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Energy Use and Carbon Footprint Assessment in Retrofitting a Novel Energy Saving Device to a Ship

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Abstract: The Gate rudder system (GRS) was recently introduced as an innovative energy-saving device (ESD) for ships, and it is the most attractive ESD currently used in the market, with double figures of fuel savings in full-scale (>10–35%) compared with a ship with a conventional rudder system (CRS). Although there are few new ship applications of GRS, the recently completed EC-H2020 GATERS project successfully demonstrated its unique energy-saving and manoeuvrability benefits as a "retrofit" solution for an existing general cargo vessel for the first time. The project results suggested that the GRS holds significant potential for retrofitting existing ships to enhance fuel efficiency (~35%) and improve manoeuvrability. Nevertheless, the application was a comprehensive undertaking requiring various work tasks such as component manufacturing, removing existing systems, and modification and upgrading works, with substantial energy consumption and environmental impacts. Therefore, it was insightful to study energy use and environmental impacts in a GRS retrofit process. This study developed and implemented a comprehensive energy consumption and carbon footprint assessment framework for the GRS retrofit in the GATERS project. A detailed assessment of energy consumption and related carbon emissions was performed during the major stages of manufacturing, system removals, and modifications and assembly in the GRS retrofit. Also, the potential savings in energy use and emissions were addressed. The results demonstrated that the manufacturing stage was the most energy-intensive phase, being responsible for 91.4% of total electricity and 46.7% of fuel-based thermal energy use. The system removals accounted for 53.3% of the fuel-based thermal energy, whereas the modification and assembly work accounted for about 7.7% of the total electricity use. Additionally, various measures such as clean electrification, energy efficiency, mould/tool reuse, and component reuse to reduce the energy consumption and related carbon emissions in future GRS retrofit applications were addressed and discussed together with their reduction potentials.

Keywords: gate rudder system; GATERS; carbon footprint; energy consumption; energy-saving device; ship retrofitting; energy efficiency; GHG emissions; climate change

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1. Introduction

The shipping industry is one of the major contributors to global warming, accounting for 2% of all energy-associated emissions in 2021 [1]. Future projections by the International Maritime Organisation (IMO) show that emissions from shipping activities will increase and can reach up to 30% of their levels in 2008 by 2050 [2]. Consequently, it is imperative to reduce the carbon emissions from the ship activities in order to facilitate the transition to a net-zero economy [3]. The IMO established challenging targets for reducing GHG emissions under the initial IMO Strategy; the objective is to reduce the total GHG emissions from international shipping by a minimum of 50% by 2050 and 40% by 2030 in comparison with 2008 levels [2].

In line with the above, there are ever-increasing pressures on GHG emissions from waterborne transportation, and the shipping industry is currently confronted with the challenge of reducing emissions [4]. The task of reducing emissions from ship activities has been garnering significant attention. The cleaner solutions are considered the key for carbon-neutral shipping [5], and there is a rapid increase in low-carbon and innovative clean technologies [6]. A variety of technological solutions, ranging from new-built ships to existing ones, have been proposed [7]. One of the most effective solutions to reduce energy consumption and associated emissions is retrofitting existing ships with energy-saving technologies [8,9]. Retrofitting refers to the process of making modifications and upgrades to existing ships with the aim of improving their energy and environmental performance, whereby ships can comply with associated rules, regulations, and standards [8,10,11]. The adoption of retrofitting technologies can also provide shipowners with significant opportunities to reduce GHG emissions and other pollutants. In addition to compliance, retrofitting can enhance the competitiveness of shipping companies by reducing operational costs through improved energy efficiency [8]. This is particularly important because fuel costs account for 50–70% of a ship's overall operating costs, making it a significant cost element for shipping companies [12].

Nevertheless, there are a variety of risks that must be taken into account when retrofitting existing ships, including those related to technical, economic, and environmental factors [10]. While evaluating the environmental benefits of retrofitting applications, a life-cycle approach should be adopted, and it should be ensured that environmental benefits surpass any negative impacts throughout the manufacturing, operation, and disposal stages of the retrofitting [8]. Also, any uncertainties and risks related to the environmental impacts, such as energy use and carbon emissions throughout the manufacturing and retrofitting activities, should be well understood and considered during the strategic planning phase of any retrofitting projects. The activities in marine equipment manufacturing plants (MEMPs) where retrofitting equipment and devices are produced, as well as in shipyards where the retrofitting works are carried out, are highly energy-intensive [13]. Retrofitting activities, including the manufacturing of retrofitting technologies and devices, modifications to ships, and installation works, should be carried out with due consideration for energy use and associated emissions.

It is envisaged that about 35,000 ships will undertake retrofitting by 2056 [10]. Considering the fact that a significant number of vessels will undergo retrofits in the near future in parallel with increasing regulations and rising fuel costs, the workload in shipyards and MEMPs will increase, causing their energy use and associated environmental impact to rise. Similar to shipping companies, shipyards and MEMPs are currently facing pressure to reduce their energy use, environmental emissions, and energy costs. Reducing energy consumption in manufacturing and retrofitting activities can help shipyards and MEMPs increase their profitability and compliance with environmental rules and regulations. The overall reduction in energy costs in retrofitting activities can promote the application of retrofitting measures thanks to the lowered capital costs.

The first step towards effective management of energy and associated carbon emissions in retrofitting projects is to gain a comprehensive understanding of energy consumption within the retrofitting activities. Once energy consumption and emissions are mapped, appropriate measures and strategies can be put into action to manage energy consumption and efficiency, as well as associated emissions. Therefore, methods and tools for determining energy use and carbon emissions have become an important topic recently in various sectors [14].

This study makes a detailed assessment of the energy consumption and related carbon emissions of activities in a full-scale ship retrofitting project in which the GRS concept was applied as a retrofit solution for the first time. The GATE RUDDER® is an innovative rudder system in which the ship's rudder and propeller are arranged to act as an efficient energy-saving and manoeuvring device. In a GRS, there are two independently operated asymmetric rudder blades located on opposing sides of a ship's propeller, forming a twin rudder system with the functionality of a ducted propeller [7,15,16] (Figure 1a). The incorporation of a duct effect into the system through two rudder blades results in additional thrust from the blades by replacing the conventional rudder drag, hence enhancing propulsive efficiency and decreasing fuel consumption in comparison with the CRS [15]. The rudder blades of a GRS can be controlled independently, and this provides further steering ability to the ship to perform complex manoeuvres and motion control efficiently and, hence, more efficient navigation, particularly at slow speeds in coastal areas and harbours [7,15,16]. The GRS concept's first application was on a newly built 2400 GT container ship (Shigenobu) in 2017. It was found that the performance gain of Shigenobu with GRS (Figure 1a), compared with her sister ship Sakura with CRS (Figure 1b), was 14% in trials, while the performance in waves could be as high as 30% [15], together with other benefits such as excellent directional stability, reduced vibrations, cavitation, and underwater radiated noise [7].

Figure 1. Gate rudder system (GRS) (**a**)—Conventional rudder system (CRS) (**b**) (reproduced from [7], with permission from Elsevier, 2024).

The GRS' application as a retrofitting solution to existing ships has been successfully demonstrated on a target 90 m coastal general cargo vessel (MV ERGE) in the H2020 Innovation Action project GATERS through the application of a comprehensive GATE RUDDER® retrofit design option [16]. The project results demonstrated that the GRS retrofit reduced the fuel consumption and emission of the target vessel by around 20% per tonne nm, along with an attractive payback period of 3.7 years. Also, it was found that global maritime fuel consumption and emissions can be reduced by 10–15% if the entire world fleet is equipped with GRS propulsion systems [16]. The promising findings of the GATERS project suggested that the GRS retrofit holds a promising potential for future applications on existing ships.

Various technical aspects of GRS application, such as propulsive performance, fuel saving, manoeuvrability, etc., have been investigated by various studies (e.g., [7,17–24]). However, no study has been conducted on the energy consumption and environmental aspects of GRS retrofitting. Considering the implementation potential of GRS on existing ships as well as the energy-intensive nature of the required retrofitting activities, it is beneficial to study the energy consumption and associated environmental impacts of GRS retrofitting.

The aim of this study is, therefore, to provide a comprehensive understanding of energy use and associated carbon footprints in GRS retrofit through a comprehensive methodology framework. A comprehensive assessment is carried out to analyse the energy consumption and related GHG emissions connected with the processes during the manufacturing, system removals, modifications, and assembly stages of the GRS retrofit application for the target vessel. The energy use and consumption, as well as associated carbon emissions in each retrofit stage and process, are determined, along with a discussion of the reduction potentials.

This study is unique in the relevant literature, providing insights and results into energy usage, corresponding GHG emission, and related parameters in retrofitting an ESD to a ship through a real-life application of the novel GRS on a coastal cargo carrier. The findings of the study can guide the implementation of strategies to reduce energy consumption and emissions for such applications in the maritime manufacturing industry. Future ESD retrofitting applications can utilise this study's developed methodology framework for strategic planning and life cycle cost assessments. A GRS retrofitting has aspects of new building, ship repair, and ship dismantling. Therefore, this study can also increase awareness of energy consumption, efficiency, and associated environmental impacts in ship repair, dismantling, and new building activities. These contributions are significant to the literature and the shipbuilding industry, providing value to practitioners, scholars, and decision-makers.

Section 2 describes the GRS retrofitting studied in this paper, including the target vessel and scope of the retrofit, as well as a detailed description of the manufacturing, existing (CRS) system removals, modification of the hull system and S/G room and assembly, and installation stages. Section 3 provides a description of the methodology used in this study, including the boundaries of the assessments, approaches, and calculation methods for energy consumption and related GHG emissions. The results of the study are presented in Section 4, whereas the discussion of the results is given in Section 5. The conclusions are presented in Section 6.

