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“EEXI, CII Calculator for Steam Turbine LNG Carriers and Energy Flows Identification Method”

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“This master thesis is dedicated to the people who trust my passion to overcome challenges and become even better together. To my beloved Grandmom, family, sister and friends”

Abstract

Ship owners and operators are facing numerous difficulties as a result of the International Maritime Organization's Energy Efficiency Existing Ship Index (EEXI), which is already having a considerable influence on the industry. Put simply, the EEXI is the result of applying the Energy Efficiency Design Index (EEDI) to ships that are already in service as opposed to ones that are being built. Since the majority of departing ships do not have an EEDI value, the EEXI must be determined. Ideally, this should be less than a specific threshold. EEXI calculation is challenging since it must be based on the available data for each vessel. This data is only partly available for older vessels.

Most vessels will first choose to modify their power rating in order to comply with EEXI regulations, but investing in energy efficiency technologies (EETs), for which the power savings must be measured and confirmed, appears to be better option.

On the other hand, EEXI compliance is a technical requirement needing a single certification. The Carbon Intensity Indicator (CII), an operational indicator that requires annual improvements in operational efficiency, is more difficult.

The carbon intensity of a ship, or the amount of carbon emissions produced by one unit of transport work, or one nominal tonne of cargo transported over a nautical mile, is created on a downward trajectory by the CII. Every ship is given a "energy efficiency" rating (ranging from A to E) by the CII.

Every year, vessels in categories D and E must show progress in order to advance to category C. A mandatory review of the Ship Energy Efficiency Management Plan (SEEMP) and the creation of a corrective action plan are required for ships that have three consecutive years in category D or one year in category E. The goal is to achieve the Required Annual Operational CII.

In this master thesis, we focus on Steam Turbine LNG Carriers calculation of the EEXI, CII and energy flows among the machinery items of this type of vessel.

More specifically:

- Chapter 1 is a brief description of the Liquified Natural Gas (LNG), its properties and the LNG Carrier ship types,
- Chapter 2 presents the basic energy flows of the machinery items of a Steam Turbine LNG Carrier on Normal Sea Going Condition and at Port Condition utilizing Sankey diagrams.
- Chapter 3 analyzes the calculating process of the Required and the Attained EEXI for the Steam Turbine LNG ships.
- Chapter 4 shows the process to determine the Required and the Attained CII of a vessel.
- Chapter 5 presents the results of 2 similar ships (Steam Turbine LNG Carriers) in terms of EEXI and CII.
- Chapter 6 is the final section of this thesis incorporating the final results and conclusion regarding the EEXI, CII and energy flow identification of this specific type of vessel which examined.

Key Words

LNG Carrier, Energy Losses, Sankey Diagram, Attained EEXI, Required EEXI, Engine Power Limitation (EPL), Attained CII, Required CII

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1. Liquified Natural Gas

Liquefied natural gas (LNG) is natural gas, primarily methane, that has been transformed to a liquid state for ease of storage or transportation.

The liquefaction process entails lowering the temperature of the gas to roughly -162 °C and eliminating contaminants such as dust and carbon dioxide. LNG, as a liquid, takes up approximately 600 times less volume than gas at regular atmospheric pressure, allowing it to be transported over great distances without the use of pipes, typically in specially-designed ships or road tankers.

When LNG arrives at its final destination, it is typically re-gasified and delivered via gas networks, just like gas from pipelines. LNG is also becoming more popular as an alternative fuel for ships and trucks.[1]

1.1 The significance of LNG for the EU's supply security

One of the main goals of the EU's policy for an energy union is to guarantee that all EU nations have access to markets for liquid gas. LNG can help the EU increase the variety of its gas supply and strengthen its energy security. Nowadays, European nations with access to LNG import terminals and liquid gas markets are much more resilient to potential supply disruptions than those that rely on a single gas provider.

LNG cargoes are available from numerous different supplier nations globally, and the LNG market is experiencing rapid growth.

Because of the extraordinary state of the gas market and the need to refill gas storages, monthly gross LNG imports into the EU have surged significantly since the end of 2021. The EU has purchased 98 billion cubic meters of LNG since the beginning of 2022. This is 39 bcm greater than at the same point in 2021. The EU imported more between January and September 2022 than it did in the entire all-time record year (2019).[1]

1.2 Consumption and demand

Natural gas currently accounts for almost a quarter of the EU's total energy consumption. About 26% of that gas is used in electricity generation (including combined heat and power plants), and the remaining 23% is used in industries. The majority of the remainder is utilized in the residential and service sectors, primarily for heating in buildings.

The EU's gas demand is approximately 400 billion cubic meters. Due to diminishing domestic gas output and the present energy crisis, the EU is attempting to diversify its gas supply, reduce consumption across all sectors, and speed the rollout of renewable energy. Each step taken to phase out Russian fossil fuels puts the EU closer to a more secure and sustainable energy supply, in line with the European Green Deal objectives and the EU's 2030 energy and climate ambitions.

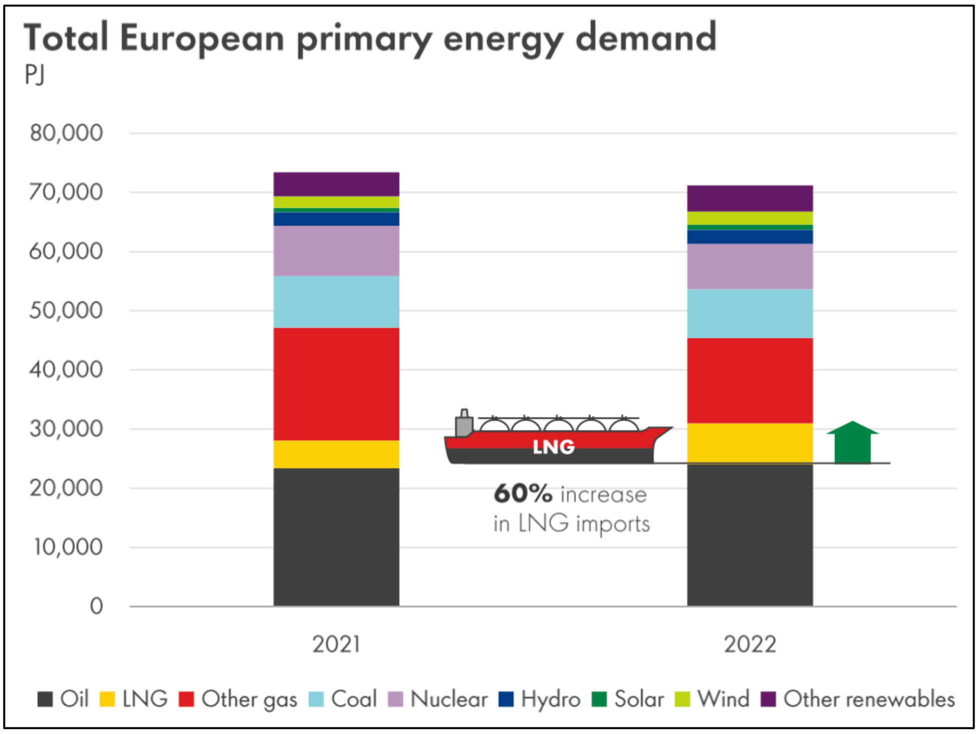

Figure 1: Total European primary energy demand [2]

Domestic production now meets about 10% of the EU's gas needs. The remainder is imported by pipeline or LNG. Russia has dominated pipeline gas imports in recent years (about 40% of all pipeline imports). However, with Russia's invasion of Ukraine in February

2022 and its weaponization of energy supplies, Russia's share of pipeline imports has dropped considerably, with Norway now the EU's primary source of pipeline gas imports.

Between January and September 2022, the United States (44%), Russia (17%), and Qatar (13%), were the top LNG suppliers to the EU. The United States is becoming increasingly crucial in the delivery of gas to the European Union. The EU and the US adopted a common declaration on growing LNG trade at the end of March 2022, and showed interest in raising EU LNG imports from the US by 15 billion cubic meters in 2022 compared to the previous year. This target was met four months early, by the end of August 2022.

The United States, Australia, and Qatar were the world's largest LNG exporters in 2022. Global liquefaction is expected to rise further as new plants in the United States and Australia arise in the coming years.

The EU's overall LNG import capability is large (approximately 157 billion cubic metres in regasified form per year) - enough to cover around 40% of total current gas consumption. However, bottlenecks and infrastructural limitations occur in various places around Europe. Several EU countries are increasing their LNG imports capacity by means of increased investments in LNG terminals.

Based on the list of EU's Projects of Common Interest' (PCIs), the LNG plan contains a list of critical infrastructure projects which are required to ensure that all EU nations may profit from LNG.

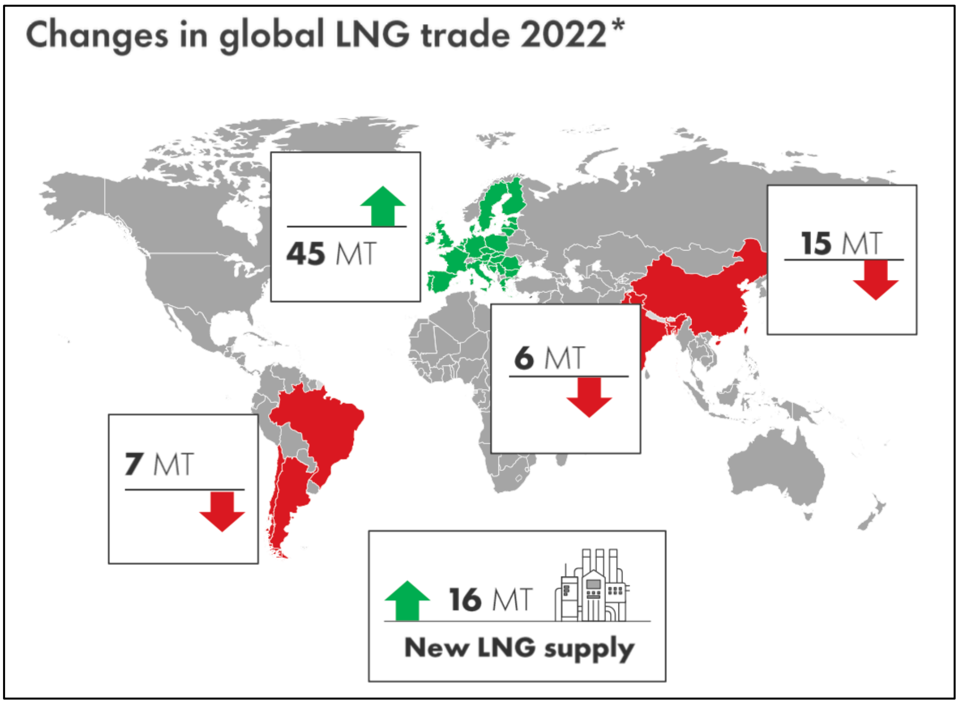

Figure 2: Changes in global LNG trade 2022 [2]

With any new infrastructure, business viability is highly vital. For an LNG terminal, its utilisation across a broad region, or the adoption of lower prices and more flexible technologies such as floating storage and regasification units (FSRUs), may greatly increase its viability [1]. As it seems in figure 2, the lower Chinese LNG imports helped the global LNG market to balance.

Based on the above mentioned market condition regarding the LNG as a fuel, we will focus on the marne transportation of it across Europe, which seems to be the main importer in order to balance the energy demands across the continent.

1.3 LNG Carriers

Marine transportation of LNG as a fuel is based on special designed vessels called LNG Carriers. Due to its local availability and clean burning characteristics, liquefied natural gas (LNG) has grown in significance as a source of energy in recent years. However, it is a difficult process that necessitates the use of specialized vessels known as LNG carriers to carry LNG securely and effectively.[3]

LNG carriers come in a variety of designs, each with specific advantages and characteristics. By construction, the main categories of LNG carriers are as follows:

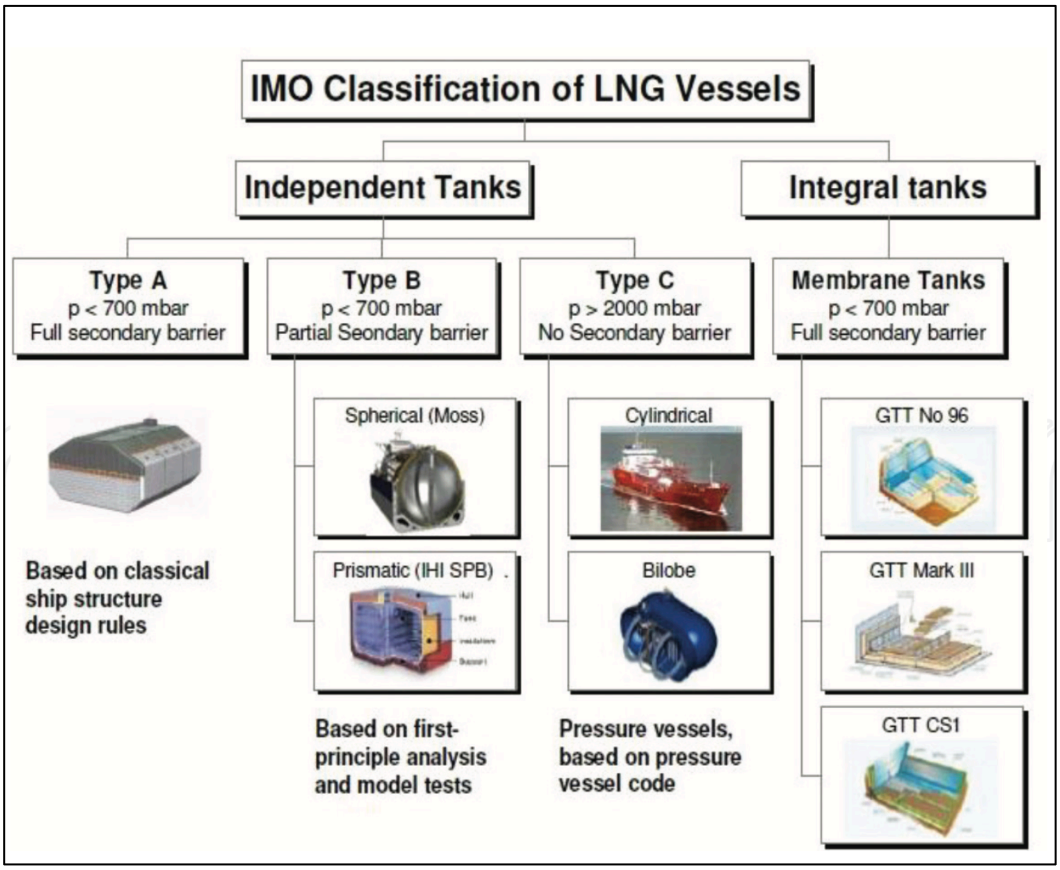

Figure 3: Categorization of containtment systems for LNG Carriers.[5]

Figure 3 depicts the classification of LNG carrier containment systems. The IGC code distinguishes two types of cargo tanks:

1. *Integrated tanks and;*
2. *Independent tanks.*

Furthermore, the integrated tanks are primarily of the membrane type, and the independent tanks are further categorized into three subcategories known as Type A, Type B, and Type C. We commonly employ type C tanks for small-scale LNG carriers and LNG-fueled ships other than LNG carriers. Type B and membrane tanks are commonly utilized on large-scale carriers. We discovered that over 70% of the operational fleet had a membrane tank based on the fleet breakdown by containment system. This is most likely due to the fact that prismatic membrane tanks exploit the hull form more efficiently, leaving less vacant space between the cargo tanks and ballast tanks. Self-supporting type B tanks, on the other hand, are more durable and resistant to sloshing pressures.[5]

The choice of which type of LNG carrier to employ will rely on the particular demands and requirements of the carrier. Each of the aforementioned LNG carrier types has its own set of advantages and disadvantages.[3]

1.3.1 LNG Carriers sizes

Each size of LNG carriers is created to fulfill the particular requirements of the market. The most typical dimensions are:

LNG carrier classes	Dimensions	Ship size—LNG capacity
Small	B:up to 40 m, LOA:up to 250 m	Up to 90,000m^3
Small conventional	B: 41–49 m, LOA: 270–298 m	120,000–149,999 m^3
Large conventional	B: 43–46 m, LOA: 285–295 m	150,000–180,000 m^3
Q-flex	B: approx. 50 m, LOA: approx. 315 m	200,000–220,000 m^3
Q-max	B: 53–55 m, LOA: approx. 345 m	More than 260,000 m^3

Table 1: LNG Carrier Classes [5]

The most common at the moment are large-scale LNG carriers. Over 100,000 cubic meter LNG tankers make up 91,6% of the global LNG fleet, or 99% of its entire capacity.[3]

1.3.2 LNG Carrier Propulsion Options

The propulsion system for LNG tankers is inextricably linked to the creation and use of BOG [6]. The industry is using and considering a variety of suggested propulsion methods. According to the classification of propulsion systems for LNG carriers depicted in Figure 3, the prime movers comprise steam turbines, gas turbines, diesel engines, and dual fuel engines.

