory gaps regarding converted FPGPs, a more thorough study of the FPGP operation in an open sea taking into consideration sloshing in adverse weather conditions. Finally, an analysis concerning the hazards during the modification and operation phase for the proposed solution should be conducted expanding the work of Nilsson [7].

ACKNOWLEDGEMENT

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APPENDIX A

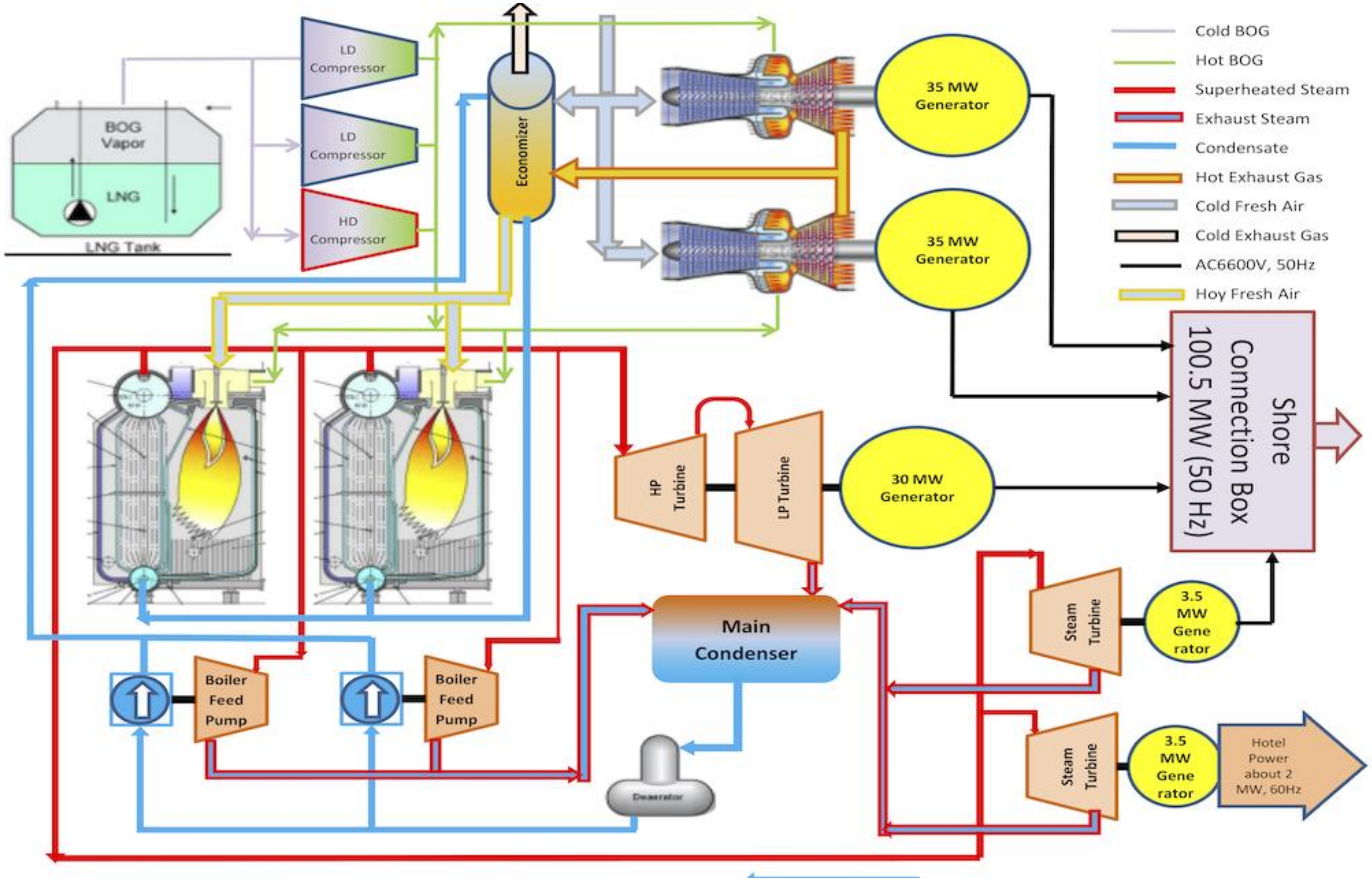

Figure 7. Steam turbine FPGP arrangement

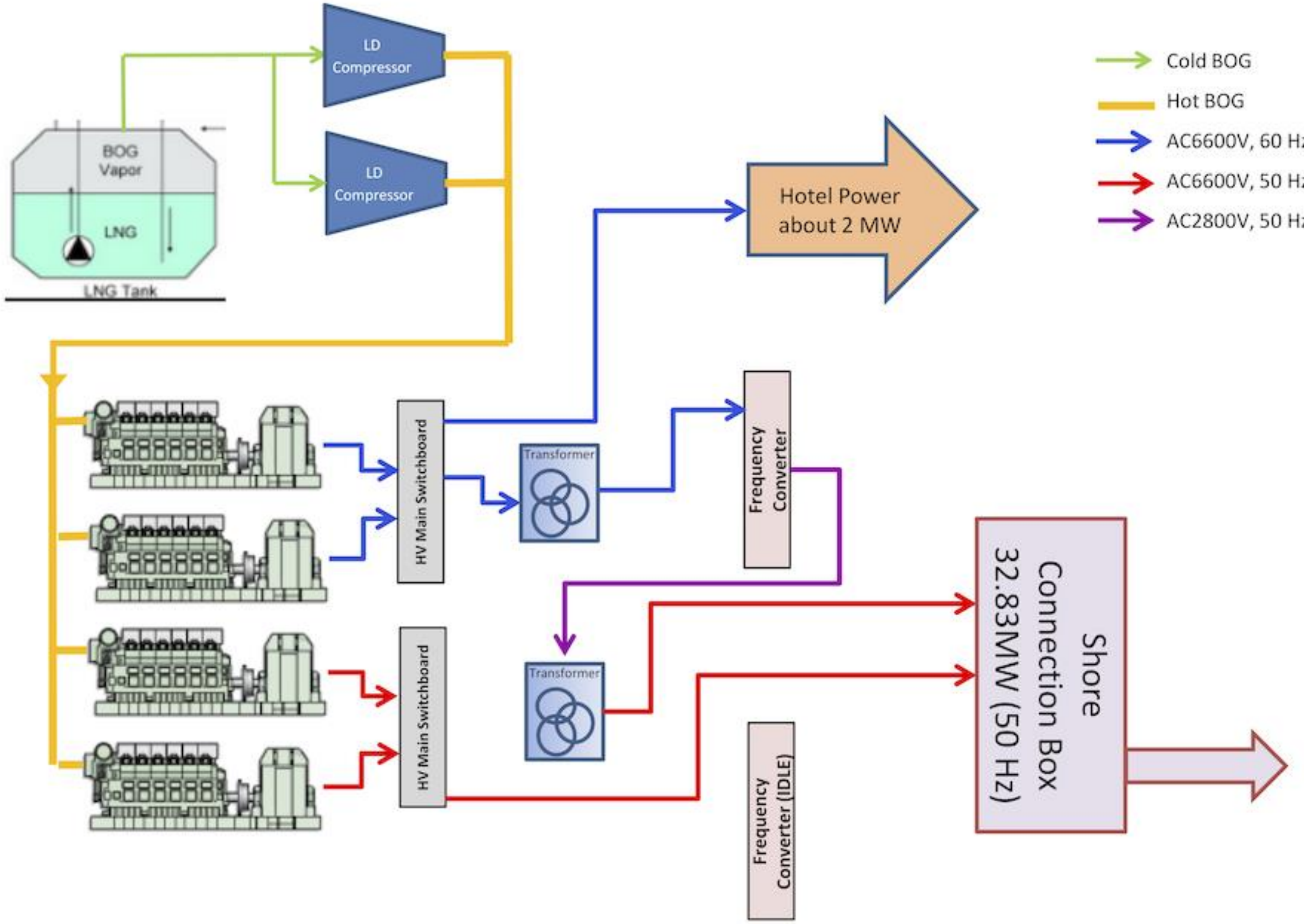

Figure 8. D/TFDE FPGP arrangement

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