2. Gate Rudder System (GRS) Retrofitting

2.1. The Target Vessel, MV ERGE

The target ship, MV ERGE, in the GATERS project is a multipurpose general cargo vessel with a DWT of 5650 tonnes and an overall length of 89.95 m (Figure 2). MV ERGE operates in European coastal waters, the Black Sea, the Red Sea, and the North. Constructed in China in 2011, it was equipped with a left-hand five-bladed fixed-pitch propeller and a conventional flap rudder (Figure 3a). Table 1 presents its main characteristics.

Figure 2. Target ship, MV ERGE (source: http://www.dadaylilar.com/erge/ accessed on 10 July 2024).

Figure 3. MV ERGE's rudder blade(s) and propeller before (**a**) and after (**b**) the GRS retrofitting.

Table 1. Target vessel main particulars.

Parameter	Value
Length overall, L_{OA}	89.95 m
Breadth, B	15.40 m
Draught (midship), T	6.46 m
Displacement, D	7262.7 t
Service Speed, Vs	12 knots

2.2. Scale and Scope of Gate Rudder Retrofit

The GATERS project has developed the concept of six potential retrofit design options, as listed in Table 2. The most comprehensive design option, Case 6, was selected and applied to MV ERGE to achieve the optimum efficiency gain, with the motivation of obtaining the unique fuel-saving potential from the GRS application. The scope of this GRS retrofit design option included the following primary design considerations [7]:

- New propeller with a new positioning. A new propeller with a diameter that is 5% greater than the existing one and a shift in the propeller's longitudinal position towards aft by 2% (Figures 3 and 4).
- New propeller shaft. The new propeller position resulted in a slightly longer shaft (Figure 4).
- New rudder blades with new positions: The gate rudder blades are in a new location aside from the propeller; each blade is on either side of the new propeller. The axes of the gate rudder stocks are to be shifted longitudinally aft by around 1600 mm relative to the existing conventional rudder stock axis (Figures 3 and 4).
- New twin S/G machinery with a new orientation: Two twin gate rudder blades on either side of the new propeller and their new locations required the use of twin S/G machinery with an opposite orientation to the existing S/G (Figure 5).

Table 2. GRS retrofit design options.

Design Options	Scope of Retrofitting
Case 1	Retrofit gate rudder blades only.
Case 2	Retrofit gate rudder blades + New propeller
Case 3	Retrofit gate rudder blades + New (longitudinal) positioning of the existing propeller
Case 4	Retrofit gate rudder blades + Positioning of the existing propeller + New shaft
Case 5	Retrofit gate rudder blades + New propeller (repositioned) + New shaft
Case 6	Retrofit gate rudder blades + New propeller (repositioned) + New shaft + Aftend modifications

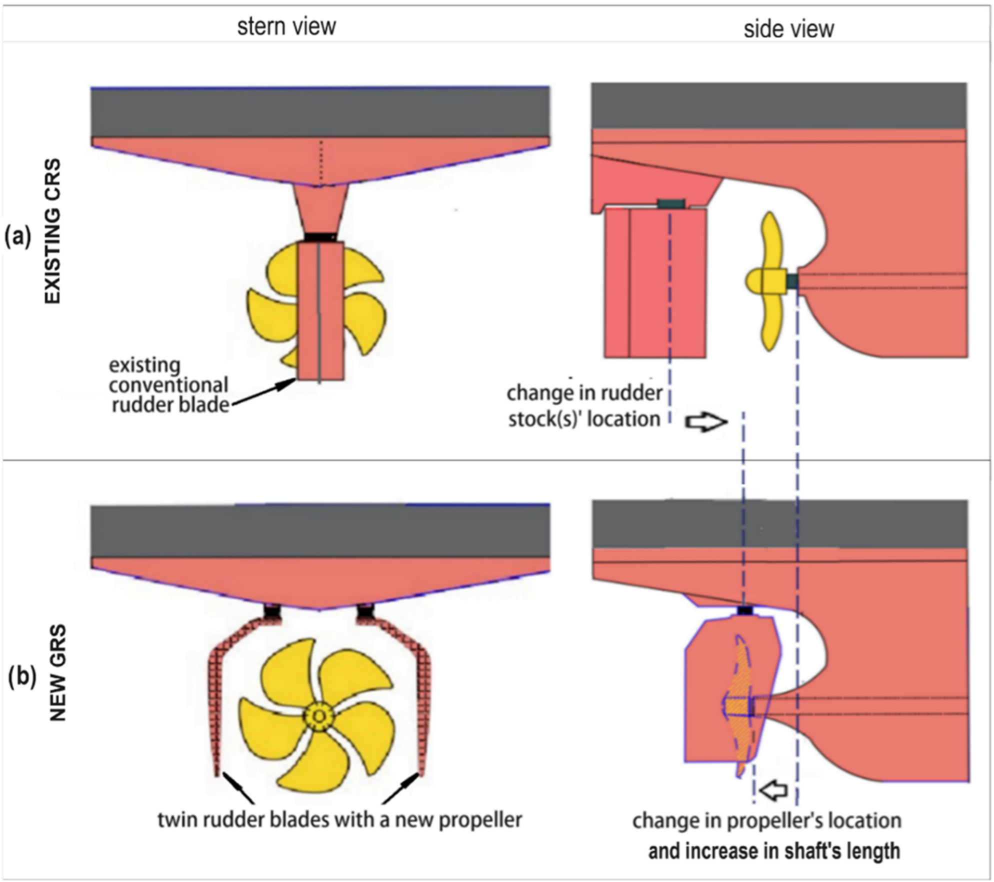

Figure 4. Simplified demonstration of the existing CRS (**a**) and new GRS (**b**), together with the changes in the locations of the propeller and rudder stock (s).

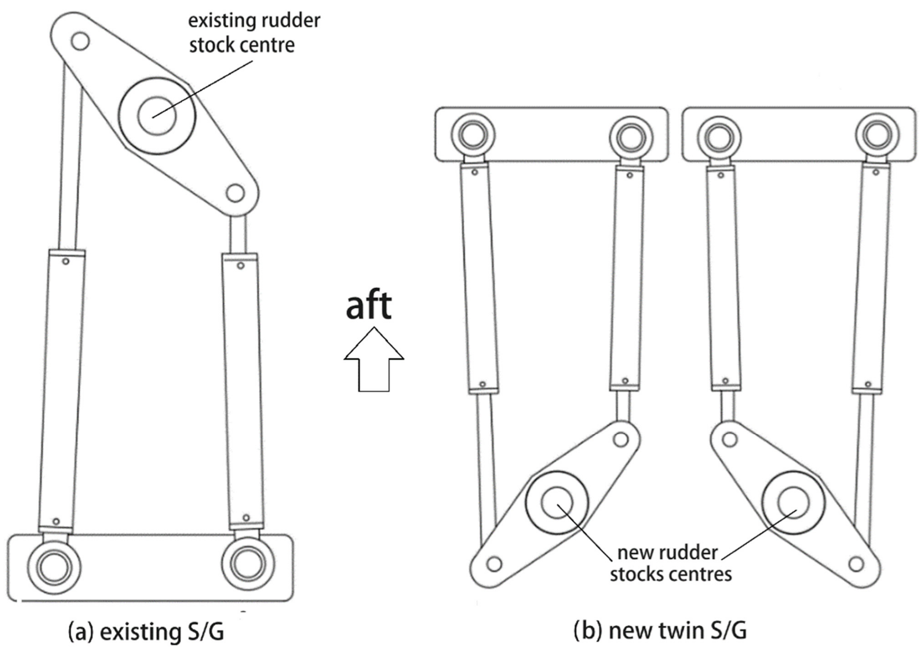

Figure 5. Orientation of the existing conventional S/G (**a**) and the new twin S/G of the GRS (**b**).

Table 3 lists the characteristic changes in MV ERGE during retrofitting the GRS. The application of these new GRS design considerations for the target ship MV ERGE necessitated the following major work stages, which are also shown schematically in Figure 6:

- Manufacturing (manufacturing of the GRS components and supporting elements) stage.
- CRS removal (dismantling and removal of the existing CRS components) stage.
- Modification of the hull system, S/G room, and assembly stage.
- Installations and commissioning stage.

Table 3. Characteristic retrofit changes in the target ship.