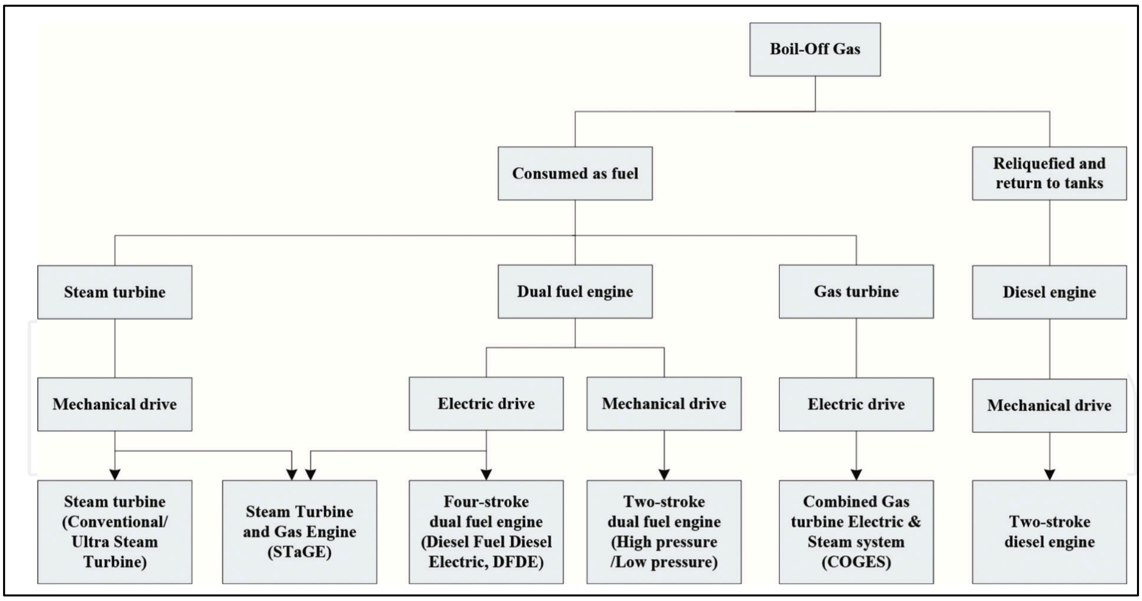

Figure 4: Categorization of propulsion systems for LNG carriers [5]

We have six propulsion system options based on the prime movers and their combinations: steam turbine propulsion, dual fuel diesel electric propulsion, slow speed dual fuel engine propulsion, gas turbine propulsion, slow speed diesel engine propulsion with re-liquefaction plant, and hybrid propulsion system based on steam turbine and gas engine.

1.3.3 Cost of LNG Carriers and Market

Building and running LNG carriers may be costly, with large-scale LNG carriers costing hundreds of millions of dollars. These expenditures include not just the ship's original construction but also continuous spending for maintaining and improving the ship, as well as staff costs.

The cost of new LNG carriers has reached a new high of $300 to $320 million per vessel, with the value increasing by 30% by 2022. The LNG tanker takes 2.5 to 3 years to build, and only a few shipyards are capable of completing this sort of ship. The order book for LNG carriers includes 54 newbuilds due in 2023, 83 in 2024, and a record 102 ships due in 2025.

Over 50 contracts have been signed for the building of LNG carriers scheduled for delivery in 2026 or later. Hudong Zhonghua, Hyundai, Hyundai Mipo, and Hudong Zhonghui are the major shipyards, with contracts for over 70 LNG carriers in early 2023.

The building and operation of LNG carriers can be funded in a variety of ways. Some shipowners prefer to finance their boats themselves, while others seek money from banks or other financial organizations. Furthermore, many shipowners opt into long-term charter arrangements with LNG producers or customers, providing a consistent stream of money to assist finance the ship's operation.[3]

Following Moscow's invasion of Ukraine last year, Europe's loss of most of its Russian pipeline gas supplies propelled global LNG demand to a record high, with European importers scurrying to obtain considerably more cargoes of the super-chilled gas to fulfill customer demand. Not only is Europe building new LNG import projects at an unprecedented rate, but suppliers throughout the world are hurrying to match the demand spike by expediting new supply initiatives.

Not only is the LNG market constrained, and is projected to remain so for several years until the next wave of additional production comes, but so is the market for LNG carriers (LNGCs), which are required to transport the fuel to markets. Some carriers have exited the worldwide fleet in order to be converted for service as floating regasification and storage units (FRSUs), mostly in Europe.

A lack of LNGCs to carry the fuel led a surge in charter prices during the peak of the LNG supply crunch last October. Spot charter rates for LNG ships, for example, reached $500,000 per day in November of last year. Prior to 2021, the record was less than $200,000 per day. Charter fees have subsequently dropped to about $200,000 as the LNG market has loosened following a mild winter in Europe and minimal industrial activity. However, analysts expect that they will improve in the second half of this year as a result of the Asian economic recovery.

The LNGC fleet currently stands at around 640 vessels. But by 2026, its size is due to exceed 1,000 vessels, according to a January market analysis released by shipbroker Howe

Robinson Partners. Howe Robinson estimates that 48 newbuilds will enter service this year alone, of which 28 will have capacities ranging between 174,000 and 200,000 m^3. The shipbroker notes that most new vessels entering the fleet over the next few years will be delivered into term charters, keeping the spot market tight.[4]

2. Energy Losses of a Steam Turbine LNG Carrier

In this chapter we are focusing on Steam Turbine LNG Carriers as presented in the previous chapter 1.3.2. This significant category of vessels is of great interest for the ship owner's side, since many of them are affected by the new marine environmental regulations. Section 2 presents a simple method to identify energy flows among machinery items of a steam turbine LNG ship and its main scope is to highlight ship's main energy losses utilizing the well known Sankey diagrams.

2.1 Basic Working Principle of a Steam Turbine LNG Carrier

A turbine propulsion plant typically consists of two boilers capable of producing 80-90 t/h of superheated steam at a pressure of 60-70 bar at 520 °C [7], which feed the high and low pressure turbines. The turbines are commonly cross-compound [8], with net power ranging between 35MW and 45MW [7, 9]. Once expanded in both turbines, the steam is condensed in the main condenser and returned to the boiler through pumps after passing through a number of heaters that boost the thermal efficiency of the cycle by utilizing residual heat.

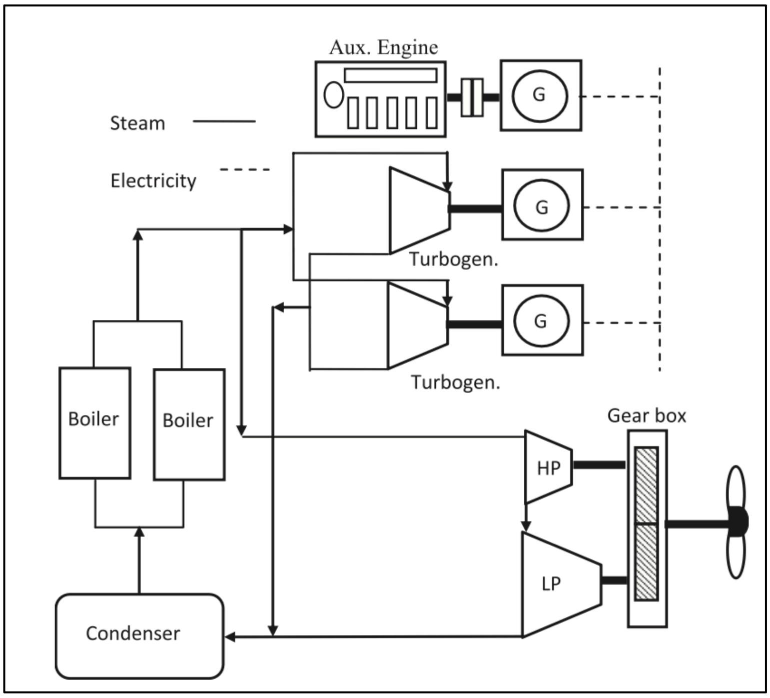

Figure 5: Configuration of a basic propulsion system through an ST [11]

Electric energy is created on board by two turbo generators, which are supplied by steam generated in both boilers, as shown in Fig. 5 [11]. Each generator has an average capacity of 10 MW, which, combined with a diesel generator of roughly 3 MW, would be enough to supply the vessel's power needs in any given circumstance [13].

The boilers are intended to consume many fuel types at the same time, such as fuel oil and BOG, providing adaptability to the system to be emphasized [10]. Gas is supplied from cargo tanks to boilers using single stage centrifugal compressors designated as LD (Low Duty).

Such compressors feature variable pitch blades and are powered by a variable speed electric engine, which regulates the gas supply to the boilers based on demand at any given time [12].

The surplus BOG created while the vessel is at port or at anchor, when the propulsion system is not in use, is likewise burnt in the boilers, producing steam without utilizing any energy. After a laminating and tempering process known as "dumping," this steam is directed directly to the condenser. The goal of this method is to give the ability to stabilize tank pressure.

2.1.1 Advantages and Drawbacks of a Steam Turbine LNG Carrier

The lack of competition in the design of propulsion systems that allow the consumption of various fuel types such as "heavy fuel oil" (HFO) and the BOG from the cargo, combined with its ease of use, intrinsic reliability, and lower maintenance costs [14,12], resulted in STs being the most popular system on board LNG vessels up until the turn of the millennium [12]. It is also worth mentioning the additional benefits of this plant type, such as simple control over the usage of BOG, minimal vibrations, and lower lubricant use [11].

The major disadvantage for which new on-board propulsion systems are being sought and deployed is their low efficiency (about 35% at full load), excessive CO_2 emissions, and big engine space as compared to other systems [15].

2.2 Method to determine energy losses of a vessel

A simplified method to determine and visualize the energy losses of a ship is based on the usage of all the available drawings and documents such as the Electric Load Analysis, Machinery Arrangement of the vessel, all the available efficiency rates, capacities in kW of the machinery items etc.

In our case, the Electrical Load Analysis and the Steam Heat Balance of the ship are the basic documents in which our simplified method was based. More specifically, a quick presentation of the above-mentioned documents will follow.

- **Steam Heat Balance and Flow Diagram**

During the past decades, many new merchant ships have been put into service using steam turbine engines. Our study focuses on the LNG Carriers for which a propulsion steam turbine plan exists. After the completion of vessel's construction in a shipyard, the ship is to be tested to determine the performance of her since every shipyard is commited to each shipowner to reach specific standards in order to obtain this asset to his ownership.

The standard practice is to perform tests to ascertain good functionality of each machinery item installed in a vessel. After the completion of these machinery trials, speed tests performed so as to confirm that the examined ship reaches certain level of speeds at different engine settings (e.g. 14 knots at 75% of Maximum Engine's Power etc.). The above tests called Sea Trials and these tests are necessary for all merchant ships.

For a Steam Turbine and Gas Engine LNG Carrier, these Sea Trials and vessel's performance are depicted in a document called Steam Heat Balance and Flow Diagram which describes all the basic parameters of the boiler plant for the production of the steam amount used for propulsion and electric generation. A typical content page and test result at 100% of the maximum boiler's capacity follow in the below figures 6 and 7:

STEAM HEAT BALANCE AND FLOW DIAGRAM	DWG NO	
	SHEET	2/14

CONTENT

Figure 6: Content Page of a typical Steam Heat Balance[1]

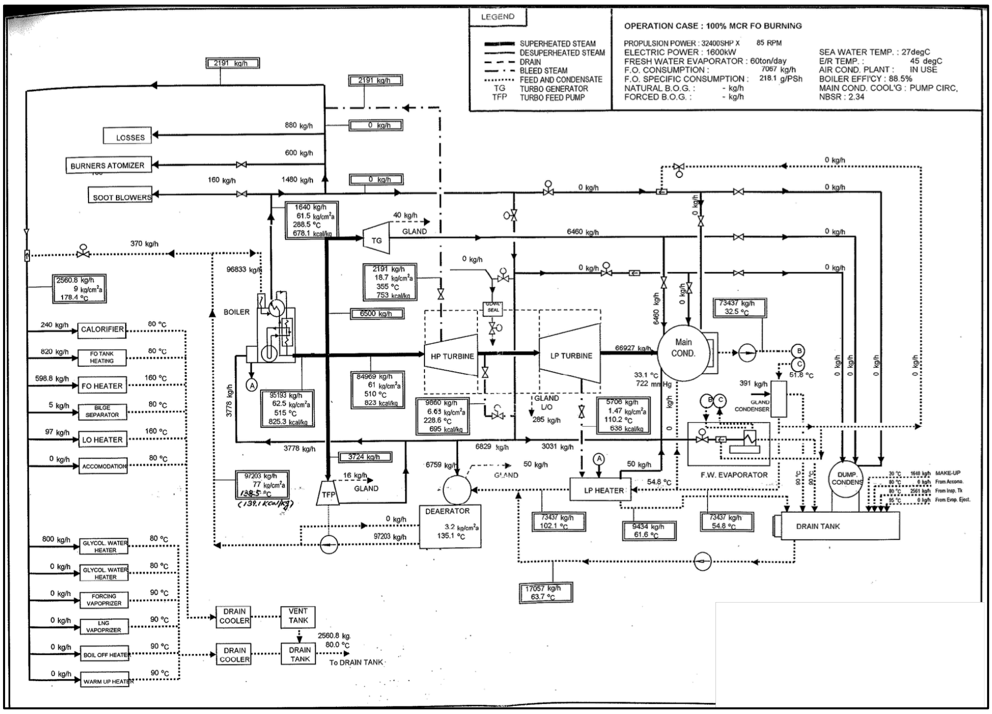

Figure 7: Indicative operation of steam boiler plant at 100%[1]

[1] All the presented vessel specific information are confidential and are used only for academic purposes.

- **Electric Load Analysis**

The main task of Electric Load Analysis is to calculate the power required by the user installed on the ship. As a direct result of this analysis, it is possible to evaluate the power that the generator must provide in the main operating situations of the ship. When knowing the required capacity for the production system, it is possible to choose the size, number and type of generators to minimize installation and management costs. Typical ship's conditions and the electrical loads are depicted in the below figures 8 and 9.

SUMMARY TABLE							
CLASSIFICATION	Sea Going	Port in/out without Thruster	Port in/out with Thruster	Cargo Load	Cargo Unload	Emergenct Black-out	Emergency Fire
CONTINUOUS LOAD	2042,2	**2828,24**	**4711,6**	**4633,8**	**6353,3**	107,6	70,99
INTERMITTENT LOAD	414,9	352,52	366,0	501,4	501,5	14,0	191,5
GROUP DIVERSITY FACTOR	0,4	0,4	0,4	0,4	0,4	1,0	1,0
ACTUAL INTERMITTENT LOAD	166,0	141,01	146,4	200,6	200,6	14,0	191,5
DECK MACHINERY	0,0	332,88	0,0	0,0	0,0	0,0	0,0
TOTAL LOAD	2208,1	**3302,13**	**4858,0**	**4834,4**	**6553,9**	121,5	262,5
NO. OF RUNNING D/G	0	0	0	0	0	1 (E/G)	1 (E/G)
NO. OF RUNNING T/G	1,0	2	**2,0**	2,0	2,0	0,0	0,0
LOAD PEAC(%) OF D/G	0,0	0	0,0 01	0,0	0,0	24,3	46,0
LOAD PERCENT(%) OF T/G	64,0	47,86	**70,41**	70,1	95,0	0,0	0,0
PREFERENTIAL TRIP LOAD 1 (PT1)	331,2	311,5	311,5	311,5	311,5	0,0	0,0
PREFERENTIAL TRIP LOAD 2 (PT2/3)	0,0	659,44	326,6	653,1	4363,2	0,0	0,0
START BLOCKING LAOD (SB)	0,0	0	1875,0	0,0	0,0	0,0	0,0
TOTAL LOAD AFTER PT 1&2,&3	1876,9	**2331,23**	**4220,0**	**3869,79**	**1879,2**	121,5	262,5
TOTAL LOAD AFTER SB&PT	1876,9	**2331,23**	**2345,0**	**3869,8**	**1879,2**	121,5	262,5
LOAD PERC(%) OF D/G AFT PT/S8	0,0	0	0,0 01	0,0	0,0	24,306	52,493
LOAD PERCENT(%) OF T/G AFT PT/SB	54,4	**33,79**	**33,98**	**56**	0,00	0,0	0,0
MAIN ENGINE: KAWASAKI S/TURBINE							

GENERATOR			
CLASSIFICATION	DG	TG	EG
CAPACITY	3.450 KW	3.450 Kw	500 KW
NO. OF SET	1	2	1
VOLTAGE	6.600 V	6.600 v	450 V
PHASE,FREQUENCY	3 PH /60 HZ	3 PH /60 HZ	3 PH /60 HZ

Figure 8: Summary table of a vessel's Electric Load Analysis[1]

ELECTRIC LOAD ANALYSIS TABLE																				
ITEM	MODE	SET	OUT PUT KW	EFF'Y (%)	INPUT KW	LOAD FACTOR	DLV FACTOR	SEA GOING		PORT IN/OUT WITH THRUSTER		CARGO LOAD		CARGO UNLOAD		EMERGENCY BLACK-OUT		EMERGENCY FIRE		PT/SB
Propulsion Plant																				
Main turbine turning gear	C	1	11,0	0,88	12,5	0,50	1,00					1,0	6,3	1,0	6,3					
M/Turbine aux . L .O. pump	C	2	55,0	0,9106	60,4	0,76	1,00			1	45,9	1,0	45,9	1,0	45,9					
Continuous load sub total (Mode=C)									-		45,9		52,2		52,2		-		-	
Intermittent Load Sub Total (Mode =C)									-		-		-		-		-		-	
Generating Plant																				
D/G engine J.W preheater	I	1			24	1,00	1,00	1	24	1	24	1	24	1	24					
D/G engine J.W preheating pump	C	1	1,5	0,79	1,9	0,80	1,00	1	1,5	1	1,52	1	1,52	1	1,52					
D/G engine D.O service pump	C	1	2,5	0,86	2,9	0,64	1,00													
D/G engine L.O priming pump	C	1	8,6	0,88	9,8	0,80	1,00	1	7,8	1	7,84	1	7,84	1	7,84	1	7,84			
Turbo gen.aux. L.O pump	C	1	3,7	0,86	4,3	0,54	1,00													
Turbo gen . Turning gear	C	1	0,8	0,73	1,1	0,40	1,00													
Continuous Load Sub Total (Mode=C)									9,4		9,4		9,4		9,4		7,84	-	-	
Intermittent Load Sub Total (Mode=I)									24,00		24		24		24	-	-	-	-	
Water Handking Equipment																				
Main cool. S.W pump	C	2	90,0	0,93	96,8	0,89	1,00	1	86,15	1	86,2	1	86,2	1	86,2					
Main cool. Circ. pump	C	3	185,00	0,94	196,8	0,81	1,00	2	318,82	1	159,4	1	159,4	1	159,4					

Figure 9: Indicative electric load analysis of propusion and generating plant[1]

To sum up, documents of Steam Heat Balance and the Electric Load Analysis of a vessel gives us a clearer view of the main energy flows of an LNG Carrier and assist us creating the Sankey diagram showing all the energy flows from a machinery item to another.