CRS Rand GRS Elements	Existing CRS	New GRS
Propeller diameter	3.42 m	5% larger than CRS
Number of propeller blades	5	5
Rudder type	Single flap rudder blade	Two asymmetric gate rudder blades
S/G machinery no	Single S/G	Twin S/G
S/G design torque	125 kNm	125 kNm (each)
Propeller shaft length	5.04 m	Slightly larger than the CRS

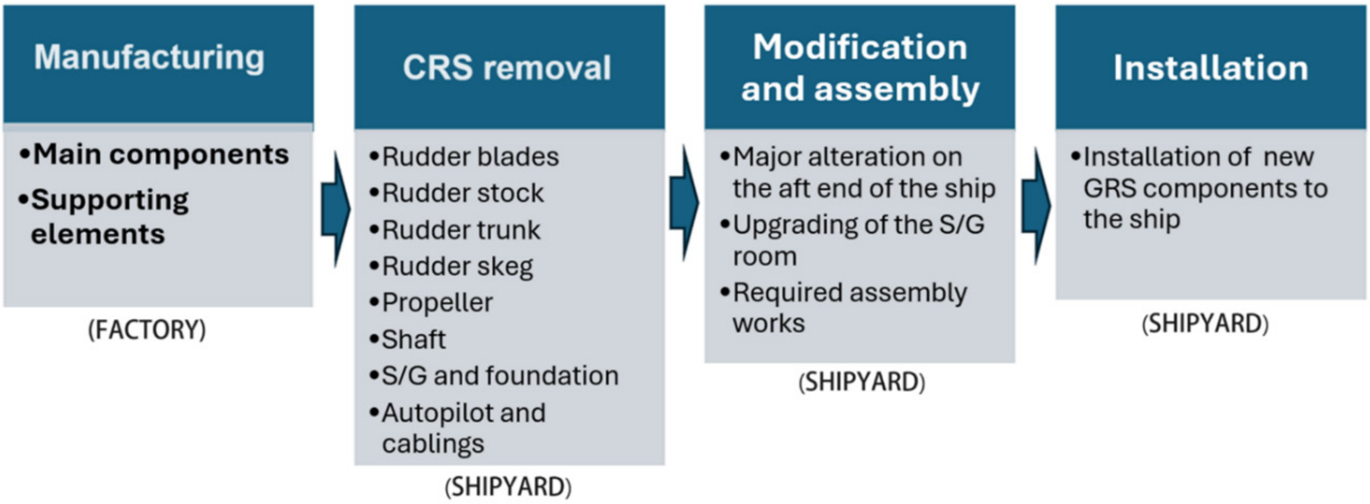

Figure 6. Main stages and scopes of the GRS retrofit in the GATERS project.

2.3. Description of Main Retrofitting Stages

2.3.1. Manufacturing Stage

The design option Case 6 required the following tasks: the installation of a new GRS, including gate rudder blades with new rudder trunks; rudder stocks; a new twin S/G machinery and hydraulic power unit; a new propeller with a new positioning; a new propeller shaft; a new stern tube; and a new autopilot. Therefore, procurement and manufacturing of the new system components were necessary. In addition to these main components of the GRS, other supporting elements, such as mould sets and structural elements for modification and retrofitting works on the target ship, were required. Hence, significant manufacturing activities including casting, cutting, welding, forging, grinding, etc. were carried out during the project.

The manufacturing works in the project can be divided into two major groups: the manufacturing of GRS retrofit main components and the manufacturing of supporting elements. The GRS retrofit main components, which were required to be directly manufactured according to the needs of the retrofit project, are as follows: new gate rudder stocks and trunks (Figure 7a,b), new gate rudder blades (Figure 7c), new propeller, new tail shaft, and new stern tube (Figure 8). Other main components, including the new S/G machinery, hydraulic power unit, the new autopilot, and associated cables, were outsourced. The supporting components include moulding sets, shell platings, and other structural components for modification works.

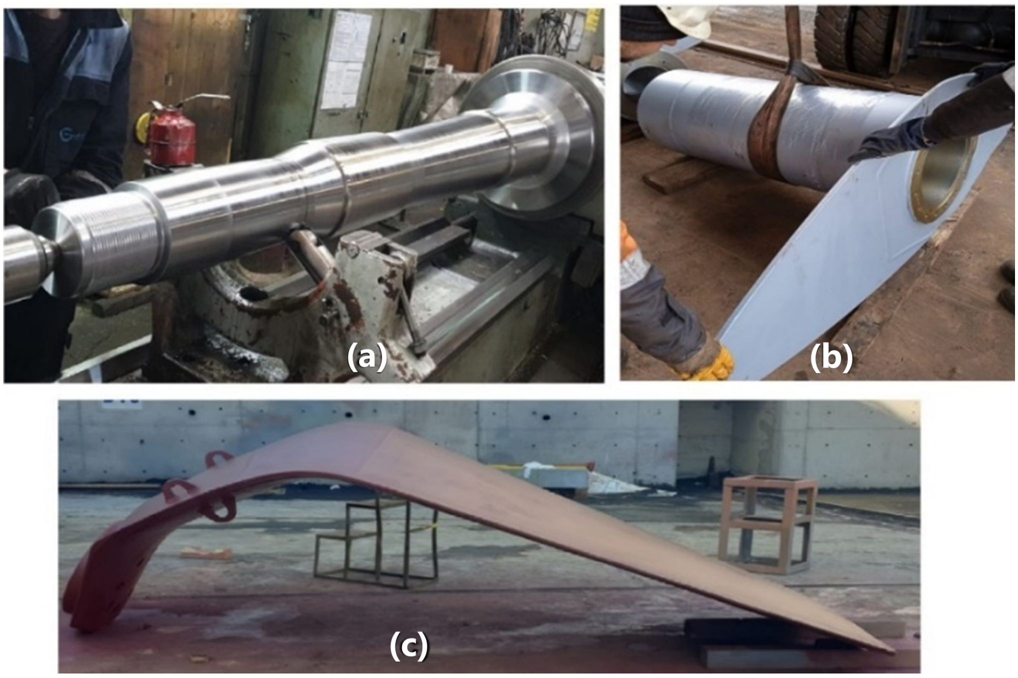

Figure 7. The new gate rudder stock(s) (**a**), rudder trunk(s) (**b**), and rudder blade(s) (**c**).

Figure 8. The new propeller and shaft manufactured and fitted (**a**), and the new stern tube (**b**).

2.3.2. CRS Removal Stage

The components of the CRS were dismantled and removed from the target ship, including the existing CRS rudder blade, stock, trunk, and associated accessory bearings, along with the entire S/G machinery and its foundation. Additionally, the existing propeller, tail shaft, stern tube, and related bearings and accessories were dismantled and removed (Figure 9). Furthermore, the existing autopilot, together with its associated cablings, was taken out. All the removal operations were accomplished utilising mechanical dismantling, oxyfuel cuttings, and hand-grinding processes.

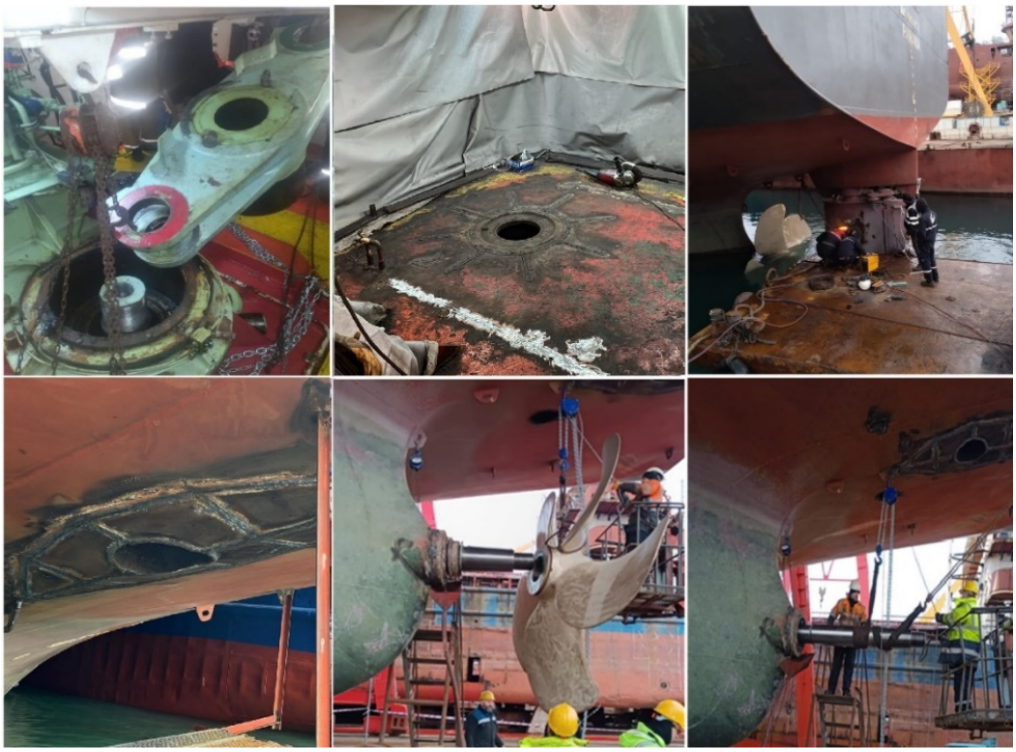

Figure 9. Removal of the existing CRS components.

2.3.3. Modification of the Hull System, S/G Room, and Assembly Stage

The target vessel's aft end underwent a local structural modification for the installation of a new propeller with a new position, a new shaft, a new stern tube, and new rudder blades on each side of the new propeller. Moreover, the S/G room underwent a substantial upgrade and modification because of the necessity to employ the new twin S/G machinery arrangement and the new locations of the rudder stocks (Figures 4 and 5).

The aft-end modifications were commenced by removing the stern boss and shell platings around it through oxyfuel cutting. The next step involved assembling the new stern tube and its bearing together with new shell platings. Additionally, the structural skegs of the new rudder stocks were welded to the hull, while the old skeg was removed through cutting and grinding works, and the opening point of the old rudder stock was closed. The aft end modification operations were finalised following the hull surface preparations, which included repairs, welding, and grinding in preparation for the subsequent painting works (Figure 10).

Figure 10. Conversion of the aft end of the target ship through removal of the CRS and modification and assembly works.

The existing S/G machinery and components were dismantled and removed, and then the entire S/G room was stripped off and prepared for modification. The old opening of the conventional rudder's trunk was closed through welded assemblies of new structural elements and plates. The new rudder trunk assembly points were opened through cutting and removal of the platings and underdeck structural elements.

2.3.4. Installations and Commissioning Stage for Retrofitting the GRS

The system components, including the new twin S/G system and the propeller and shaft, were mainly installed using mechanical assembly techniques such as threaded fasteners such as screws, bolts, and nuts, as well as mechanical fit methods such as contact or shrink fits (Figure 11). Therefore, the energy requirement of the installation operations was minimal compared with other major stages of manufacturing, removals, and modifications. After installing the components, the installation and calibration of the autopilot on the bridge, along with all other installations and cable connections, were completed. While these final tasks took place, the underwater parts of the entire hull were also recoated, and the vessel was finally ready for the sea trial.