More specifically, **the Steam Heat Balance** shows:

- the correlations of the main machinery components such as the Boiler Plant, the Turbogenerators, the steam turbines etc., and;
- the efficiencies of the above-mentioned machinery components.

The **Electric Load Analysis** inform us about:

- the electric consumption of each component and;
- the correlations among secondary machinery components of a ship.

All the above information used for the creation of representative energy flow diagrams called Sankey Diagrams.

2.3 Sankey Diagram

A Sankey diagram is a type of diagram in which the width of the arrows is proportional to the line of the large attribute represented.

Sankey charts can also visualize energy accounts, regional or national material flow accounts, and cost allocations [16]. Diagrams are commonly used to visualize material flow analysis. Sankey diagrams emphasize major transfers or flows in the system. They make it possible to identify the most important contributions to a stream. They usually show how much is conserved within the system's defined limits.

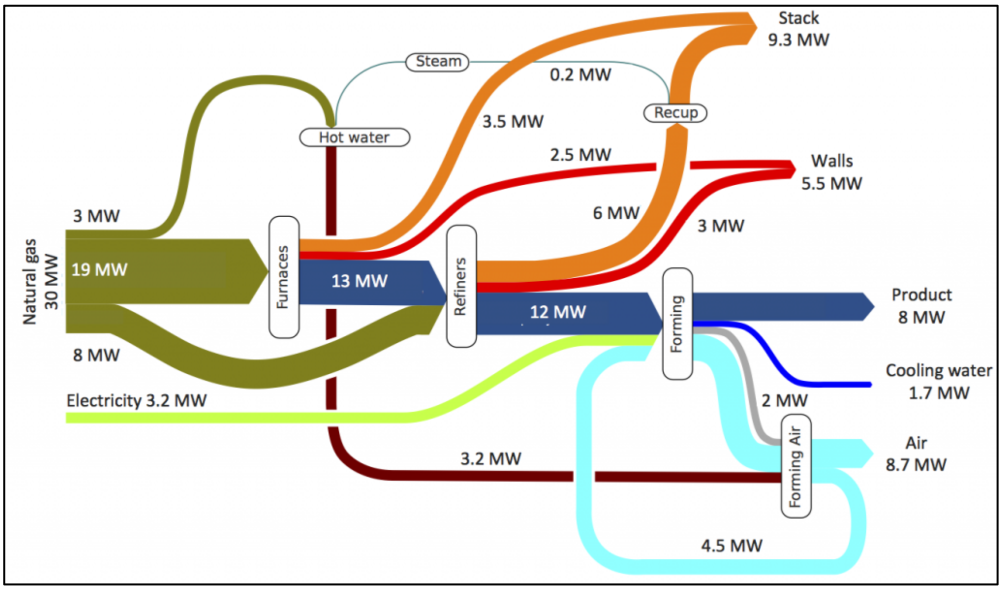

Figure 10: A Typical Sankey Diagram [17]

2.4 Steam Turbine LNG Carrier – Case Study

In this stage, composing the above knowledge, Sankey diagrams will be presented reflecting the energy flows of a Steam Turbine LNG Carrier which is used as our case study.

Firstly, the presetation of the case study-vessel follows:

The selected vessel was built in Daewoo shipbuilding & Marine Engineering Co., Ltd. on 2005. The main particulars of the vessel are:

LOA (length over all)	285.4 m
LBP (length between per.)	274.4 m
Breadth	43.4 m
Depth	26.0 m
Draft (Design – Scantl.)	11.5 – 12.5 m
Service Speed (kn)	20.0 kn at 100% MCR with 20% sea margin
Main Engine	Type: Marine Steaam Turbine MCR: 36800 PS – 88.5 RPM NCR: 33120 PS – 85.5 RPM

Table 2: Principal Particulars - Case Study Vessel[1]

In the below figure 11, the general arrangement of the ship is presented:

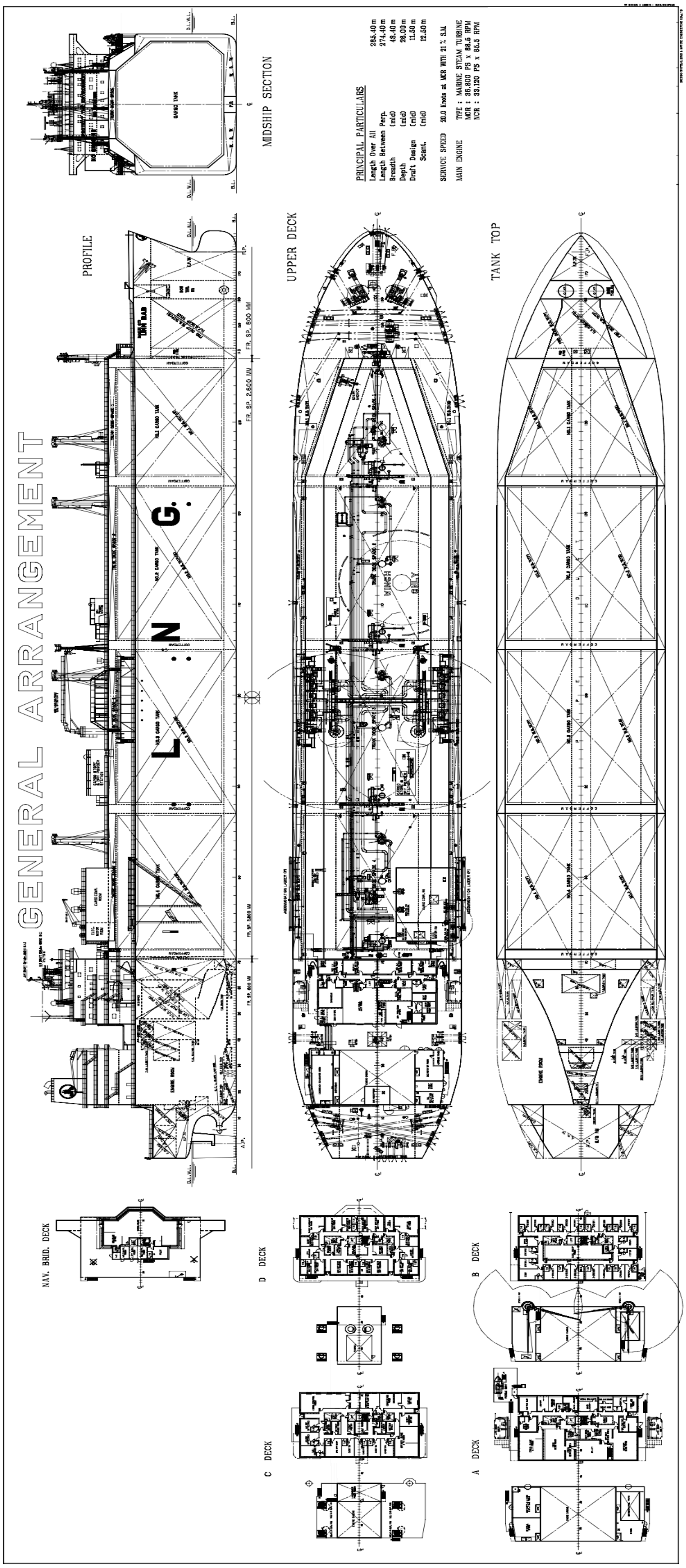

Figure 11: General Arrangement of case study vessel[1]

2.5 Sankey Diagram – Case Study

Based on the Steam Heat Balance and the Electric Load Analysis of the case study vessel, two (2) different options are presented as the most common vessel conditions during a normal operating year.

So, the first examined condition called **Normal Sea Going (NSG)** in which the vessel sails at normal circumnstances without adverse weather and we assume that represents the majority of vessels time during a year.

And the second condition, which studied, is about every stay of the ship at anchorage. This condition is called **Port Condition (PORT)** and indictes the consumption and energy flows of the ship during her anchor stay at every port.

Both conditions are presented in the below subchapters incuding the calculation method and the resulting Sankey diagrams as exported via Microsoft PowerBi.

- **What is the Microsoft PowerBI?**

A business intelligence (BI) platform called Microsoft Power BI gives non-technical business people the means to gather, analyze, visualize, and share data. With its strong interaction with other Microsoft products, Power BI is a versatile self-service tool that requires little initial training. Its user interface is fairly intuitive for Excel users [18].

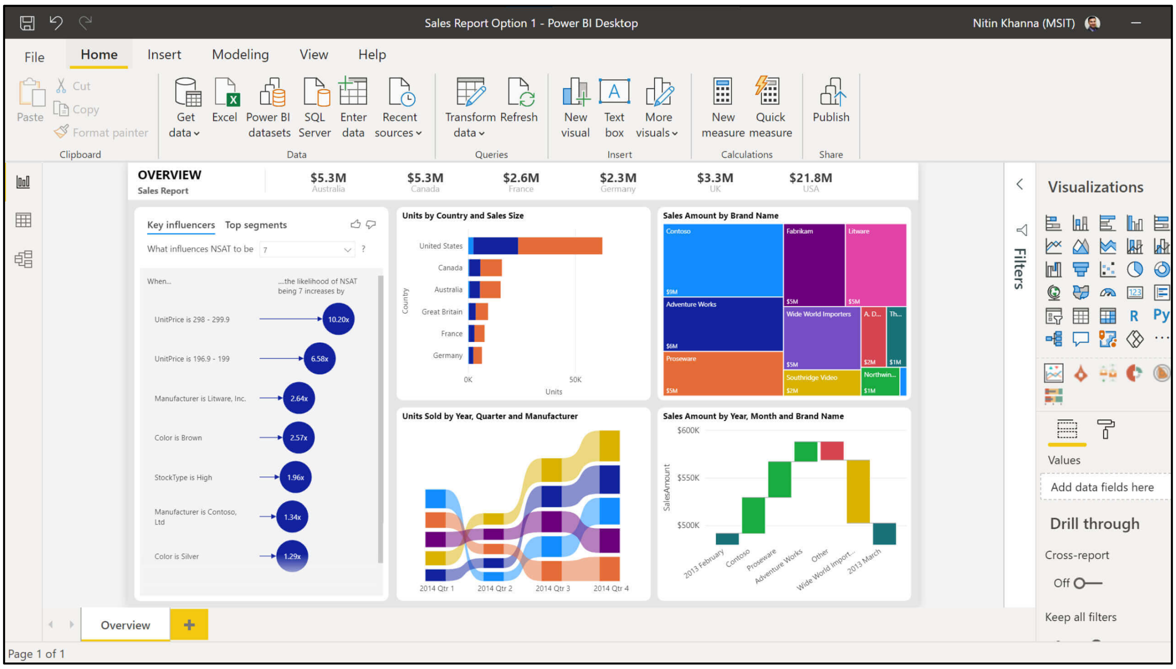

Figure 12: Indicative menu and visuals of Microsoft PowerBI [19]

2.5.1 Normal Sea Going Condition (NSG)

The identification of the main machinery components used during NSG condition, all the necessary parameters such as the maximum power of the boiler plant, efficiencies of machinery components, correlations of the presented machinery components was made via the 2 main documents presented in chaprter 2.2 above.

The compete set of used documents (Electric Load Analysis and the Steam Heat Balance) are presented in Appendix A of this study.

The following tables are created including the inputs (efficiencies and electric consumptions in kW of each machinery component – table 3) and the correlations among the subsustems of the ship (table 4).

Boiler Efficiency (%)	88,42%
Steam Turbine Efficiency (%)	80,00%
Steam Turbine Power (kW)	19064,16
Turbogenerator Power (kW)	2208,10
Propulsion Plant (kW)[22]	0,00
Generating Plant (kW)[2]	18,90
Water Handling Equipment (kW)[2]	607,70
Oil Handling Equipment (kW)[2]	22,78
Boiler Plant (kW)[2]	329,40
Other Equipment in Machinery Space (kW)[2]	235,58
Cargo Handling Equipment (kW)[2]	365,02
Ship Systems (kW)[2]	22,72
Manoeuvring Equipment (kW)[2]	28,00
Deck Machinery (kW)[2]	0,00
A/C & Ventilation Equipment (kW)[2]	392,40
Miscellaneous Equipment (kW)[2]	35,60
Lighting, Nav & control Equipment (kW)[2]	150,00

Table 3: Input data for Normal Sea Going (NSG) Condition

[2] All the values are selected via Electric Load Analysis of the examined vessel.

Source	Destination	Fuel Utilization (%)
Fuel	Boiler	100,0%
Boiler	Losses	11,6%
Boiler	Steam Turbine HP - LP	79,2%
Steam Turbine HP - LP	Propulsion System	63,4%
Steam Turbine HP - LP	Losses	15,8%
Boiler	Turbogenerator No. 1	9,2%
Turbogenerator No. 1	Losses	1,8%
Turbogenerator No. 1	Generator No. 1	7,3%
Generator No. 1	Propulsion Plant	0,0%
Generator No. 1	Generating Plant	0,1%
Generator No. 1	Water Handling Equipment	2,0%
Generator No. 1	Oil Handling Equipment	0,1%
Generator No. 1	Boiler Plant	1,1%
Generator No. 1	Other Equipment in Machinery Space	0,8%
Generator No. 1	Cargo Handling Equipment	1,2%
Generator No. 1	Ship Systems	0,1%
Generator No. 1	Manoeuvring Equipment	0,1%
Generator No. 1	Deck Machinery	0,0%
Generator No. 1	A/C & Ventilation Equipment	1,3%
Generator No. 1	Miscellaneous Equipment	0,1%
Generator No. 1	Lighting, Nav & control Equipment	0,5%

Table 4: Correlations of vessel's Machinery systems for NSG condition and fuel utilization in %

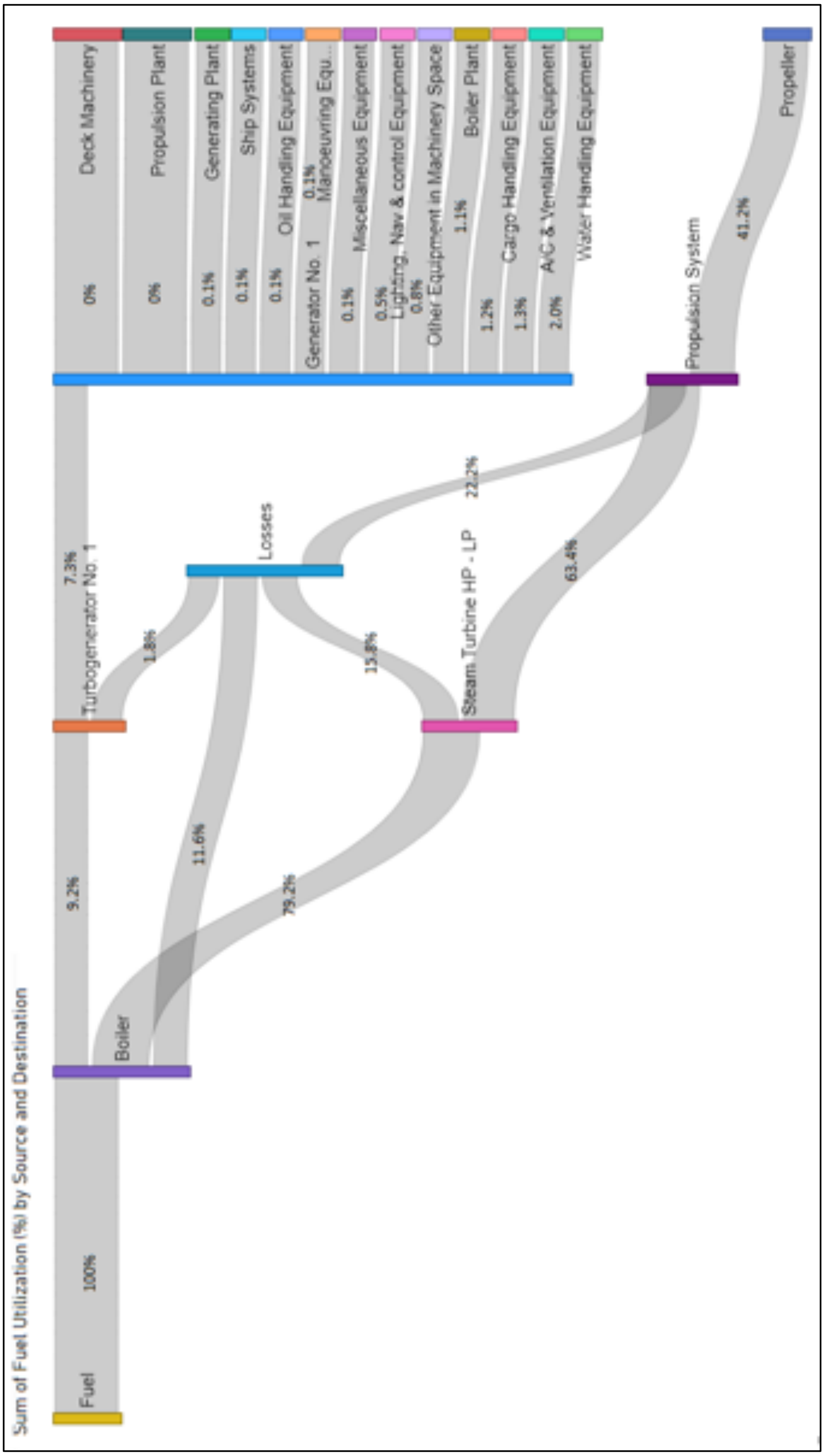

Figure 13: Sankey diagram for NSG condition

2.5.2 Port Condition (PORT)

The same procedure followed for the production of the input table and the correlation table for the identification of energy flows of the ship when is at anchorage. Consequently, the below tables are presented:

Boiler Efficiency (%)	88,42%
Steam Turbine Efficiency (%)	80,00%
Steam Turbine Power (kW)	0,00
Turbogenerator Power (kW)	4603,91
Propulsion Plant (kW)[3]	45,90
Generating Plant (kW)[3]	18,90
Water Handling Equipment (kW)[3]	428,60
Oil Handling Equipment (kW)[3]	18,95
Boiler Plant (kW)[3]	298,70
Other Equipment in Machinery Space (kW)[3]	227,30
Cargo Handling Equipment (kW)[3]	365,02
Ship Systems (kW)[3]	341,74
Manoeuvring Equipment (kW)[3]	1940,30
Deck Machinery (kW)[3]	333,00
A/C & Ventilation Equipment (kW)[3]	392,40
Miscellaneous Equipment (kW)[3]	35,60
Lighting, Nav & control Equipment (kW)[3]	157,50

Table 5: Input data for Port Condition (PORT)

Source	Destination	Fuel Utilization (%)
Fuel	**Boiler**	**100,0%**
Boiler	Losses	11,6%
Boiler	Steam Turbine HP - LP	0,0%
Steam Turbine HP - LP	Propulsion System	0,0%
Steam Turbine HP - LP	Losses	0,0%
Boiler	Turbogenerator No. 1	88,4%
Turbogenerator No. 1	Losses	17,7%
Turbogenerator No. 1	Generator No. 1	70,7%
Generator No. 1	Propulsion Plant	0,7%
Generator No. 1	Generating Plant	0,3%
Generator No. 1	Water Handling Equipment	6,6%
Generator No. 1	Oil Handling Equipment	0,3%
Generator No. 1	Boiler Plant	4,6%
Generator No. 1	Other Equipment in Machinery Space	3,5%
Generator No. 1	Cargo Handling Equipment	5,6%
Generator No. 1	Ship Systems	5,3%
Generator No. 1	Manoeuvring Equipment	29,8%
Generator No. 1	Deck Machinery	5,1%
Generator No. 1	A/C & Ventilation Equipment	6,0%
Generator No. 1	Miscellaneous Equipment	0,5%
Generator No. 1	Lighting, Nav & control Equipment	2,4%

Table 6: Correlations of vessel's Machinery systems for PORT condition and fuel utilization in %

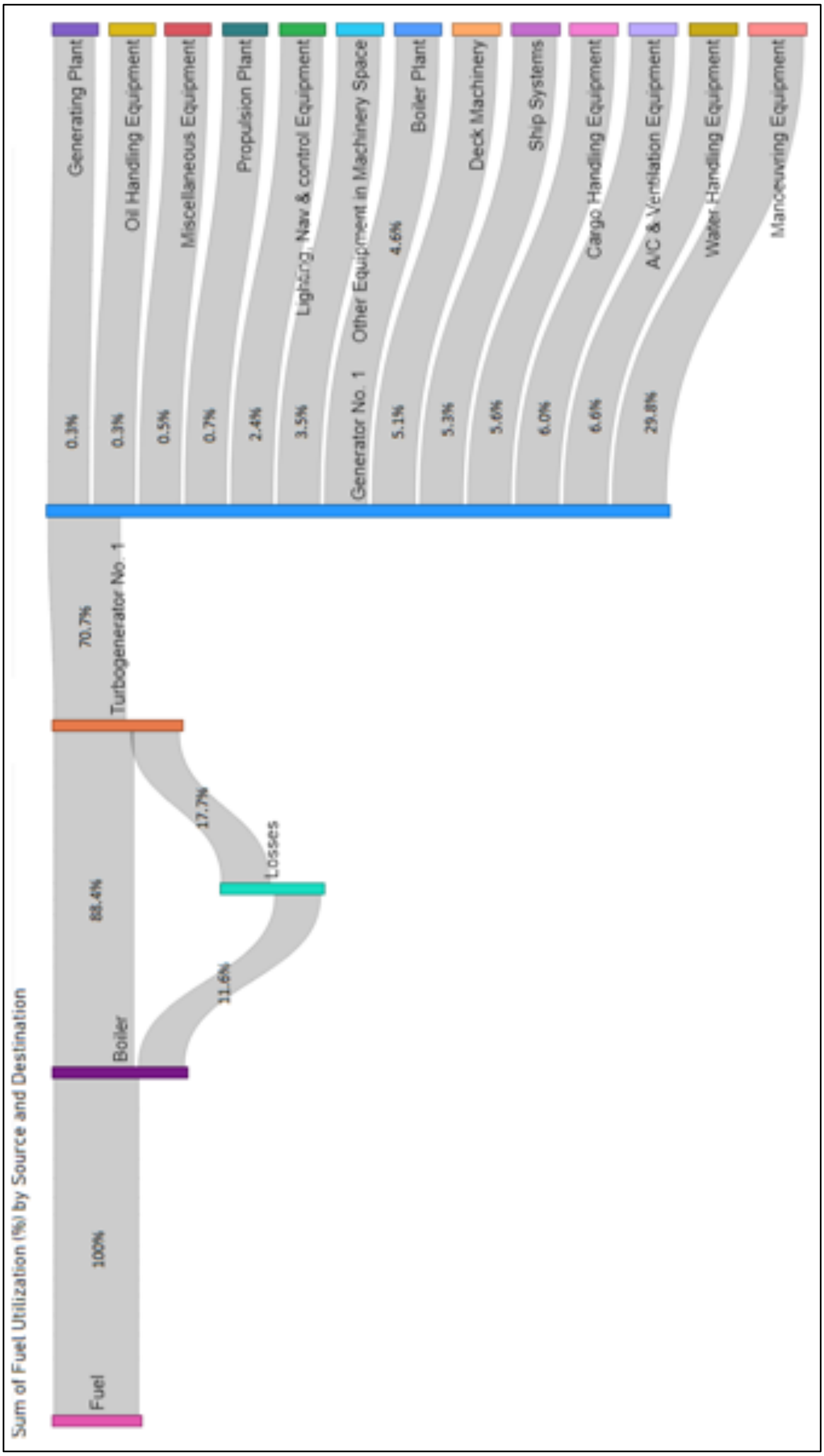

Figure 14: Sankey diagram for PORT condition

3. Energy Efficiency Existing Index (EEXI) Calculation

The IMO implemented the Energy Efficiency Existing ship Index (EEXI) as a metric to lower ship emissions of greenhouse gases. An indicator of a ship's technical design is the EEXI. Once in a lifetime, by the first periodic survey in 2023 at the latest, ships must have EEXI approval.

The maximum permissible attainable EEXI value is the required EEXI value, which is based on the ship type, capacity, and propulsion principle.

For each ship that is subject to the rule, the attained EEXI must be determined.

3.1 Required EEXI Calculation for LNG Carriers

The calculation of the required EEXI sets the limit which a specific vessel cannot exceed. Practically, the required EEXI is the technical indicator of a vessel to comply with. As per MEPC.328 (76), the required EEXI is calculated after the deduction of the reference value based on ship specific ship category.

In our case, the LNG Carriers reference line is as below:

$$\boldsymbol{Reference\ Line\ Value = ab^{-c}} \qquad \textbf{(1)}$$

Where a, b and are the parameters given in table 7.

Ship Type	a	b	C
LNG Carrier	2253.7	DWT of the ship	0.474

Table 7: Parameters for the calculation of the Required EEXI

After the calculation of the reference line value for our vessel, the reduction factor is to be identified for the calculation of the required EEXI. More specifically, as per the presented table 8, the reduction factor for the category of the LNG Carriers is 30% based on the MEPC. 328 (76) regulation 25.

Ship Type	Size	Reduction Factor
LNG Carrier	10000 DWT and above	30%

Table 8: Reduction Factor for LNG Carriers

Based on the above equation (1) and tables 7 and 8, we derive the equation for the calculation of an LNG Carrier:

$$\boldsymbol{Required\ EEXI = 2253.7 * DWT^{-0.474}} \quad (2)$$

3.2 Attained EEXI Calculation for steam-turbine LNG Carriers

After the calculation of the required EEXI of the vessel which sets the maximum limit to comply with, the calculation of the attained EEXI is needed to be specified.

The attained EEXI is a calculated value which is based on the basic technical standards of the examined vessel. In order to evaluate vessel's energy efficiency existing design index, the first step is to collect all the technical documents/ drawings and to identify the necessary values. To identify these values, the formula of the attained EEXI is presented as:

$$\boldsymbol{Attained\ EEXI = \frac{P_{ME} * SGC * C_{F,LNG}}{DWT * V_{ref}}} \quad (3)$$

Where,

$\boldsymbol{P_{ME}}$ equals to 0.83*MCR (Maximum Continuous Rating),

$\boldsymbol{SGC}$ is the specific gas consumption,

$\boldsymbol{C_{F,LNG}}$ Conversion factor between fuel consumption and CO_2 emission, for LNG, C_F=2.750 t-CO_2/t-Fuel,

$\boldsymbol{DWT}$ is the deadweight of the vessel,

$\boldsymbol{V_{ref}}$ is the reference vessel's speed.

According to MEPC.333 (76) par. 2.2.1, the power from combustion of excessive natural boil- off gas in the engines or boilers to avoid releasing to the atmosphere or unnecessary thermal oxidation, should be deducted from $\boldsymbol{P_{ME}}$.

- ***What is the boil-off gas on an LNG vessel?***

Natural gas, a byproduct of oil extraction and production, has a lower density than conventional fuels, making transportation problematic.

Liquifying natural gas into LNG allows it to be transported safely and cost-effectively across long distances when pipelines are not available or practical. LNG is commonly stored and transported as a cryogenic liquid in tanks loaded onto vessels at temperatures of -163°C (-261°F) to increase its density.

Despite the fact that the tanks are insulated, some warming occurs, causing the LNG cargo to evaporate as it approaches its boiling point. This natural evaporation is unavoidable, and the resultant boil-off gas (BOG) must be evacuated to keep the tanks' pressure stable.[20]

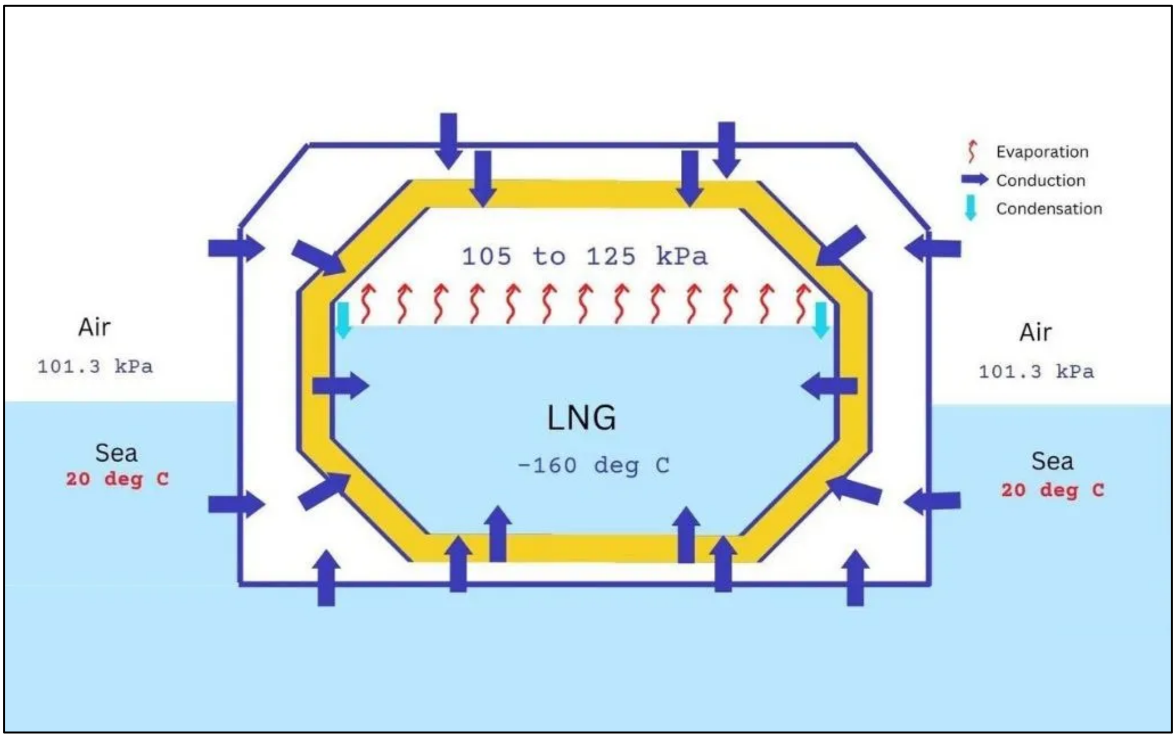

Figure 15: Boil-off Gas on LNG prismatic tank [21]

After the deduction of the excessive boil-off gas, the formula changes to:

$$\boldsymbol{Attained\ EEXI} = \frac{\boldsymbol{P_{ME\_revised} * SGC(P_{ME\_lim}) * C_{F,LNG}}}{\boldsymbol{DWT * V_{ref}(P_{ME\_lim})}} \quad \textbf{(4)}$$

The above indicated calculation cannot be applied prior the engine power limitation.