Figure 11. Installation of the new twin S/G system and shaft and propeller.

3. Methodology

3.1. Boundary of Assessment

While Section 2 has summarised the unique retrofitting stages of the GRS, as stated earlier, the main focus of this study is the investigation of the energy consumption and associated GHG emissions related to the main work activities during the entire retrofitting task, i.e., through the stages of manufacturing, system removals, modification, and assemblies.

The energy and GHG emissions assessment in this study focused on the primary work activities that were conducted during the main retrofit stages of manufacturing, system removals, and modification and assembly. Table 4 provides a list of major energy-consuming activities of the retrofitting task, along with energy type and GHG emissions.

It is worth noting that the assessment related to the manufacturing stage in this study focuses on only the manufacturing of GRS retrofit main components, which were directly produced from raw materials according to the needs of the project. For example, the gate rudder blades were manufactured to the design specifications using a combination of manufacturing methods, including welding and casting. On the other hand, some components, such as S/G machinery, were not directly manufactured; instead, they were prepared by the suppliers by assembling the sub-components, such as a hydraulic power unit and hydraulic mechanism components readily available in the market. In addition, various materials, such as bolts, nuts, etc., were procured. These were categorised as outsourced components or systems and not included in the energy use and carbon emissions assessment in this study.

In addition to the above, energy use and associated emissions related to the production of raw materials and consumables such as steel plates, sections, scraps, welding wires, fitting components, and other materials (i.e., embodied energy), as well as the supply chain, transportation, use, and disposal activities, were beyond the scope of this study.

Table 4. Major energy-consuming activities, tasks, processes, and energy types and GHG emissions.

Retrofit Main Stages	Component/System/Task	Major Processes										Energy Type			GHG Emissions	
		Casting	Forging	Plasma Cutting	Machining	Grinding	Welding	Arc Gouging	Hot/Cold Bending	Oxyfuel Cutting	Heating/ Heat Treatment	Electricity	Natural Gas	LPG-Propane	Indirect—CO_2eq	Direct—CO_2eq
Manufacturing stage	GR blades	√		√			√		√			√			√	
	GR stocks		√		√						√		√		√	√
	GR trunks			√		√	√								√	
	New propeller	√			√	√									√	
	New tail shaft		√		√						√		√		√	√
	New stern tube	√			√										√	
	Supporting elements—moulds and structural elements	√		√			√		√		√				√	
CRS removal stage	Removal of the existing CRS components, including the entire S/G machinery with its foundation, rudder blade, rudder stock and trunk, rudder skeg, rudder system accessories such as bearings, propeller, tail/intermediate shaft, shaft bearings, stern tube and stern tube boss, and autopilot and cablings.									√	√			√	√	√
Modification of the hull system and assembly stage	Modification and upgrade of the S/G room and aft end					√	√	√		√				√	√	√

3.2. Approach for Energy Consumption and GHG Estimations

The most accurate and reliable approach for determining the energy consumption of a process or system is direct measurement. However, this is very challenging in such a retrofitting project because it is a highly complex task requiring the execution of a lot of diverse processes. Therefore, adopting a practical approach based on the available data is necessary to estimate energy consumption.

Figure 12 shows the flowchart of the methodology approach adopted in this study. A component and work breakdown of the GRS retrofit for the target vessel was created (Table 4). The components' manufacturing processes, as well as the execution of the dismantling and removal of the CRS, modification and upgrading of the hull system, and installation of the GRS work, were identified. All pertinent data related to these processes were gathered. These included the man-hours required for the processes, the quantity and specifications of the basic materials used in each process, such as steel plates and sections, and the consumables required to perform the processes, such as welding electrodes and gases. Energy consumption by process and activity was estimated using the data obtained from the GATERS project and valid literature resources. Following this, the energy-related GHG emissions are calculated based on the energy consumption data and emission factors.

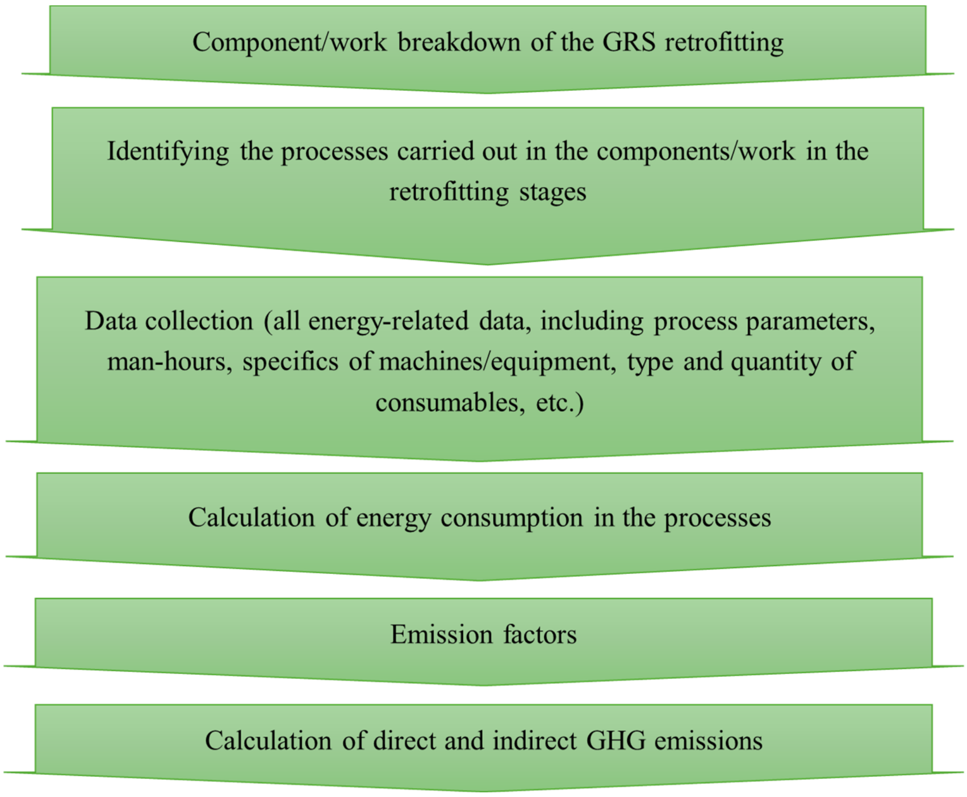

Figure 12. Flow chart of the methodology approach.

3.2.1. Energy Consumption Calculations

Plasma Arc-Cutting Process

Plasma arc cutting was one of the major processes in the manufacturing stage of the GRS retrofitting. It is a process that uses a focused plasma to heat and melt the metal as well as remove the melted metal, allowing it to penetrate and cut through the workpiece [25]. It was used to cut the steel plates precisely to the necessary dimensions for the manufacturing of the main components as well as the supporting elements.

The plasma arc-cutting process uses electricity to produce plasma. The electricity consumption by plasma cutting, EC_{PC} is estimated as follows:

$$EC_{PC} = P_{PC}T_C(kWh) \quad (1)$$

where P_{PC} is the power demand by the plasma cutting process (kW) and T_C is the process duration, which can be calculated as follows:

$$Tc = \frac{C_L}{V_{CSP}}(kWh) \quad (2)$$

where C_L is the cutting length (mm) and V_{CSP} is the cutting speed (mm/min). The operators set the optimal cutting speed based on the plate thickness. The thickness of the steel plates used in the retrofit project varied between 15 mm and 30 mm. In order to calculate the total electricity consumption of the plasma cutting using Equations (1) and (2), the C_L values were obtained from the production records of the plasma cutting system, together with the associated V_{CSP} and P_{PC} values.

Casting Process

The casting process took place in the manufacturing of the propeller, stern tube, and other various parts for the fabrication of the gate rudder blades and rudder trunks, and hydraulic nuts for the rudders and propeller shaft. The melting processes in all castings were performed in induction furnaces.

The electricity consumption of the casting process (EC_{cp}) is calculated as follows:

$$EC_{cp} = SEC_{cp}\, C_w \ \ (kWh) \quad (3)$$

where SEC_{cp} is the specific energy consumption of the casting process (kWh/kg), and C_W is the total casting mass (kg), including the final product and other casting elements such as gates, feeders, and risers.

The casted parts of the rudder blades and rudder trunks and hydraulic nuts were produced in a foundry that had previously been energy-audited by the first author. The SEC_{cp} of the casting process (melting + finishing operations) in the foundry was about 650 kWh/tonne [26]. The total mass of castings for the rudder blades and rudder trunks was 6025.3 kg whereas it was 3033.8 kg for the hydraulic nuts Additionally, another major component of the GRS retrofit, the new propeller, was also produced by casting. The total casting mass of the propeller is assumed to be 3505 kg based on a 25% yield rate. The SEC was assumed to be 0.60 [27].

Welding Process

Welding was one of the essential processes extensively used both in the manufacturing and modification/assembly stages of the GRS retrofitting. The welding technology employed in the manufacturing and modification/assembly tasks was a gas metal arc welding technique, which uses consumable electrodes and active shielding gas to protect the welding pool. The shielding gas was CO_2.

The electric energy consumption by gas metal arc welding (EC_{WP}) can be estimated as follows [28,29]:

$$EC_{WP} = \frac{m_w}{EDE\eta}(kWh) \quad (4)$$

where EDE is the welding electrical deposition efficiency (kg/kWh), m_w is the total mass of the welding wire used in the welding process in kg, η is the wall-plug efficiency. In this study, an average EDE value of 0.6516 kg/kWh and a wall-plug efficiency of 84.9% were assumed based on [29].

The welding processes took place within the manufacturing and modification/upgrading activities of the retrofit. The welding in the manufacturing activities was mainly due to the gate rudder blades and mould sets because their manufacturing was based on welded fabrication techniques. The filler material in the welding works in the project was a standard 1.2 mm wire electrode. The amount of welding filler material used for the manufacturing activities was 300 kg, whereas it was 495 kg used for the modification and assembly works.

Air-Carbon-Arc-Gouging (ACAG)

ACAG is a metal cutting and removal process that uses compressed air and an electric arc created between the metal workpiece and the carbon electrode [30]. The process is similar to the arc welding process; arc welding equipment is used together with carbon gouging electrodes and compressed air.

The ACAG was often performed as part of the welding processes for proper weld preparations, mainly in the modification and assembly stage of the retrofit project in this paper, particularly for full-penetrant welds.

The energy consumption of the ACAG process, EC_{ACAG}, can be estimated as follows:

$$EC_{ACAG} = EC_{ARC} + EC_{CA} \ \ (kWh) \tag{5}$$

where EC_{ARC} is the electricity consumed by the welding equipment for arc creation, and EC_{CA} is the energy consumed to generate compressed air.

EC_{ARC} can be calculated as follows:

$$EC_{ARC} = \frac{VI}{1000\eta} T_{arc}(kWh) \tag{6}$$

where V and I are the voltage and current values used in the ACAG process, respectively. T_{arc} is the total arc time in the ACAG process, which can be estimated as follows:

$$Tarc = \frac{L}{V_C}(hours) \tag{7}$$

where V_C is the carbon electrode consumption speed, and L is the total length of the carbon electrodes consumed in the ACAG.

The electricity consumption due to the compressed air use by the ACAG process, EC_{CA}, can be estimated based on the approximate power load on the shipyard's air compressor to generate the compressed air used during the ACAG.

The power required to compress the air from atmospheric pressure to a certain pressure (i.e., gouging pressure), Pc, can be estimated as follows [31]:

$$Pc = \frac{P_i\left(\frac{1}{C_2}\right)V_f\left(\frac{k}{k-1}\right)N\left(\left(\frac{P_o}{P_i}\right)^{\frac{k-1}{kxN}} - 1\right)}{E_a E_m}(kW) \tag{8}$$

where P_i is the atmospheric pressure (101.3 kPa), P_o is the compressed air pressure (i.e., gouging air pressure) (550 kPa), C_2 is the conversion constant (3600 sh^{-1}), V_f is the volumetric flow rate of the compressed air, k is the specific heat ratio of air (i.e., 1.4), N is the number of compressor stages (i.e., 2), E_a is the compressor isentropic efficiency (i.e., 0.82), and E_m is the compressor electric motor efficiency (i.e., 0.939) [26,31].

Thus, EC_{CA} can be calculated as follows:

$$EC_{CA} = P_C\ T\ (kWh) \tag{9}$$

where T is the compressed air generation period and can be assumed equal to the arc period, T_{arc}, calculated using Equation (7).

The ACAG in the project was carried out using 300 A, 50 V, and a carbon electrode of Ø6.4 × 305 mm. The total quantity of the carbon electrode consumed was 300, making a total electrode length of 9.15 m. The carbon electrode consumption speed was 120 mm/min. The compressed air consumption rate, Vf, was 934 L/min.

Grinding Process

Angle grinding is an essential finishing process that is commonly used in almost all metal fabrication work. It was extensively used throughout all stages of the GATERS project application, from manufacturing to assembly, to achieve a variety of tasks, including removing welds, burrs, and sharp edges; cleansing metal surfaces; removing rust, corrosion, paint, and coatings; preparing for welding; and finishing for smoothing out welding. The process was basically executed by using an angle grinder and a grinding disc, depending on the type of grinding work.

The electric energy consumption by a grinding process (EC_{GP}) can be estimated as follows:

$$EC_{GP} = P_{GD}\, T_g \ \ (\text{kWh}) \tag{10}$$

where P_{GD} is the power demand of the angle grinder, and T_g is the operation period (hours).

The power rating of the angle grinders used in the project was 3.5 kW. The P_{GD} of the grinders was assumed to be 80% of the power ratings. The total T_g for the grinding process was estimated based on the man-hours of the grinder workers. The total man-hour of the grinder workers in the shipyard operations of system removals, modifications, and assembly works was 233.5 h, whereas it was 1290 h for the manufacturing activities of the rudder blades, rudder trunks, stern tubes, and moulding sets at the factory. Based on the grinder workers in the project, the operation period of the angle grinding machines is assumed to be 50% of the associated man-hours. Therefore, the total T_g of the angle grinders in the shipyard and factory works were 116.8 h and 645 h, respectively, making a total operation period of 761.8 h.

Machining Process

Machining is a manufacturing technique that involves shaping metal parts to the desired geometry, dimensions, and surface quality through material removal operations such as turning, milling, drilling, grinding, etc. using machine tools such as lathes and milling machines [32]. In the GRS retrofitting project, the machining process took place during the manufacturing of rudder stocks and propeller shafts. The rudder stocks and propeller shaft were produced by machining the forged steel to the final dimensions and surface quality using a horizontal lathe.

The electricity consumption by machining, EC_{MC}, can be calculated as follows:

$$EC_{MC} = SEC_M\, M_r \ \ (\text{kWh}) \tag{11}$$

where SEC_M is the specific energy consumption of the machining process (kWh/kg), and M_r is the amount of the material removed in the machining process (kg).

Based on the machining operator, the M_r for the propeller shaft and two rudder stocks were 1346 kg and 1292 kg, respectively. The SEC_M is assumed to be 0.735 kWh/kg [26].

Cold and Hot Bending Process

The bending process was used to bend the steel plates to get the required surface curvature. In the hot bending process, the steel plates were heated to a certain temperature and then bent using the hydraulic press. Therefore, the energy consumption in a hot bending process (EC_{HBP}) is the sum of the energy consumption for heating the plates, EC_{HP}, and energy consumption for the bending of the plates, EC_{BP}, and can be calculated as follows:

$$EC_{HBP} = EC_{HP} + EC_{BP} \ \ (\text{kWh}) \tag{12}$$

Electric Heating

Heating of the steel plates was performed by using an electric furnace. The electric energy consumption of the furnace to heat up the steel plates to a certain temperature,

EC_{HP}, can be estimated based on the thermal energy required to increase the temperature of the steel plates and the efficiency of the electric furnace as follows:

$$EC_{HP} = \frac{Qw}{\eta_{ef}}(kWh) \quad (13)$$

where Q_W is the thermal energy transferred to the workload to increase the temperature of the workload from T_1 to T_2, and ηef is the furnace efficiency. Q_W can be calculated as follows:

$$Q_w = Cm_w(T_2 - T_1) \ (kWh) \quad (14)$$

where C is the specific heat of the steel (i.e., 420 J/kg°C), m_w is the total mass of the workload heated, T_1 is the initial temperature of the workload, and T_2 is the final temperature of the workload.

The amount of steel plates heated for the hot bending process in this study was 1413 kg, and the electric furnace efficiency is assumed to be about 85% based on [33]. The steel plates were heated from 20 °C to 900 °C.

Bending Press

The electricity energy consumption by the hydraulic press for the bending process can be calculated as follows:

$$EC_{BP} = P_{HP}\,T_b \ (kWh) \quad (15)$$

where P_{HP} is the power demand by the hydraulic press in kW and T_b is the operation hours.

The bending process was carried out using a 600-tonne-45 kW hydraulic press. Based on the operator, the hydraulic press worked for about 2.6 h for both cold and hot bending processes, and the power load was assumed to be 0.8 of the rated power.

Forging Process

The new propeller shaft and rudder stocks were manufactured from forged steel in the retrofitting application in the GATERS project. Forging begins by heating steel ingots to a certain temperature. After this, a press machine forges the hot steel ingots to the necessary shape and dimensions on the forging press workbench. Final finishing procedures, including grinding and shot blasting, complete the forging process after a post-forging heat treatment [34]. The forged shaft is then machined to the required dimensions and surface quality by machining process on a horizontal lathe.

The total energy consumption in a forging process, EC_{TFP}, can be estimated as follows:

$$EC_{TFP} = EC_{PH} + EC_{FP} + EC_{HT} + EC_{AP} \ (kWh) \quad (16)$$

where EC_{PH} is the energy consumption in the preheating process, EC_{FP} is the energy consumption of the forging press, EC_{HT} is the energy consumption of the post-forging process heat treatment process, and EC_{AP} is the energy consumption of the auxiliary process such as cutting, quality control, grinding, blasting, and repairing works.

In the GATERS project application, the preheating and heat treatment processes of the propeller shaft and rudder stocks were conducted in a natural gas-fired oven, whereas the forging process was carried out by using a hydraulic forging press.

The electric energy consumption by the forging process by the hydraulic press can be estimated by Equation (15). However, the data for the power demand of the forging press and associated operation period, as well as the auxiliary processes and post-forging heat treatment processes, were not available. In this study, the total energy consumption by the forging press, auxiliary processes, and post-forging heat treatment process was estimated based on a correlation to the energy consumption of the preheating processes. According to [34], the share of the pre-forging heating, post-forging heat treatment, forging press, and auxiliary processes in the overall energy consumption of a forging process is 20–25%, 30–35%, 25–30%, and 15–20%, respectively. In the study, these shares were assumed to be as follows: 25% for EC_{PH}, 35% for EC_{HT}, 25% for EC_{FP}, and 15% for EC_{AP}.