3.3 Analysis of the Attained EEXI Equation Variables [22]

The terms used for the calculation of the attained EEXI according to the equation (4) can be determined as follows:

- $P_{ME\_revised}$ The relevant power value after deduction of $P_{Excessive}$.

$$P_{ME\_revised} = 0.83\, MCR_{lim} - P_{Excessive} \quad (5)$$

- MCR_{lim} The new MCR to which the propulsion system must be limited to comply with the Required EEXI.
- $P_{Excessive}$ The excessive power from combustion of excessive natural boil-off gas is defined as the difference between nominal power generated by consuming all boil-off gas from the cargo tanks and MCR_{lim}.

$$P_{Excessive} = P_{BOG} - MCR_{lim} \quad (6)$$

- **Calculation of the P_{BOG}:**

The power generated by the boil-off gas from LNG's vessel cargo tanks are defined following the below steps:

a. Determination of V_{Cargo} which is the maximum cargo volume based on the capacity plan of the vessel in m^3.

b. Calculation of BOR_{LNG}. This is the daily Boil-off rate in t/day:

$$BOG_{LNG} = 0.000864 V_{Cargo} \quad (7)$$

c. **Steam Heat Balance and Flow Diagram** of the vessel is to be used. More specifically, this is an essential document of a vessel of this type and contains information regarding the Specific Fuel Oil Consumption (SFC) at different engine power levels in gr/kwh. This indicated special consumption (in gr/kwh) can be converted to Daily LNG Consumption using the ratio of the Lower Calorific Values as stated by IMO in MEPC.308(73) in tons LNG/ day.

$$LNG\ Consumption = \frac{Fuel\ Oil\ Consumption\ \left(\frac{kg}{hr}\right) 24}{1000} \frac{LCV_{FO}}{LCV_{LNG}}\ in\ {}^{tons}/_{day}$$

Based on the above consumption conversion in tons of LNG per day, the below diagrams will be created:

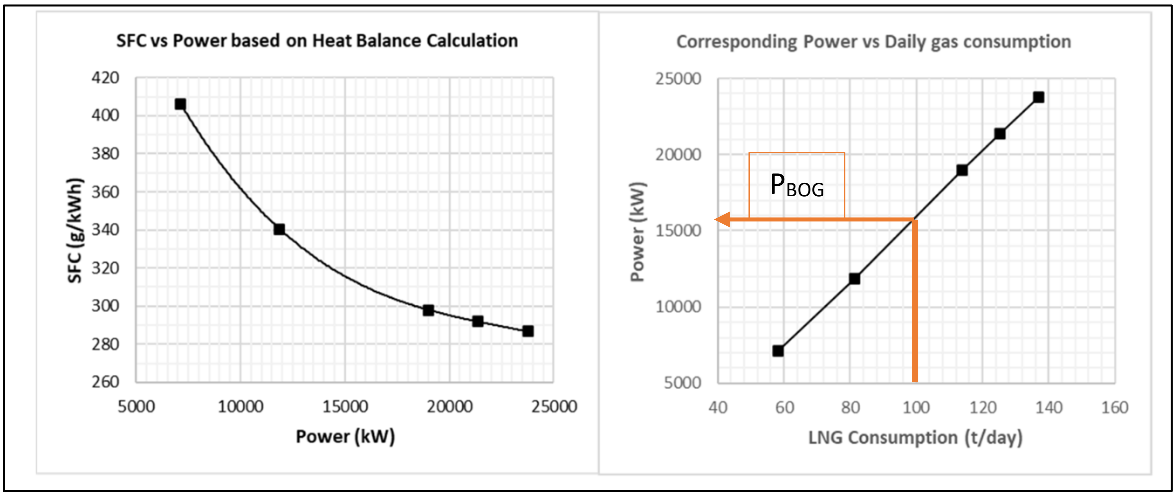

Figure 16: Example of SFC vs Power from Heat Balance and Corresponding Power vs Daily LNG Consumption for a typical LNG Steam Turbine Ship [22]

Then the $\boldsymbol{P_{BOG}}$ can be defined as the corresponding power in the calculated LNG Consumption (t/ day), which equals to $\boldsymbol{BOR_{LNG}}$

- $\boldsymbol{P_{ME\_lim}}$ equals to $\mathbf{0.83}\ \boldsymbol{MCR_{lim}}$,
- $\boldsymbol{SGC(P_{ME\_lim})}$ is the specific gas consumption at $\boldsymbol{P_{ME\_lim}}$, the specific gas consumption at different loads is available in the Steam Heat Balance & Flow Diagram design. If the gas consumption is shown on the Steam Heat Balance & Flow Diagram drawing (3 or more load points), these figures should be used. When the tests during the sea trials of the vessel were conducted using different fuel than LNG, then conversion to LNG is to be done:

$$\boldsymbol{SGC = SFC\frac{LCV_{Fuel\,Oil}}{LCV_{LNG}}}$$

- $\boldsymbol{C_{F,LNG}}$ Conversion factor between fuel consumption and CO_2 emission, for LNG, C_F=2.750 t-CO_2/t-Fuel,
- $\boldsymbol{DWT}$ is the deadweight of the vessel,
- $\boldsymbol{V_{ref}}$ is the reference vessel's speed and can be defined by the sea trials report in which speed- power curves are presented at different drafts of the ship. Two cases can be noticed in this stage:
  a. ***Speed – Power Curve is available at scantling/ design draft:*** This curve is to be used for the definition of the reference vessel's speed at $\boldsymbol{P_{ME\_lim}}$.

b. ***Speed – Power Curve is not available:*** In this case paragraph 7.4 of the No. 172 IACS EEXI Implementation Guidelines is to be utilized. Specifically, the formulas can be used are the following with or without power limitation:

$$\boldsymbol{V_{ref,app} = \left(V_{ref,avg} - m_v\right)\left[\frac{\sum MCR_{SteamTurbine}}{MCR_{avg}}\right]^{\frac{1}{3}}}$$ **(8)** without power limitation

$$\boldsymbol{V_{ref,app} = \left(V_{ref,avg} - m_v\right)\left[\frac{MCR_{lim}}{MCR_{avg}}\right]^{\frac{1}{3}}}$$ **(9)** with power limitation

Where,

$\boldsymbol{V_{ref,avg}}$ is a statistical mean of distribution of ship speed in given ship type and ship size, to be calculated as follows:

$$\boldsymbol{V_{ref,avg} = 11.0536 \times DWT^{0.05030}} \quad \boldsymbol{(10)}$$

$\boldsymbol{m_v}$ is a performance margin of a ship, which should be 5% of $\boldsymbol{V_{ref,avg}}$ or one (1) knot, whichever is lower; and

$\boldsymbol{MCR_{avg}}$ is a statistical mean of distribution of MCRs for main engines in given ship type and ship size, to be calculated as follows:

$$\boldsymbol{MCR_{avg} = 20.7096 \times DWT^{0.63477}} \quad \boldsymbol{(11)}$$

The above equations 10 and 11 are derived from MEPC.350(78) 2022 Guidelines On The Method Of Calculation Of The Attained Energy Efficiency Existing Ship Index (EEXI). [23]

When the power of the ship's engine is reduced, the power, namely MCRlim, is reduced. The MCRlim is calculated iteratively, with a reduction factor Rf (Rf < 1) applied to the recorded MCR until the Attained EEXI is less than or equal to the Required EEXI.

3.4 Flow Chart for iterative calculation of the Attained EEXI

Based on the chapter 3.3 and the detailed described steps for the determination of the necessary values for the calculation of the Attained EEXI, the presented flow diagram depicts all the steps for easier identification.

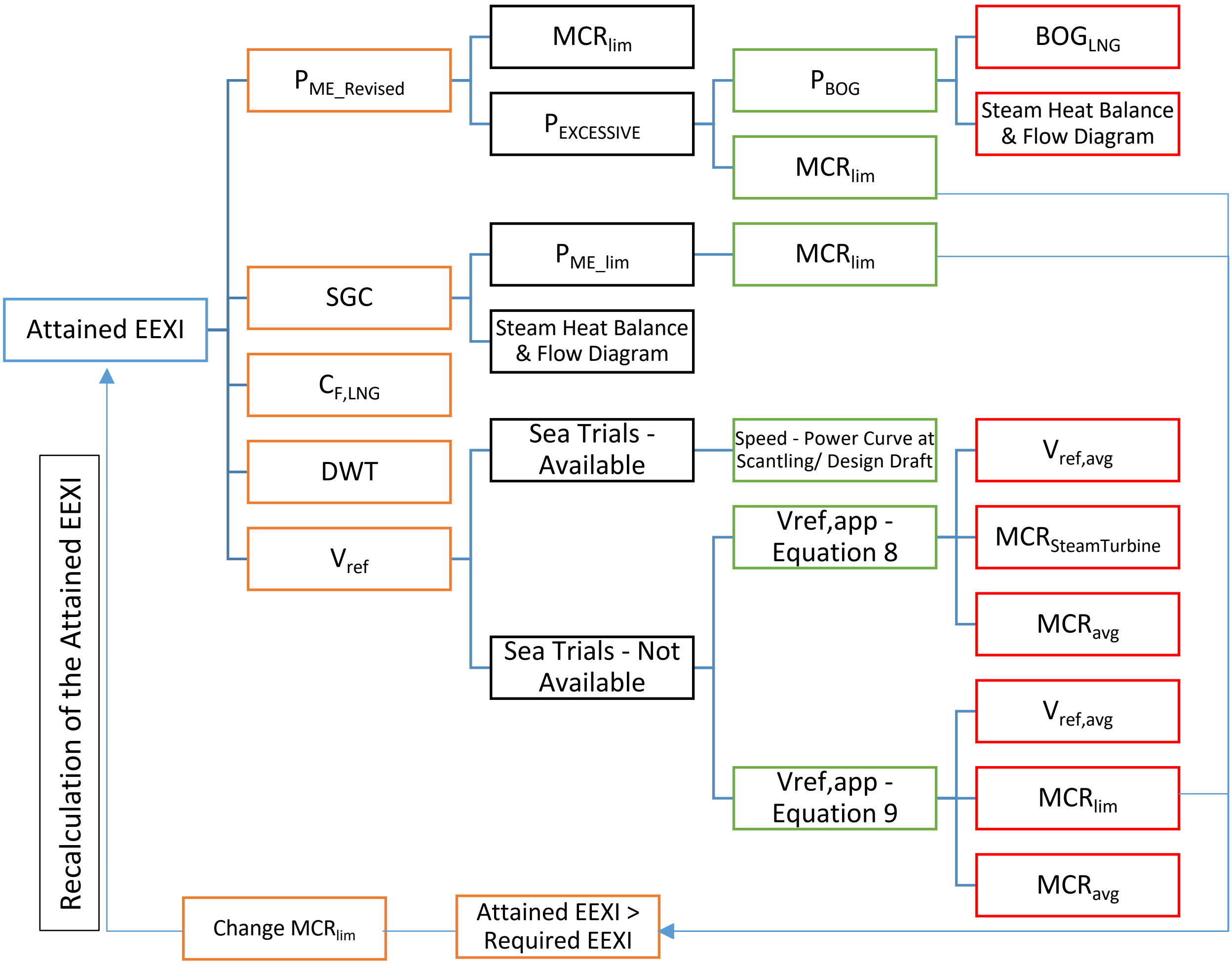

Figure 17: Flow Chart for the calculation of the Attained EEXI for LNG Steam Turbine vessels

From the above analysis, the term of MCRlim is the most important since the selection of this limited Maximum Continous Rating of the vessel difines the majority of other values and affects the final calculation of the attained EEXI of the vessel. In this stage to empahsise that this calculation is an iterative method in which the limited MCR is a reducted percentage of the initial MCR of the vessel. This method finalizes only when the attained EEXI equals the required EEXI (equation 2 equals equation 4).

4. Calculation of Carbon Intensity Indicator (CII) for Steam-Turbine LNG Carriers

The International Maritime Organisation is a United Nations institution that adopts and develops legislation to promote safe, secure, and pollution-free international shipping.

One of its objectives is to ensure that international shipping takes active steps to meet UN Sustainable Development Goal (SDG) targets.

These safeguards ensure that the oceans, seas, and other marine resources are used in a sustainable manner.

The Marine Environment Protection Committee (MEPC) advises the maritime community on environmental issues under the remit of the IMO. The MEPC focused on greenhouse gas issues at its 62nd session in July 2011, introducing the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

The CII is an essential component of the SEEMP. As we are in 2023, it is critical for ship owners, ship managers, and every seafarer to comprehend the CII.

It is made required under MARPOL Annex VI and goes into effect in 2023.

The CII calculations for all cargo, RoPax, and cruise ships with more than 5000 gross tonnes (GT) that trade internationally must begin by 2023, with the first report due to the IMO no later than March 31, 2024. [24]

4.1 Defining the term of Carbon Intensity Indicator (CII)

The abbreviation CII stands for Carbon Intensity Indicator, and here is what it signifies in three brief sentences [24]:

1. The Carbon Intensity Indicator (CII) calculates a ship's polluting capacity. It compares the carbon footprint of a ship to the advantages it delivers to society by transporting products by sea.
2. Larger ships emit more pollution, but they also carry more goods. As a result, the CII can provide a reasonable assessment of a ship's air pollution potential regardless of size or propulsion type.
3. The CII rating is divided into five categories: A, B, C, D, and E. As we progress from A to E, the vessel's efficiency falls. We have a range of CII rating values inside each grade. A vessel, for example, may be on the better or worse side of the C rating. Vessels with D rating for three years or E rating must improve their score.

4.2 Calculation of the Attained CII [25]

According the MEPC.352(78) - 2022 Guidelines On Operational Carbon Intensity Indicators And The Calculation Methods (CII Guidelines, G1), the ratio of the total mass of CO_2 (M) emitted to the total amount of transport work (W) completed in a particular calendar year is used to determine the Attained Annual Operational CII of a ship.

$$\boldsymbol{Attained\ CII_{ship} = \frac{M}{W}} \quad (12)$$

- **Mass of CO_2 Emissions:**

The total mass of CO_2 is calculated as the sum of CO2 emissions (in grams) from all fuel oil consumed on board a ship in a given calendar year, as follows:

$$\boldsymbol{M = FC_j \times C_{F_j}} \quad (13)$$

Where,

$\boldsymbol{j}$ is the fuel oil type;

$\boldsymbol{FC_j}$ is the total mass of CO_2 in grams of the consumed fuel oil of type $\boldsymbol{j}$ in the calendar year, as reported under IMO DCS; and

$\boldsymbol{C_{F_j}}$ represents the fuel oil mass to CO2 mass conversion factor for fuel oil type.

- **Transport Work:**

In the lack of actual transport work data, supply-based transport work (Ws) can be used as a proxy, which is defined as the product of a ship's capacity and distance traveled in a given calendar year, as follows:

$$\boldsymbol{W_s = C \times D_t} \quad (14)$$

Where,

$\boldsymbol{C}$ is the vessel's capacity;

For bulk carriers, tankers, container ships, gas carriers, LNG carriers, general cargo ships, refrigerated cargo carrier and combination carriers, deadweight tonnage (DWT) should be used as Capacity;

For cruise passenger ships, ro-ro cargo ships (vehicle carriers), ro-ro cargo ships and ro-ro passenger ships, gross tonnage (GT) should be used as Capacity; and

$\boldsymbol{D_t}$ represents the total distance travelled (in nautical miles), as reported under IMO DCS.

4.3 Calculation of the Required CII

According the MEPC.353(78) - Guidelines on the Reference Lines For Use with Operational Carbon Intensity Indicators (CII Reference Lines Guidelines, G2), the first step is to calculate the CII reference value:

$$\boldsymbol{CII_{ref} = aCapacity^{-c}} \quad \textbf{(15)}$$

The above presented $\boldsymbol{CII_{ref}}$ is the reference value for the calendar year of 2019, the term "Capacity" is specified based on the different ship type as the Deadweight or the Gross tonnage of the vessel (see par. 4.2) and a and c parameters are as follows:

Ship Type		Capacity	a	c
LNG Carrier	DWT > = 100,000	DWT	9.827	0.000
	65,000 = < DWT < 100,000	DWT	14479E10	2.673
	DWT < 65,000	DWT	14779E10	2.673

Table 9: Parameters for determining the 2019 reference CII for LNG Carrier [26]

After the calculation of the reference CII for the calendar year of 2019, the Required Annual Operational CII is calculated as per the below formula:

$$\boldsymbol{Required\ CII = \left(1 - \frac{z}{100}\right) \times CII_{ref}} \quad \textbf{(16)}$$

$\boldsymbol{z}$ is the reduction factors of the required annual operational CII for the calendar years of 2023 to 2026, which are presented in table 10.

Year	Reduction Factor (z)
2023	5%
2024	7%
2025	9%
2026	11%

Table 10: Reduction factor (z %) for the CII for years 2023 to 2026 [27]

$\boldsymbol{z}$ reduction factors (%) for years 2027 to 2030 are to be further strengthened and are to be released in the future.

4.4 Carbon Intensity Indicator (CII) Rating

The CII has a rating system in place to grade ships based on how much air pollution they emit. Such cargo and passenger vessel grading can assist us in distinguishing more efficient vessels from less efficient ones.

This enables us to create incentives for higher-performing vessels, encouraging more and more vessels to strive for higher ratings. These incentives will be provided by the administration, port facilities, and other stakeholders.