Hence, the EC_{FP} and EC_{AP} were calculated based on EC_{PH} as follows:

$$EC_{FP} = EC_{PH}\ (\text{kWh}) \quad (17)$$

$$EC_{AP} = 0.6\ EC_{PH}\ (\text{kWh}) \quad (18)$$

$$EC_{HT} = 1.4\ EC_{PH}\ (\text{kWh}) \quad (19)$$

The preheating process of the steel ingots was conducted using a natural gas-fired furnace. The energy consumption by a natural gas-fired furnace can be estimated as follows:

$$EC_{NGF} = \frac{Q_w}{\eta_f}(\text{kWh}) \quad (20)$$

where Q_W is the thermal energy transferred to the workload, and η_f is the furnace efficiency. Q_W is calculated using Equation (8). In the preheating of forging, the steel ingot is heated up to 1200 °C from the ambient temperature of 20 °C. The efficiency of a gas-fired furnace is assumed to be 60% based on [35]. The mass of the steel ingots for the propeller shaft and two rudder stocks is 3846 kg and 3692 kg, respectively.

The fuel consumption by a natural gas-fired furnace, FC_{NG}, is calculated as follows:

$$FC_{NG} = \frac{EC_{NGF}}{NCV\rho}(\text{m}^3) \quad (21)$$

where NCV and ρ are the net calorific value and density of the natural gas, which are 13.3 kWh/kg and 0.72 kg/cm^3, respectively [36].

Oxyfuel Cutting

Oxyfuel cutting is a thermal cutting technology that utilises a mixture of oxygen and fuel gas to generate heat through combustion in order to cut through materials effectively [37]. Oxyfuel-cutting technology was widely employed in the retrofit project in this paper, specifically for the removal and dismantling of existing systems and modification operations at the shipyard.

The energy consumption in the oxyfuel-cutting processes in this study was estimated based on the data on the amount of oxygen and fuel gas. The energy consumption in the oxyfuel cutting through the combustion of the propane and LPG, EC_{OXY}, can be calculated as follows:

$$EC_{OXY} = FC\ NCV\ (\text{kWh}) \quad (22)$$

where FC is the amount of fuel gas consumed (kg), and NCV is the net calorific value of the fuel gas.

In the retrofit process, propane and LPG were used as fuel for the oxyfuel cutting processes. The amounts of propane and LPG consumed were 270 kg and 90 kg, respectively. The NCV for the propane and LPG were 13.14 kWh/kg [36].

3.2.2. Energy-Related GHG Emission Calculations

In this study, the total energy-related GHG emissions from the activities in the GRS retrofit were expressed based on the carbon dioxide equivalent (CO_2e). In the CO_2e approach, the amounts of GHGs are converted to the equivalent amount of carbon dioxide with the same global warming potential (GWP) as follows [38]:

$$CO_2e = CO_2 + CH_4\ GWP_{CH_4} + N_2OGWP_{N_2O} \quad (23)$$

The GWP values of methane and nitrous oxide relative to carbon dioxide are given in Table 5.

Table 5. GWP values of CO_2, CH_4, and N_2O according to the IPCC fifth assessment report (AR5) (adapted from [36]).

GHG	GWP
CO_2 (carbon dioxide)	1
CH_4 (methane)	28
N_2O (nitrous oxide)	265

Emission Sources

In the study, the energy-related Scope 1 and Scope 2 GHG emissions from the activities within the GRS retrofit were investigated. Scope 1 included the direct GHG emissions that emanated from the combustion of the fuels, whereas Scope 2 was the scope of the indirect emissions due to the consumption of purchased electricity. Table 6 lists the activities and processes that caused the direct GHG emissions. The sources of the direct GHG emissions were the combustion of LPG and propane, which were used as fuels for oxyfuel cutting processes, and the natural gas used in the natural gas-fired furnace used for the heating of the forging processes. Regarding the indirect emissions (Scope 2), these were due to the electricity consumption for the plasma cutting, welding, grinding, casting, bending, and forging processes.

Table 6. Energy consumption related to direct and indirect GHG emission sources in the GRS retrofit.

<table>
<tr><th>Emission Scopes</th><th>Energy Activity</th><th>Activity/Process</th></tr>
<tr><td rowspan="9">Indirect GHG emission sources</td><td rowspan="9">Electricity consumption</td><td>Casting</td></tr>
<tr><td>Forging</td></tr>
<tr><td>Plasma cutting</td></tr>
<tr><td>Machining</td></tr>
<tr><td>Grinding</td></tr>
<tr><td>Welding</td></tr>
<tr><td>Air-carbon-arc-gouging</td></tr>
<tr><td>Bending</td></tr>
<tr><td>Heating</td></tr>
<tr><td rowspan="3">Direct GHG emission sources</td><td>Combustion of LPG</td><td>Oxyfuel cutting</td></tr>
<tr><td>Combustion of propane</td><td>Oxyfuel cutting</td></tr>
<tr><td>Combustion of natural gas</td><td>Heating process in natural gas-fired furnaces</td></tr>
</table>

Emission Factors and Calculations

- Indirect CO_2 emissions

The indirect CO_2e emissions due to the electricity consumption, GHG_{EC}, can be calculated as follows:

$$GHG_{EC} = EC\ EF\ \ (kg - CO_2e) \tag{24}$$

where EC is the electricity consumption of the activity (kWh), and EF is the emission factor of the consumed electricity (kg-CO_2eq/kWh). Because a major part of the retrofit activities were carried out in Türkiye, the emission factor for electricity consumption is assumed to be 0.499 kg-CO_2eq/kWh [39].

- Direct CO_2 emissions

The direct emissions because of the combustion of fuels in the retrofit activities, GHG_{FC}, can be calculated as follows:

$$GHG_{FC} = FC\ EF_{fuel} (kg - CO_2e) \quad (25)$$

where FC is the amount of fuel combusted, and EF_{fuel} is the CO_2e emission factor of the fuel.

Table 7 lists the GHG emission factors for the LPG and natural gas used in the GHG assessment in this study. The CO_2e emission factors for LPG and natural gas were calculated using Equation (23) based on the emission factors of CO_2, CH_4, and N_2O gases and their GWP values given in Table 5. As shown in Table 7, the CO_2e factors for LPG and natural gas are 0.2273 kgCO_2e/kWh and 0.2021 kgCO_2e/kWh, respectively.

Table 7. Emission factors for GHG emissions and CO_2e for LPG and natural gas (for stationary combustion in manufacturing and construction activities) (adapted from [36]).

	GHG Emissions			
	CO_2 kg CO_2/kWh	**CH_4 kg CH_4/kWh**	**N_20 kg N_2O/kWh**	**CO_2e kg CO_2e/kWh**
LPG	0.2271	0.0000036	0.00000036	0.2273
Natural gas	0.2019	0.0000036	0.00000036	0.2021

4. Results

4.1. Energy Consumption Results

The total energy consumption in the main stages of manufacturing, CRS removals, and modification and assembly during the GRS retrofit of the GATERS project was 19,507.21 kWh of electricity and 8881.3 kWh of thermal energy through fuel combustion. The fuel sources for the thermal energy generation were natural gas, LPG, and propane. The results for the energy consumption estimations by major retrofit activity and associated processes are presented and discussed in the following sections.

4.1.1. Energy Consumption in Retrofit Stages

Figure 13 shows the overall electricity and thermal energy consumption with regard to the main stages of the GRS retrofit project. The overall energy consumption in the manufacturing stage was 17,835.41 kWh of electricity and 4150.87 kWh of thermal energy. The thermal energy consumption and electricity consumption during the CRS removal stage were 4730.4 kWh of thermal energy and 164 kWh of electricity. The modification and assembly stage required 1507.8 kWh of electricity, whereas no thermal energy was required.

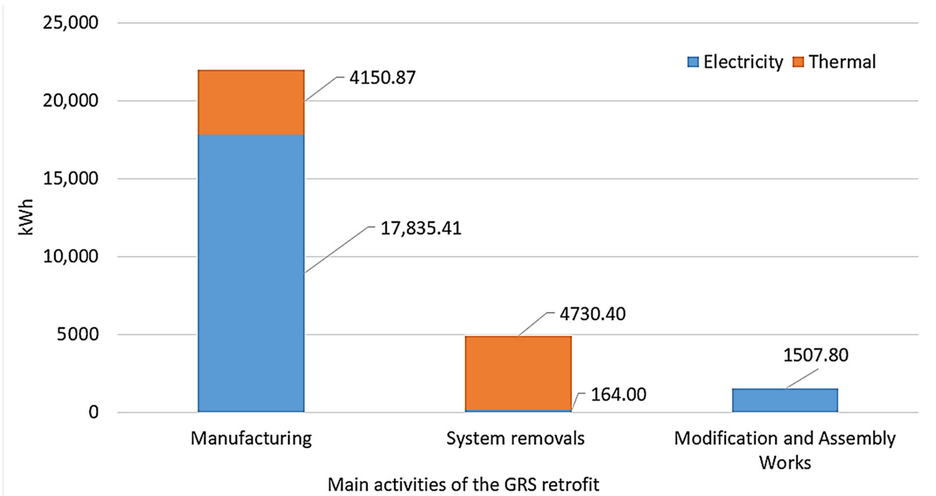

Figure 13. Overall electricity and thermal energy consumption with regard to the main activities.

Manufacturing Stage

The GRS retrofit's manufacturing activities were divided into two primary groups: the production of the main components, which included the gate rudder blades, rudder stocks, rudder trunks, new propeller, new shaft, and new stern tube, and the production of the supporting elements, which included the structural materials and the moulds for bending steel plates. All the manufacturing activities were carried out in a factory environment.

In total, the manufacturing activities consumed 17,835.41 kWh of electricity and 4150.87 kWh of thermal energy. The production of the main GRS components, including the gate rudder blades, rudder stocks, rudder trunks, new propeller, new shaft, and new stern tube, resulted in 14,520.81 kWh of electricity consumption and 4150.87 kWh of thermal energy. The manufacture of the supporting elements, including the moulds and other materials for modification and assembly work, resulted in an electricity consumption of 3314.6 kWh, with no thermal energy consumption.

Table 8 shows the electricity and thermal energy consumption by process in the manufacturing of main components and supporting elements. Among other processes, casting is the most significant electricity consumer. The electricity consumption by the casting process in the manufacturing of the main GRS components was 8070 kWh, which is about 45.24% of the electricity consumption in the entire manufacturing activities and 41.3% of that of the entire retrofitting project. The casting process took place only during the manufacturing of the main GRS components. Figure 14 provides a breakdown of the casting energy consumption for the GRS components. The casting of the structural elements for the fabrication of the rudder trunks and rudder blades was responsible for about 3917 kWh of electricity. The new propeller's casting required 2103 kWh of electricity. The stern tube's casting required about 78 kWh. The other cast elements, hydraulic nuts, consumed 1972 kWh of electricity.

Table 8. Energy consumption by process in manufacturing of the main components and supporting elements (kWh).

	Electricity (kWh)		**Thermal Energy (kWh)**	
Processing	**Manufacturing of Main Components**	**Manufacturing of Supporting Elements**	**Manufacturing of Main Components**	**Manufacturing of Supporting Elements**
Casting	8070	0	0	0
Forging	2767.11	0	4150.87	0
Plasma	563.7	1907.6	0	0
Machining	1939	0	0	0
Grinding	722	1084	0	0
Welding	220	323	0	0
Bending	239	0	0	0
TOTAL	14,520.81	3314.6	4150.87	0
OVERALL	17,835.41		4150.87	

The forging process accounted for the second-largest electricity consumption and was the sole and most significant thermal energy consumer in the manufacturing stage activities. The forging process took place in the manufacturing of the propeller shaft and rudder stocks through a combination of the following sub-processes: preheating, forging, heat treatment, and auxiliary processes such as cutting and finishing. The heating processes were conducted using a natural gas-fired furnace, resulting in thermal energy use through the combustion of the natural gas. The total thermal energy consumption by the forging process was 4150.8 kWh through the combustion of 443.5 m^3 of natural gas. As can be seen in Figure 15, the preheating process and the post-forging heat treatment process had a share of 1729.45 kWh and 2421.42 kWh, respectively. The thermal energy consumptions for the propeller shaft's preheating and heat treatment were 882.45 kWh and 1235.42 kWh, respectively, whereas those for the rudder stocks were 847 kWh and 1186 kWh. The electricity consumption in the forging processes was due to the forging of the preheated steel using a hydraulic press and auxiliary processes such as cutting and finishing. Therefore, the total energy consumption for the entire forging process in the manufacturing of the propeller shaft was 2117.8 kWh of thermal energy from natural gas combustion and 1412 kWh of electricity. In contrast, the energy spent for the two gate rudder stocks was 2033 kWh of thermal energy and 1355.2 kWh of electricity, respectively.

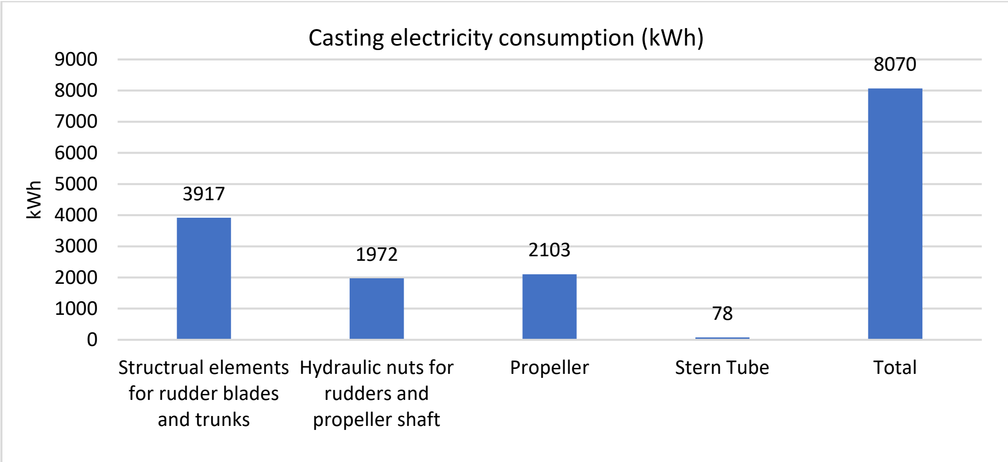

Figure 14. Casting process energy consumption by the GRS components.

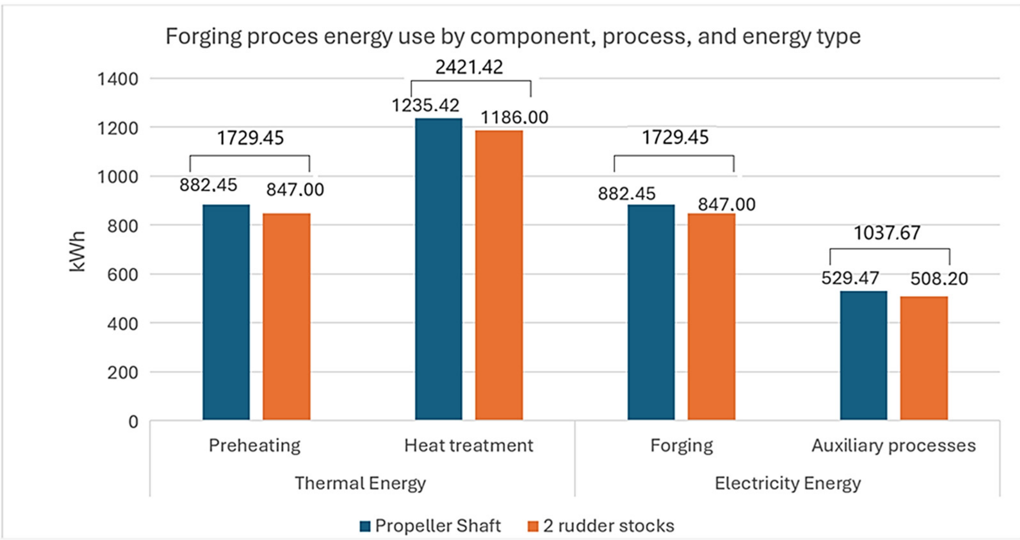

Figure 15. Forging processes energy use in the manufacturing activities by component, process, and energy type.

The total electricity consumption in the forging process for the propeller shaft and rudder stocks was 2767.11 kWh, which is 14.1% of the overall retrofit project electricity consumption. As can also be seen in Figure 15, the share of the electricity consumption by the forging of the propeller shaft and two rudder stocks (i.e., forging press energy use) was 882.45 kWh and 847 kWh, respectively, whereas the share of the auxiliary process in the propeller shaft and rudder stocks was 529.47 kWh and 508.2 kWh, respectively.

The plasma cutting process was the third largest electricity consumer in manufacturing activities, accounting for 2471.3 kWh of electricity consumption. It accounted for about 12.6% of the total electricity consumption in the entire retrofitting project. The plasma cutting process took place in both the manufacturing of the GRS components and supporting elements for cutting the steel plates to the required dimensions. Figure 16 shows the breakdown of the plasma process's electricity consumption with respect to the components. As can be observed, most of the plasma-cutting process occurs during the manufacturing of supporting elements, specifically during the construction of moulds and the production of construction elements. The steel plate cutting for mould construction consumed 1145 kWh of electricity, while the steel plate cutting for various construction works, including modification and assembly activities, consumed 762.6 kWh. Hence, the total electricity consumption by the plasma processes in the manufacturing of the supporting elements was 1907.6 kWh. On the other hand, plasma cutting was utilised in the manufacturing of the main GRS components, specifically for the purpose of cutting steel plates used in the fabrication of rudder blades and rudder trunks. The plasma cutting used to manufacture the rudder blades and rudder trunks consumed 331.2 kWh and 232.5 kWh, respectively, for a total consumption of 563.7 kWh.

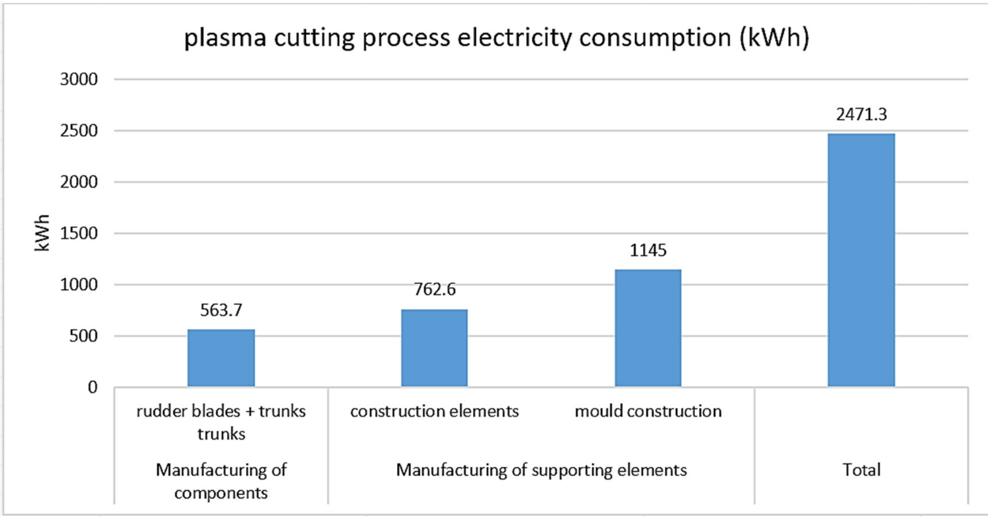

Figure 16. Plasma cutting electricity consumption in the manufacturing of main GRS components and supportive elements.