A to E ratings are classified as follows:

A – Major superior performance level

B – Minor superior performance level

C – Moderate performance level

D – Minor Inferior performance level

E – Inferior performance level

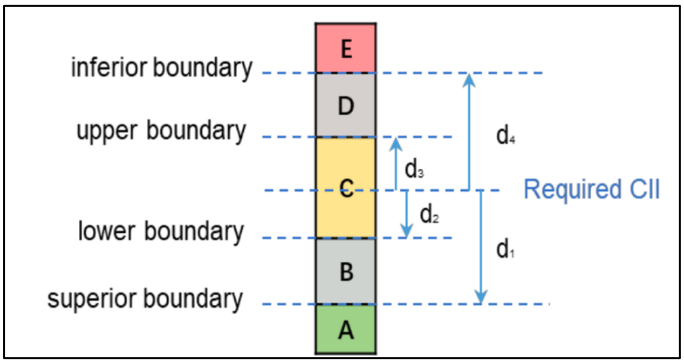

Figure 18: Rating Boundaries of the CII

All vessels must strive to be C-rated. The rating will be kept on file in the Ship Energy Efficiency Management Plan (SEEMP).

Based on the above, the four boundaries (inferior, upper, lower and superior) of an LNG Carrier can be identified comparing the ratio of the Attained CII with the Required CII with the following vectors as presented in the below table 11.

Ship Type	a	d1	d2	d3	d4
LNG Carrier	DWT > = 100,000	0.89	0.98	1.06	1.13
	DWT < 100,000	0.78	0.92	1.10	1.37

Table 11: dd vectors for determining the rating boundaries of LNG Carriers [28]

For easier identification of an LNG Carrier's CII rating the below diagrams can be utilized after the calculation of the ratio:

$$\boldsymbol{CII\ Ratio} = \frac{\boldsymbol{Attained\ CII}}{\boldsymbol{Required\ CII}} \quad (17)$$

- **For deadweight >= 100,000:**

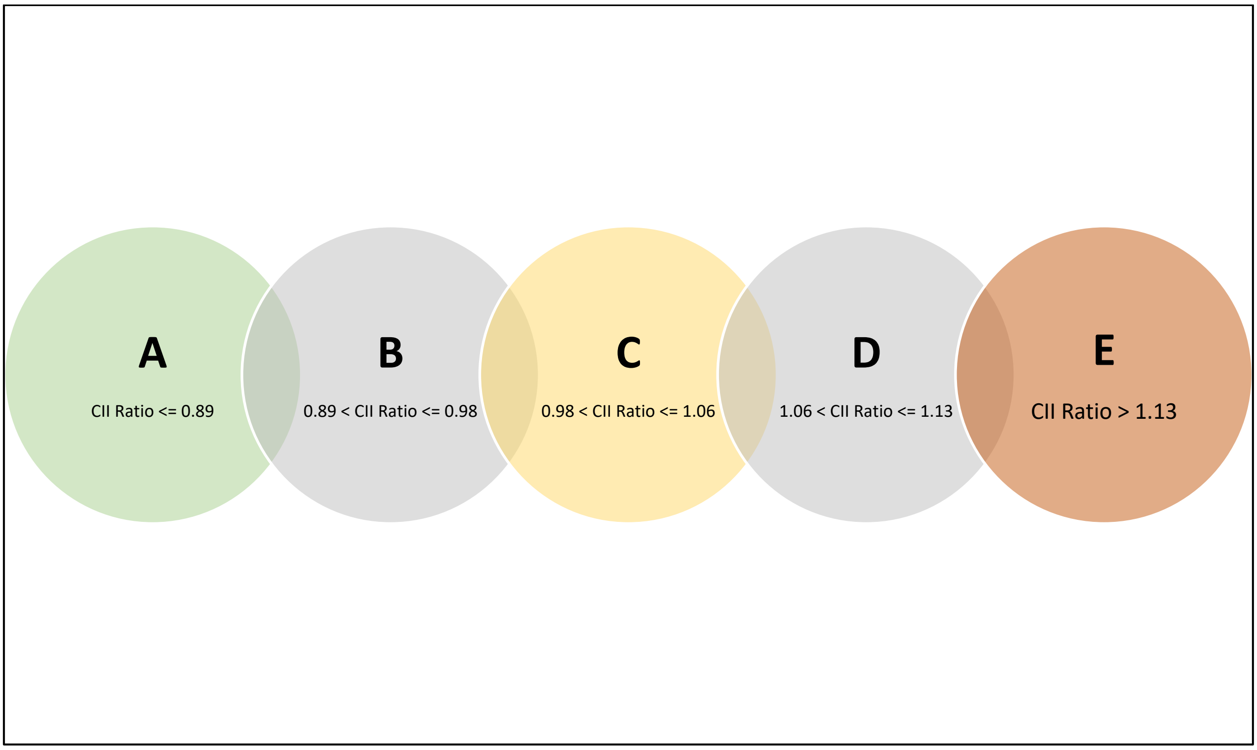

Figure 19: CII Rating based on CII Ratio for LNG Carriers with DWT >= 100,000

- **For deadweight < 100,000**

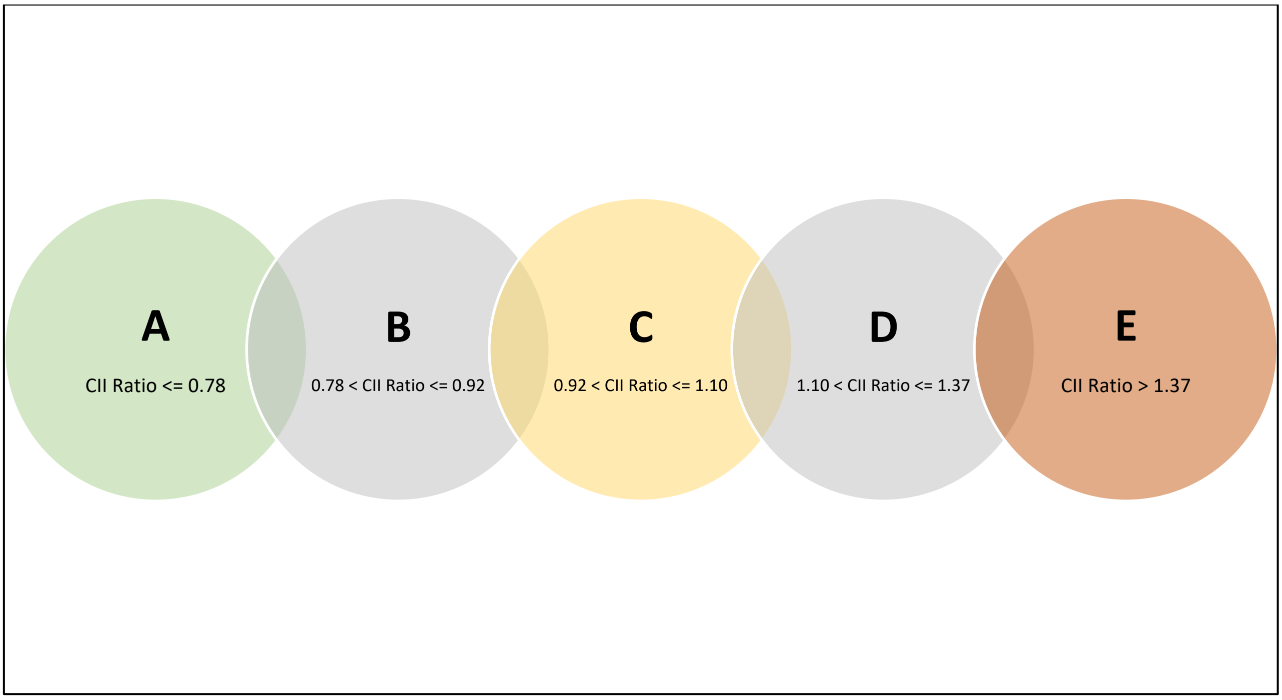

Figure 20: CII Rating based on CII Ratio for LNG Carriers with DWT < 100,000

5. Case Studies

This study presents the calculation of the Attained/ Required EEXI and CII for two Steam Turbine LNG Carriers. For confidentiality reasons, the vessels are named as Ship A and Ship B and the main particulars of them are shown in the below table 12.

Particulars	Ship A	Ship B
Ship Type	**LNG Carrier**	**LNG Carrier**
Shipbuilder	Daewoo Shipbuilding & Marine Engineering Co., Ltd	Daewoo Shipbuilding & Marine Engineering Co., Ltd
Year of Delivery	2003	2004
LOA (m)	279.8	285.4
LBP (m)	268.8	276.8
B (m)	43.3	43.4
D (m)	26.0	26.0
Design Draft (m)	11.5	11.5
Scantling Draft (m)	12.5	12.5
LWT (tons)	30,105.9	30,849.0
DWT Scantling (tons)	74,893.6	79,664.4
Propulsion System	Marine Steam Turbine	Marine Steam Turbine
Steam Turbine MCR (kW)	23,830.0	27,066
No. of the installed A/Es	2	1
A/E MCR (kW)	1,800.0	3,680

Table 12: Main Particulars of Ship A and Ship B

All the calculations are made using the Excel based tool developed in the framewotk of this master thesis. The presentation of the usage of this tool is presented in Appendix A.

5.1 EEXI and Engine Power Limitation Calculation

In this section, calculation of the required and the attained EEXI is presented for Ship A and Ship B.

- **SHIP A**

According to the developed tool the attained and required EEXI are as follows:

Based on equation (3) as presented in section 3.2:

$$\boldsymbol{Attained\ EEXI = 10.02\ \frac{gCO_2}{ton * mile}}$$

Based on equation (2), as presented in section 3.1:

$$\boldsymbol{Required\ EEXI = 7.72\ \frac{gCO_2}{ton * mile}}$$

It can be easily noticed that the A. EEXI is higher than the R. EEXI and as a consequence measures are to be taken for compliance of the vessel. The easiest way to comply with the required EEXI is the reduction of the Maximum continuous Rating of vessel's Main Engine. In our case, the reduction of the Steam Turbine maximum power is the way the attained to reach the required EEXI.

The method used for the calculation of the limitation of the vessel is presented in section 3.4 as the flow chart indicates.

The final reduction of vessel's total power is 28.5% and the limited MCR equals 17,036.4 kW.

Finally , $\boldsymbol{Attained\ EEXI = Required\ EEXI = 7,72\ \frac{gCO_2}{ton*mile}}$

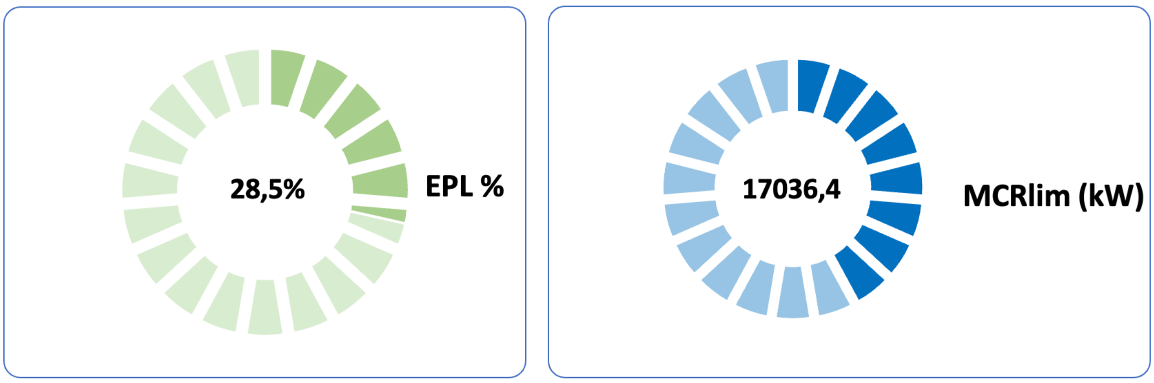

Figure 21: EEXI Results of Ship A

In this case study is necessary to note that the Sea trial report is not available in vessel's records. This led us to calculate the reference vessel's speed using approximate statistical models for this specific ship type which is more conservative approach than using the actual sea trials data of the vessel. Calculations for Ship B highlighs this point.

- **SHIP B**

According to the developed tool the attained and required EEXI are as follows:

Based on equation (3) as presented in section 3.2:

$$\boldsymbol{Attained\ EEXI = 8.43\ \frac{gCO_2}{ton * mile}}$$

Based on equation (2), as presented in section 3.1:

$$\boldsymbol{Required\ EEXI = 7.50\ \frac{gCO_2}{ton * mile}}$$

It can be easily noticed that the A. EEXI is higher than the R. EEXI and as a consequence measures are to be taken for compliance of the vessel. The easiest way to comply with the required EEXI is the reduction of the Maximum continuous Rating of vessel's Main Engine. In our case, the reduction of the Steam Turbine maximum power is the way the attained to reach the required EEXI.

The method used for the calculation of the limitation of the vessel is presented in section 3.4 as the flow chart indicates.

The final reduction of vessel's total power is 20.5% and the limited MCR equals 21,519.6 kW.

Finally , $\boldsymbol{Attained\ EEXI = Required\ EEXI = 7,50\ \frac{gCO_2}{ton*mile}}$

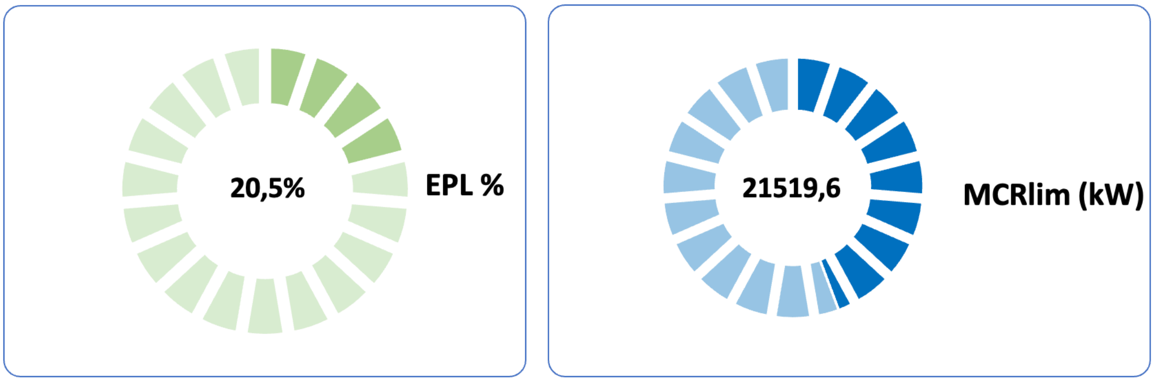

Figure 22: EEXI Results of Ship B

Comparing the above 2 results, it can be easily noticed that using the Sea Trials power curve at design draft in this case, the result is 8% better than using the approximate vessel's speed which is based on statistical values. Generally, it can be said that the more vessel specific information you have, the better result can be attained in terms of engine power limitation and EEXI.

5.2 CII Calculation

As per chapter 4 of this thesis, the calculation of the attained and required CII is presented for Ship A and Ship B using the IMO-DCS data for year 2022.

- **SHIP A**

According to the developed tool the attained and required CII are as follows:

Based on equation (12) as presented in section 4.2:

$$\boldsymbol{Attained\ CII = 13.82\ \frac{gCO_2}{ton * mile}}$$

Based on equation (16), as presented in section 4.3:

Year	Required CII	CII Rating
2023	12,85	C
2024	12,58	C
2025	12,31	D
2026	12,04	D

Table 13: Required CII and CII rating per year from 2023-2026

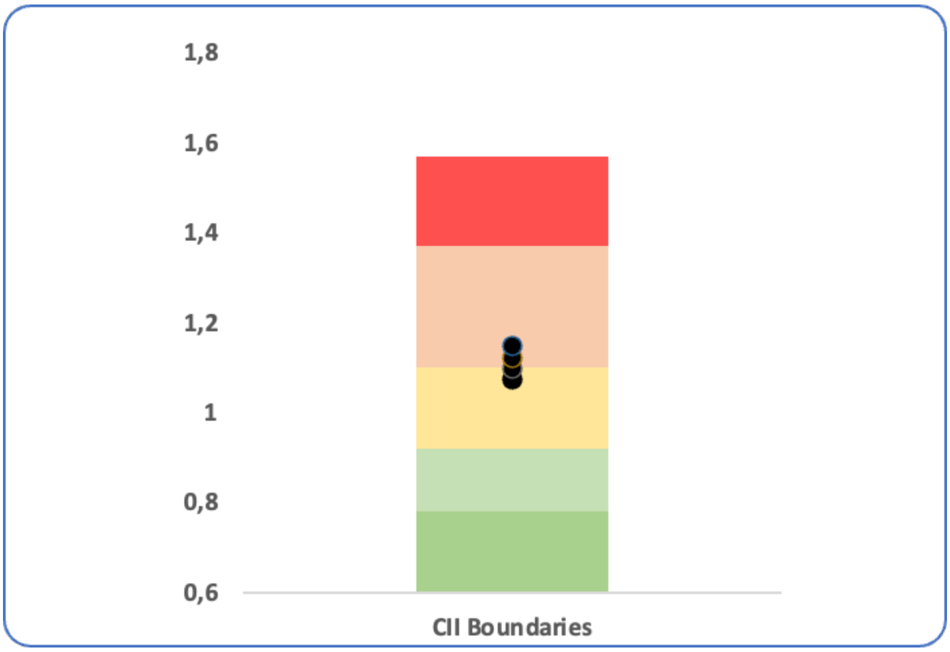

Figure 23: CII rating for years 2023 to 2026

From the above table 13, it is noted that Ship A must take actions to improve the CII rating in year 2024 since the CII rating is D based on the operational profile of 2022, which used as a baseline. In this case, the vessel can improve her rating by:

1. Changing the operational profile of the vessel (route, no. of ballast/ laden voyages) or;
2. Selecting improving technical/ operational measures for the reduction of the fuel consumption.

- **SHIP B**

According to the developed tool the attained and required CII are as follows:

Based on equation (12) as presented in section 4.2:

$$\boldsymbol{Attained\ CII = 12.97\ \frac{gCO_2}{ton * mile}}$$

Based on equation (16), as presented in section 4.3:

Year	Required CII	CII Rating
2023	10,90	D
2024	10,67	D
2025	10,44	D
2026	10,21	D

Table 14: Required CII and CII rating per year from 2023-2026

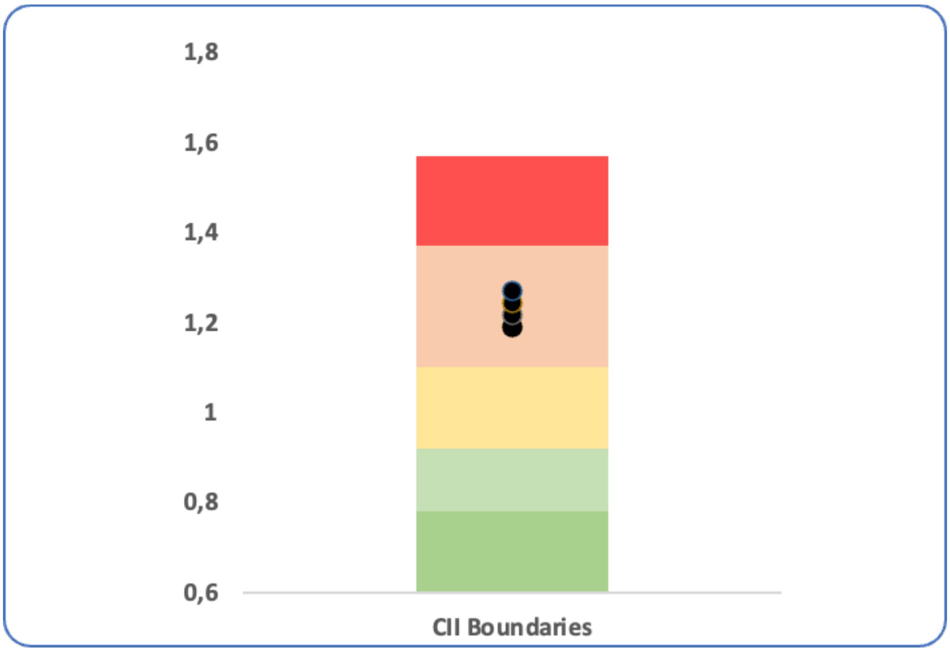

Figure 24: CII rating for years 2023 to 2026

From the above table 14, it is noted that Ship B must take actions immediately to improve the attained CII since the CII rating is D during years 2023-2026 based on the operational profile of 2022, which used as a baseline. In this case, the vessel is to study all the available options which improves the CII rating during 2023. These options that can improve her rating are:

1. Changing the operational profile of the vessel (route, no. of ballast/ laden voyages) or;
2. Selecting improving technical/ operational measures for the reduction of the fuel consumption.

6. Discussion

In this chapter are presented the basic outputs of this thesis and the further research that can be arised from this study.

6.1 Conclusions

To begin with, the type of the vessel which is studied is the Steam Turbine LNG Carrier. This vessel type is selected due to high fuel consumption and the obvious need for this ship type to become energy efficient reducing the fuel in use.

In order to reduce the fuel consumption of a vessel, there is a need to identify the most energy intensive systems. This identification can be done utilizing the so called Sankey diagrams, which are detailed described in chapter 2. Actually, a Sankey diagram depicts the energy flow of the fuel among the machinery items of the ship at different conditions. The examined conditions are the Sea Going condition and the condition of the ship at Port stay.

- **Normal Sea Going Condition**

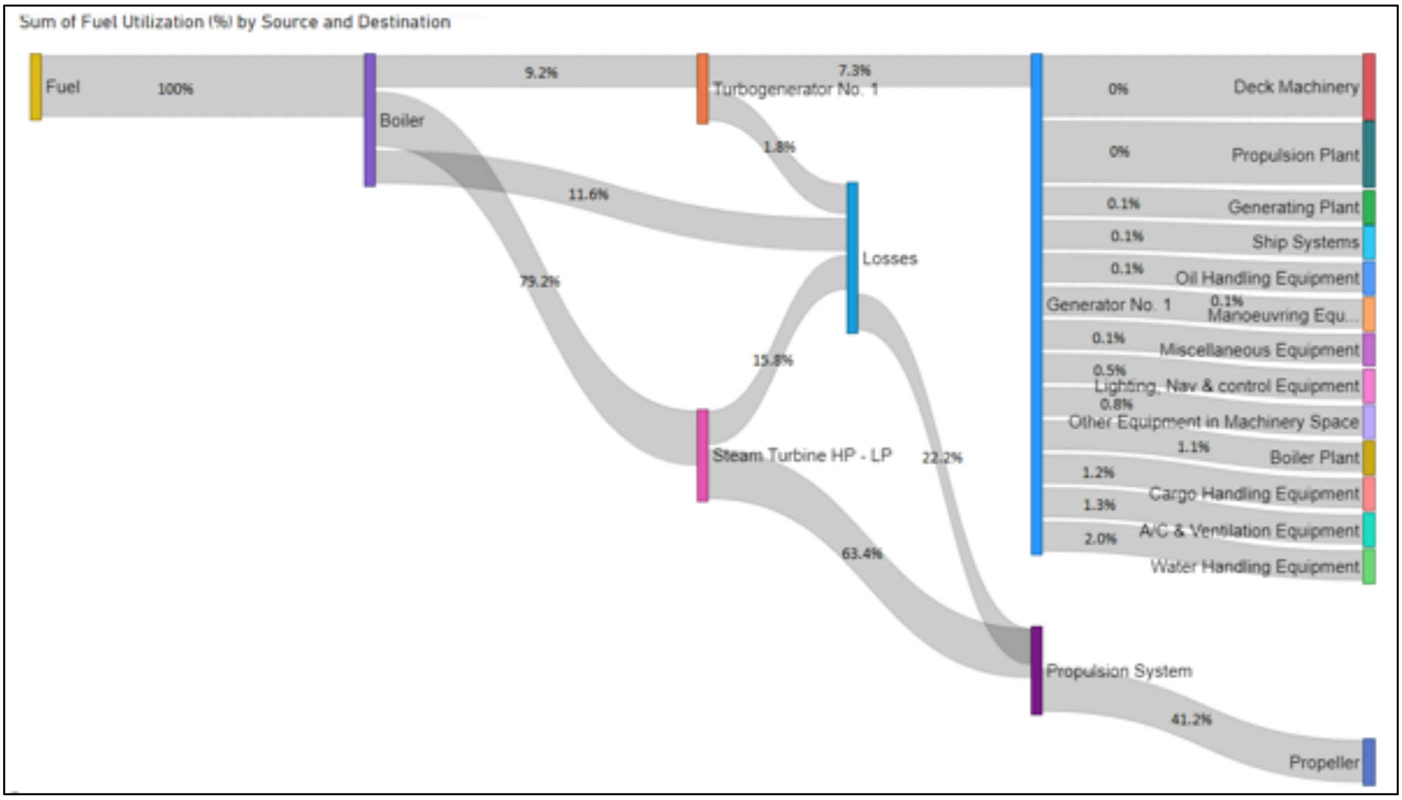

Figure 25: Sankey Diagram at Normal Sea Going

Source	Destination	Fuel Utilization (%)
Fuel	Boiler	100,0%
Boiler	Losses	11,6%
Boiler	Steam Turbine HP - LP	79,2%
Steam Turbine HP - LP	Propulsion System	63,4%
Steam Turbine HP - LP	Losses	15,8%
Boiler	Turbogenerator No. 1	9,2%
Turbogenerator No. 1	Losses	1,8%
Turbogenerator No. 1	Generator No. 1	7,3%
Propulsion System	Propeller	41,2%
Propulsion System	Losses	22,2%

Table 15: Fuel Utilization Percentages and Energy Flow at Normal Sea Going Condition

In the above table the propeller efficiency was taken equal to 65% as a representative value for this study since the average age of this vessel type is around to 18 to 20 years.

Based on the above figure 25 and the presented values in table 15, the energy consuming parts of the vessel are categorized in declining order regarding energy losses as follows:

- Propeller → 22,2%
- Steam Turbine HP-LP → 15,8%
- Boiler → 11,6%
- Turbogenerator No.1 → 1,8%

- **Port Condition**

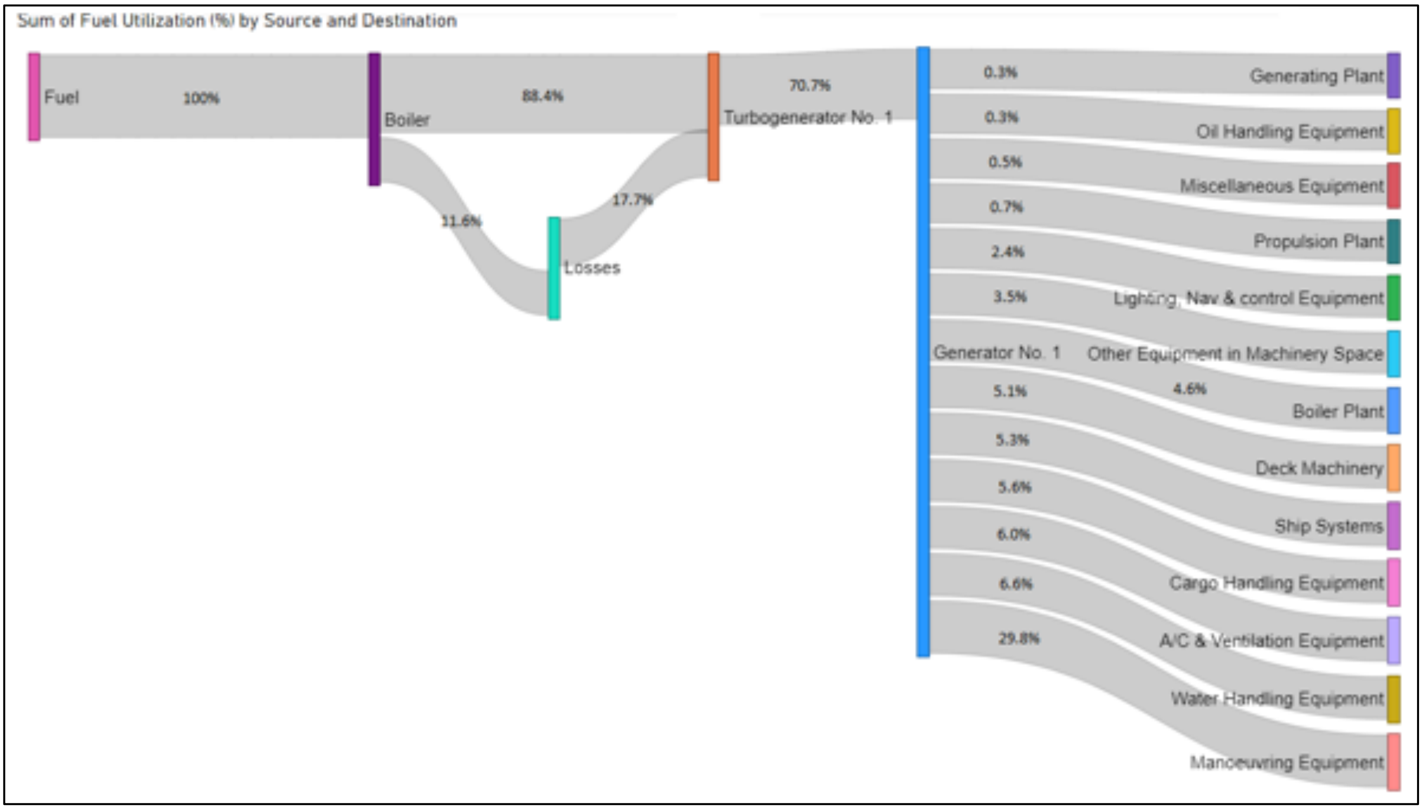

Figure 26: Fuel Utilization Percentages and Energy Flow at Port Condition

Source	Destination	Fuel Utilization (%)
Fuel	**Boiler**	**100,0%**
Boiler	Losses	11,6%
Boiler	Turbogenerator No. 1	88,4%
Turbogenerator No. 1	Losses	17,7%
Turbogenerator No. 1	Generator No. 1	70,7%
Generator No. 1	Propulsion Plant	0,7%
Generator No. 1	Generating Plant	0,3%
Generator No. 1	Water Handling Equipment	6,6%
Generator No. 1	Oil Handling Equipment	0,3%

Generator No. 1	Boiler Plant	4,6%
Generator No. 1	Other Equipment in Machinery Space	3,5%
Generator No. 1	Cargo Handling Equipment	5,6%
Generator No. 1	Ship Systems	5,3%
Generator No. 1	Manoeuvring Equipment	29,8%
Generator No. 1	Deck Machinery	5,1%
Generator No. 1	A/C & Ventilation Equipment	6,0%
Generator No. 1	Miscellaneous Equipment	0,5%
Generator No. 1	Lighting, Nav & control Equipment	2,4%

Table 16: Fuel Utilization Percentages and Energy Flow at Normal Port Condition

Based on the above figure 26 and the presented values in table 16, the energy consuming parts of the vessel are categorized in declining order as follows:

- Maneuvering Equipment → 29,8%
- Turbogenerator No.1 → 17,7%
- Boiler → 11,6%
- Water Handling Equipment → 6,6%
- A/C & Ventilation Equipment → 6,0%
- Cargo Handling Equipment → 5,6%
- Ship Systems → 5,3%
- Deck Machinery → 5,1%
- Boiler Plant → 4,6%
- Other Equipment in Machinery Space → 3,5%
- Lighting, Nav & control Equipment → 2,4%
- Propulsion Plant → 0,7%
- Miscellaneous Equipment → 0,5%
- Oil Handling Equipment → 0,3%
- Generating Plant → 0,3%

In both conditions, special focus is to be given in the most energy consuming parts examining ways to improve their efficiency.

The second part of this thesis presents case studies for the calculation of EEXI and CII of two Steam Turbine LNG Carriers.

	Ship A	Ship B
Required EEXI	7,72	7,50
Attained EEXI (Before EPL)	10,02	8,43
Attained EEXI (After EPL)	7,72	7,50
Initial MCR (kW)	23,830.0	27,066
Limited MCR (kW)	17,036.4	21,519.6
Engine Power Limitation (%)	28,5%	20,5%
Deadweight (MT)	74,893.6	79,664.4
Distance Travelled (kn)	93,625.49	105,898.79
Fuel Type (Diesel/ LFO/ HFO/ LNG)[3]	65.2/ 93.9/ 14828.4/ 18258.8	14.3/ 121.6/ 16970.3/ 20420.1
Attained CII	13,82	12,97
Required CII – 2023	12,85	10,90
Required CII – 2024	12,58	10,67
Required CII – 2025	12,31	10,44
Required CII – 2026	12,04	10,21
CII Rating - 2023	C	D
CII Rating – 2024	C	D
CII Rating – 2025	D	D
CII Rating - 2026	D	D

Table 17: Summary Table (EEXI, CII) of Ship A & B

Table 17 shows the required and the attained EEXI and CII of two similar vessels. It can be easily noticed that the Engine Power Limitation (EPL) is lower for Ship B than Ship A. The reason why there is such a difference, is the calculation of the reference vessel's speed of Ship B due to the fact that the Sea Trial report is available. The existence of the Sea Trial report gives the opportunity to calculate vessel's speed utilizing the most representative condition of the vessel instead of using the statistical equation that the EEXI Guidelines

[3] Data based on IMO-DCS reported values of year 2022.

presents in the absence of sea trials details. As a conclusion, the calculation of the attained EEXI of a ship is closer to required EEXI than using the ship specific details (such as the ship specific fuel oil consumption, sea trials etc.) instead of using the proposed generalized data in case of lack of information.

The calculation of the attained and the required CII depends on the reported IMO-DCS data of any previous year starting from 2022. As the required CII values are already known for years 2023 to 2026, then each company should well organize vessel’s schedule and operation since the two main factors are the travelled distance and the consumed fuel.

For the factor of travelled distance each company should organize the annual schedule of the vessel which seems to be significantly difficult since the shipping sector is easily changeable.

The consumed fuel is more feasible factor to be adjusted since an LNG Carrier can use more LNG as a fuel which emits lower CO_2 because of the lower carbon content of it (0.75) compared to standard marine fuels (HFO or MDO). Furthermore, alternative fuels may be examined as the main or secondary source of propulsion such as methanol, ethanol or others which have even lower carbon content and as a consequence lower CO_2 emissions.

6.2 Further Research

As a future work, proposals regarding the examination of the available technologies for the improvement of vessel’s efficiency can be done. More specifically, each one of the machinery components, for which the energy flows and losses are presented in chapter 2, can be examined for energy utilization improvement.

Appendix A: Presentation of the Calculator - Excel Based Tool

In this section is presented the basic manual for the usage of the developed Excel Based Tool for the calculation of the attained and required EEXI and CII.

All the input values are inserted in the first tab of the tool. The name of the tab is "Inputs" for easy identification. The tool has 3 different sections which are to be filled out with data. These sections are presented below:

- **LNG Carrier Fuel Consumption Data at Sea Going and Port Condition**

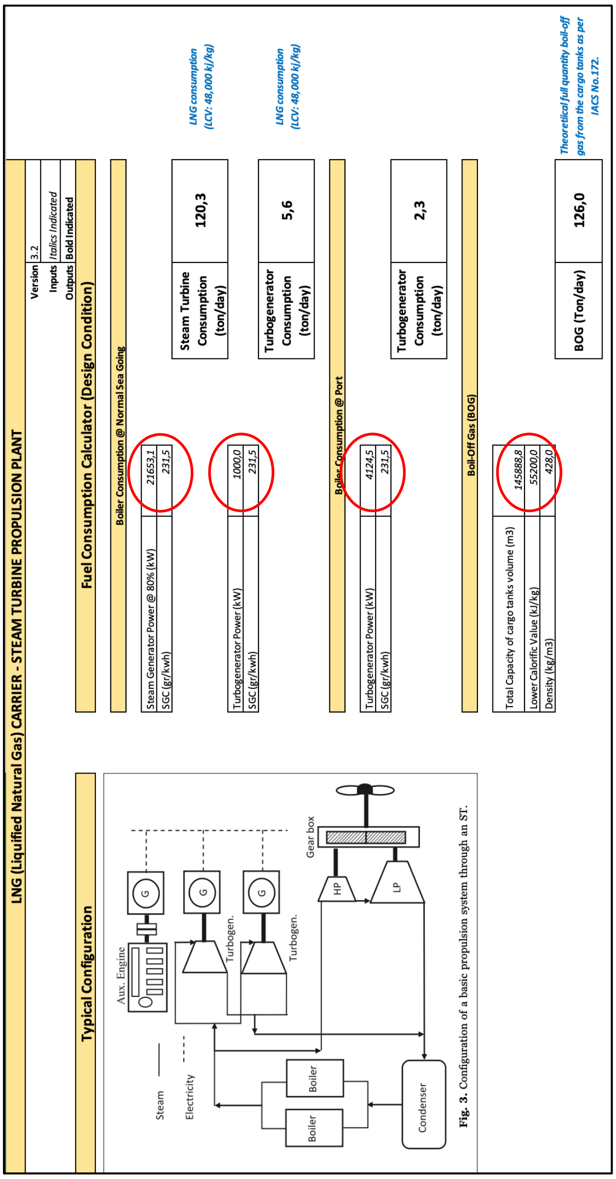

Figure 27: LNG Carrier Fuel Consumption Data at Sea Going and Port Condition

All the indicated as input values in the red circles can be found in vessel's Steam Heat Balance and Flow Diagram.

- **EEXI Calculator Inputs**

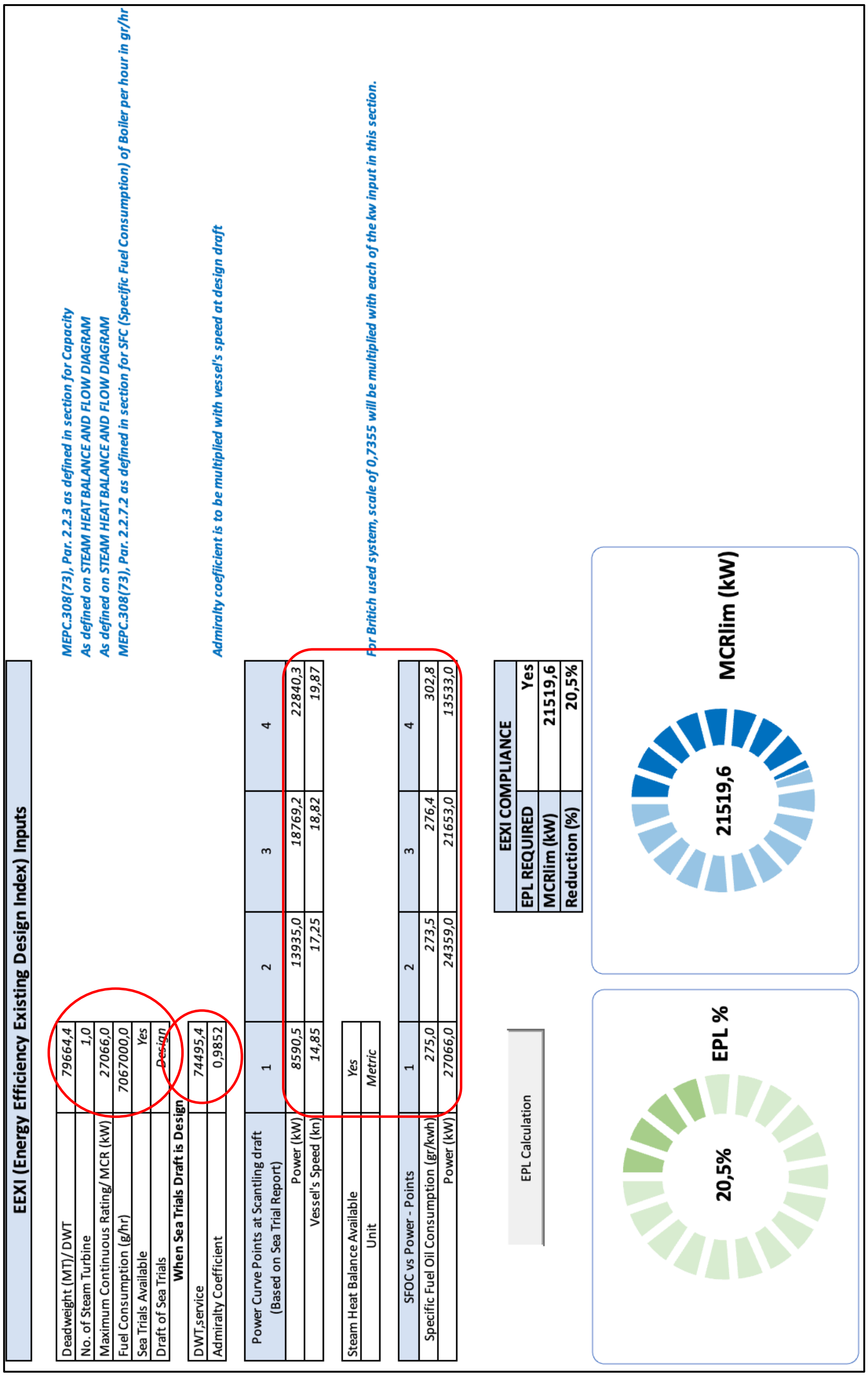

Figure 28: EEXI Calculator Inputs

All the indicated as input values in the red circles and boxes can be found in vessel's Trim and Stability Booklet, Sea Trial Report and Steam Heat Balance and Flow Diagram.

After filling all the cells with the correct values pushing the button "EPL Calculation" will automated calculated the limted Power in which vessel's propulsion system will be limited and the power reduction as percentage.

- **CII Calculator Inputs**

Carbon Intensity Indicator (CII) Inputs

Ship Particulars	
Deadweight (MT)/ DWT	79664,4
Distance Travelled (kn)	105898,79

Fuel Consumption (ton)	
Diesel/ Gas Oil	14,28
LFO	121,55
HFO	16970,3
LNG	20420,09
Methanol	0
Ethanol	0
LPG (Butane)	0
LPG (Propane)	0

CII Rating and Forecasting	
2023	D
2024	D
2025	D
2026	D

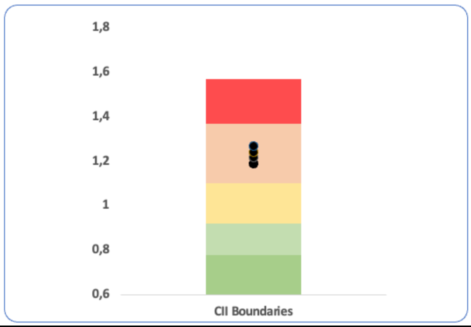

Figure 29: CII Calculator Inputs

All the data for the calculation for the CII calculator can be retrieved by the official IMO-DCS report of the vessel for the previous operating year.

Appendix B: Indicative Steam Heat Balance and Flow Diagram – Indicative Sea Trial Report

In this Appendix are indicated the most necessary vessel's documents for reference.

- **Steam Heat Balance and Flow Diagram**

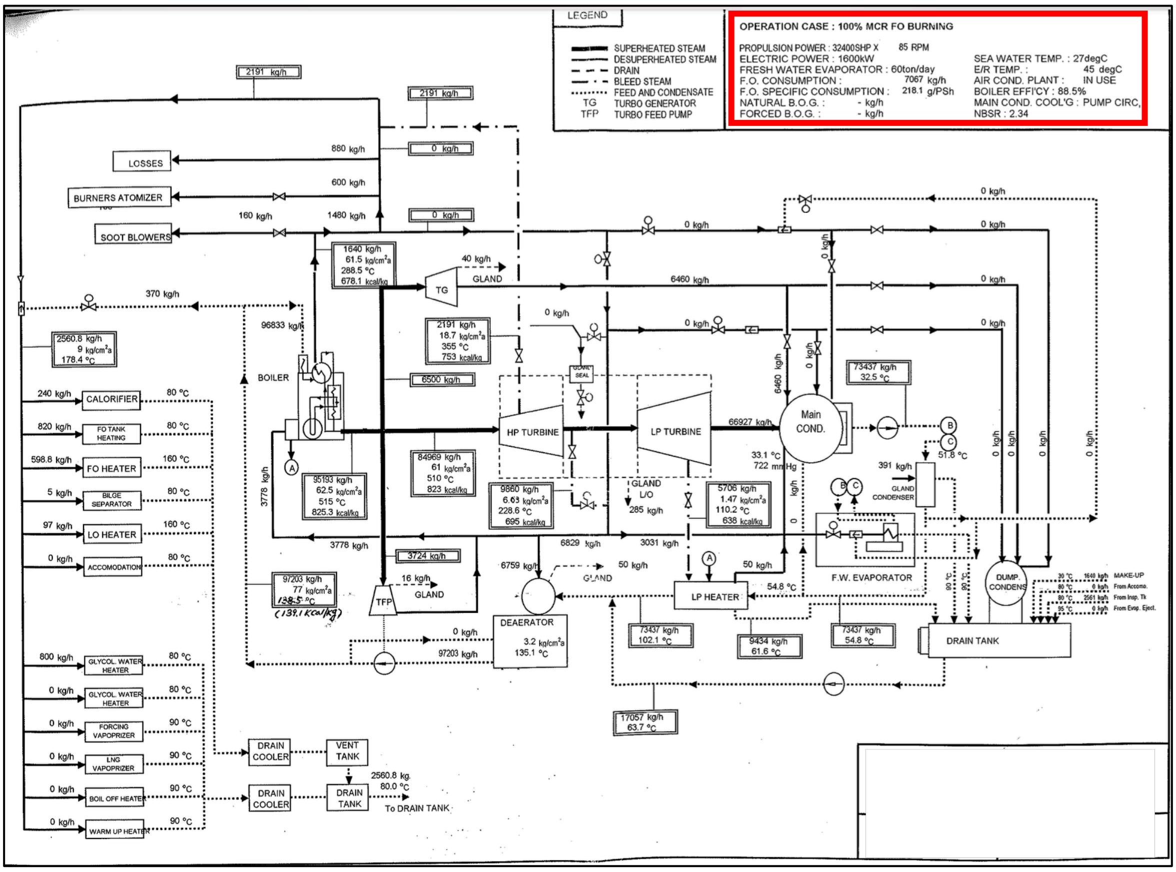

Figure 30: Indicative Steam Heat Balance and Flow Diagram

This document provides basic information regarding the specific fuel oil consumption of the vessel's main propulsion system at different engine settings. In the red box are shown these details for the main propulsion system of the ship.

- **Sea Trial Report**

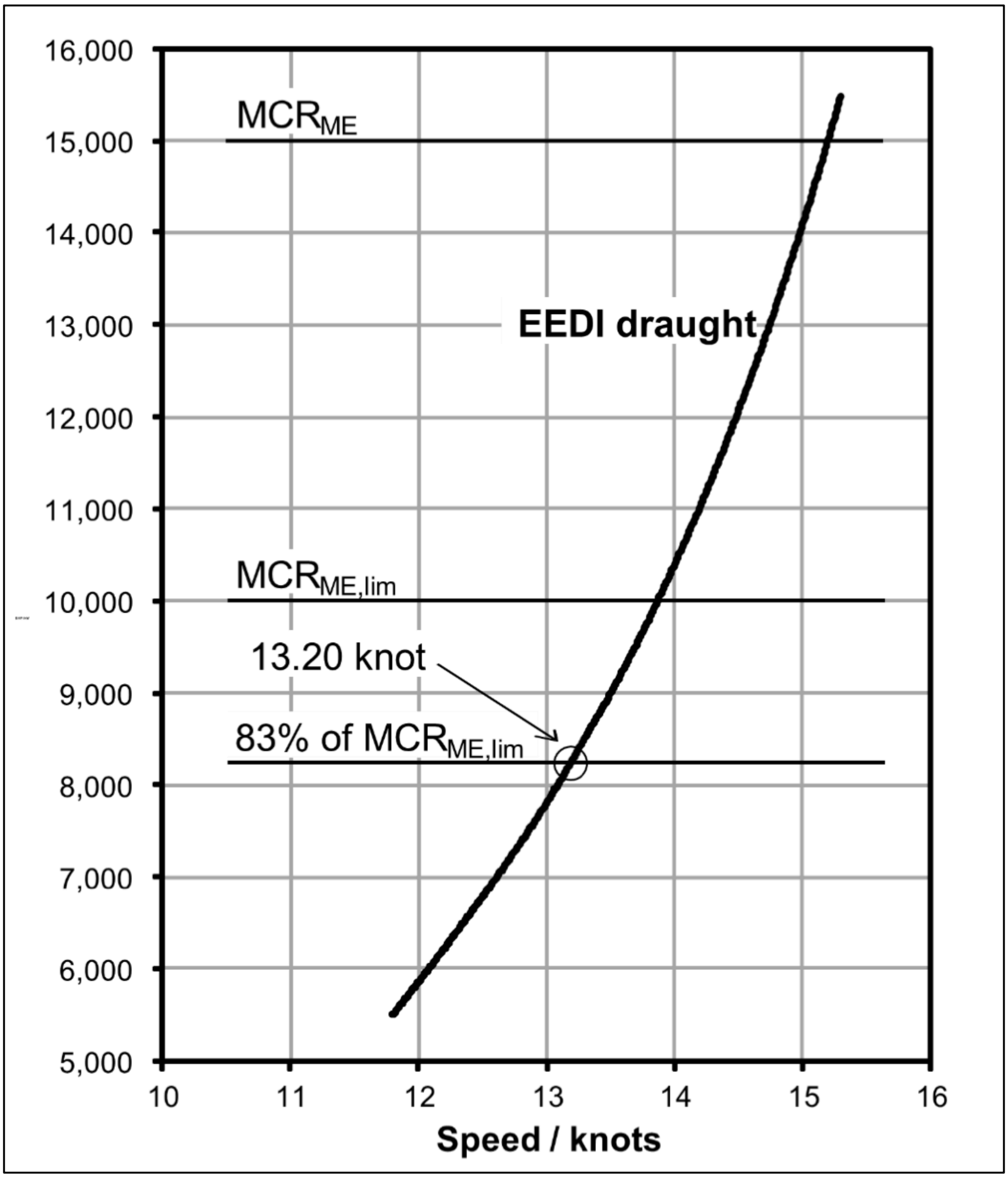

Figure 31: Indicative Sea Trial Report [29]

This document provides the information for the calculation of the reference vessel’s speed. More specifically, the sea trial report indicates the power curve at specific drafts of the vessel. As per the EEXI Guidelines, the power curve, which will be utilized, is to be at EEDI/ EEXI draft. In our case of LNG Carriers this draft is the scantling draft.

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