The machining process was the fourth largest electricity consumer in manufacturing activities, resulting in an electricity consumption of 1939 kWh, which is around 10.8% of the electricity consumption in the manufacturing activities and about 10% of the total electricity consumption in the retrofit project. The total electricity consumption of the machining process is shown in Figure 17 by the main components. The rudder stocks and propeller shaft were manufactured by machining the forged shaft steels to the final dimensions and surface quality. The electrical consumption values for the machining processes were 949.6 kWh for the rudder stocks and 989.3 kWh for the propeller shaft.

The grinding process in manufacturing activities consumed 1806 kWh of electricity, accounting for approximately 10.1% of the overall electricity consumption in manufacturing activities. As can be seen in Table 8, 1084 kWh of the grinding process electricity consumption in the manufacturing activities was due to the manufacturing of the supporting elements, such as mould sets, whereas 722 kWh was consumed during the main component manufacturing. The welding process was another important consumer of energy in manufacturing operations. The process of welding was widely employed in the construction and joining of the new gate rudder blades, rudder trunks, and moulding sets. An amount of 542.3 kWh of electricity was consumed during the welding production operations in the manufacturing stage activities.

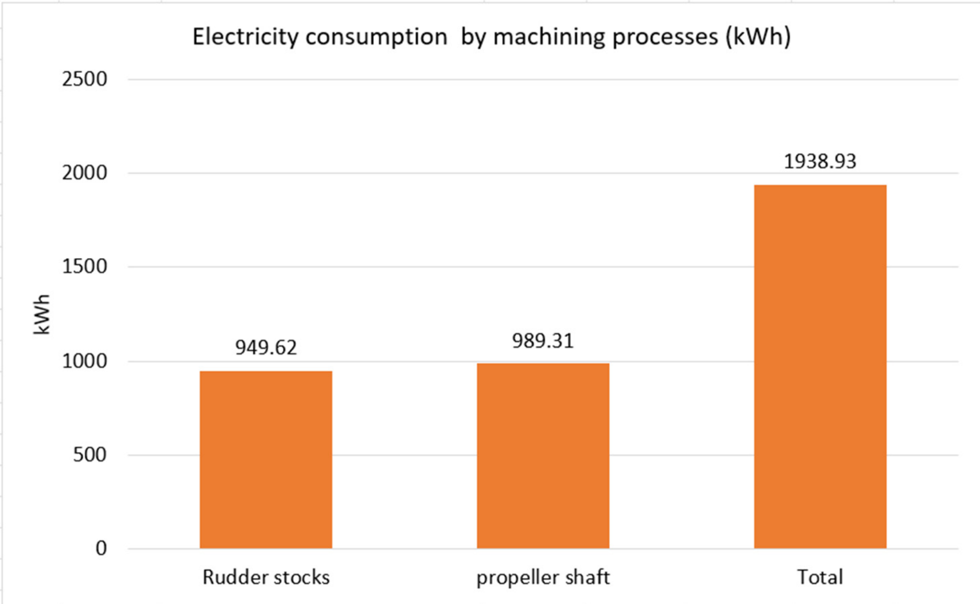

Figure 17. The total electricity consumption of the machining process and breakdown with respect to the components.

The hot and cold bending processes had the lowest electricity consumption among the various manufacturing activities. The coating plates for the rudder blades were shaped to the desired form by the hot bending process. The hot bending process entailed the preheating of the thicker steel plates to facilitate the bending process in the bending press. The total electricity consumption in the bending process was 239 kWh. The electric heating furnace accounted for 145 kWh of the preheating process, while the hydraulic press consumed a total of 94 kWh during the bending process.

Stages of CRS Removal, Hull System Modification, and Assembly

Table 9 shows the electricity and thermal energy consumption by the processes during the main retrofit stages of the CRS removals, hull system and S/G room modifications, and assembly conducted at the shipyard. In these stages, the total electricity consumption was 1672 kWh, whereas the total thermal energy consumption was 4730.4 kWh. The welding process, which consumed 895 kWh of electricity, was the major electricity consumer. The ACAG process, which was used for welding preparations, accounted for 449 kWh of electricity consumption. During the CRS removal, there was no welding activity. The grinding process was responsible for 328 kWh of electricity. It was estimated that the workload shares of the stages of system removals and modifications, as well as assembly work in the grinding process, were equal. Thus, the energy consumption of the grinding in system removals and modification and assembly work was equal to each other, 164 kWh.

Table 9. Energy consumption by process in system removals and modification and assembly work stages.

CRS Removal, Hull System Modifications and GRS Assembly	Electricity (kWh)	Thermal Energy (kWh)
Grinding	328	0
Welding	895	0
ACAG	449	0
Oxyfuel cutting	0	4730.4
TOTAL	1672	4730.4

The total thermal energy consumption during the CRS removal, hull system, S/G room modifications, and GRS assembly activities was 4730.4 kWh. The oxyfuel cutting was the only major consumer of thermal energy. It was estimated that the oxyfuel cutting processes were conducted mainly during the CRS removal operations. The LPG and propane gases were the fuel sources for the generation of thermal energy of 4730.4 kWh. The amount of LPG and propane gases combusted during the oxyfuel cutting processes was 90 kg and 270 kg, respectively. Both the LPG and propane were used for the cutting processes during the system removals. The LPG was chosen for the smooth and precise cutting of certain areas on the ship.

4.2. GHG Emissions Results

The total GHG emissions from the main stages of manufacturing, system removals, modification, and assembly during the GRS retrofit application in the GATERS project were 11,648.2 kg CO_2e. Figure 18 shows the shares of indirect and direct GHG emissions. The indirect emissions (Scope 2) due to the electricity consumption activities were 9734.1 kg CO_2e, accounting for a significant share (83.56%) of the total GHG emissions. As for the direct GHG emissions (Scope 1), these were due to the combustion of the fuels and amounted to 1914.1 kg CO_2e, accounting for 16.44% of the overall GHG emissions in the GRS retrofit project.

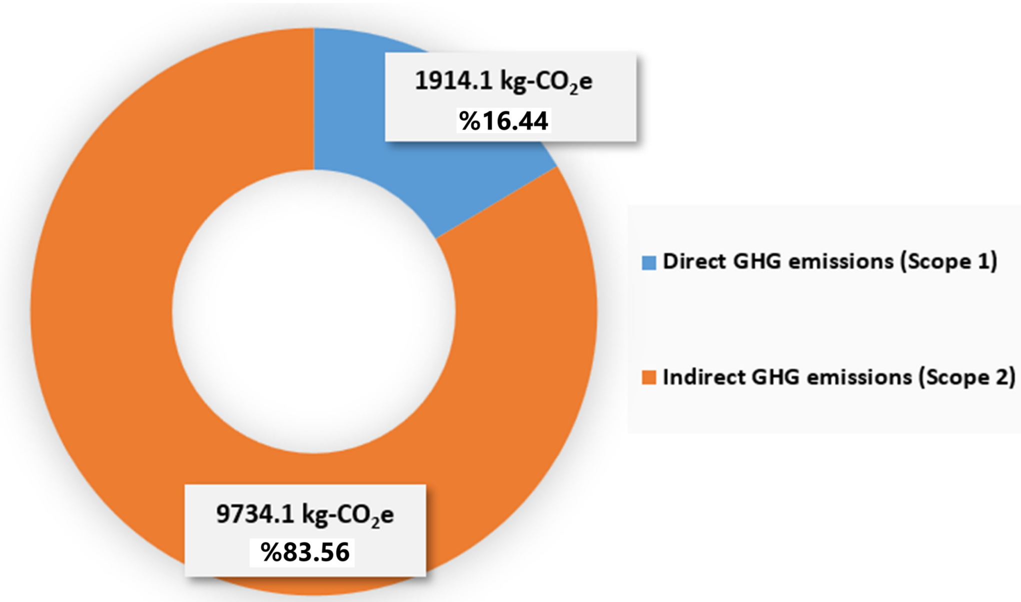

Figure 18. Comparison of direct (scope 1) and indirect (scope 2) emissions in the GRS retrofit.

The indirect emissions resulted from the consumption of electricity during the retrofit activities. Therefore, the indirect GHG emissions are directly proportional to electricity consumption. The indirect GHG emissions by retrofit stages are depicted in Figure 19. As seen, the activities in the manufacturing stage were the primary cause of the indirect GHG emissions, accounting for 8899.87 kg CO_2e, which is about 91.4% of the overall indirect CO_2e emissions, in parallel to the electricity consumption proportions. The manufacturing of the main components, such as the propeller, shaft, and rudder system components, was responsible for about 81.4% of the overall manufacturing stage indirect GHG emissions, whereas the manufacturing of the supporting elements accounted for 18.6%.

Figure 20 shows the main sources of direct carbon emissions in the GRS project. Natural gas was identified as the primary contributor to direct GHG emissions due to its more significant usage compared with other fuels. The combustion of natural gas produced 838.9 kg of CO_2e, which accounted for 43.8% of the total direct GHG emissions. The combustion of propane resulted in 806.41 kg of CO_2e, accounting for 42.1% of the total direct GHG emissions. LPG accounted for 14.1% of the overall direct GHG emissions, resulting in a GHG emission of 268.8 kg CO_2e.

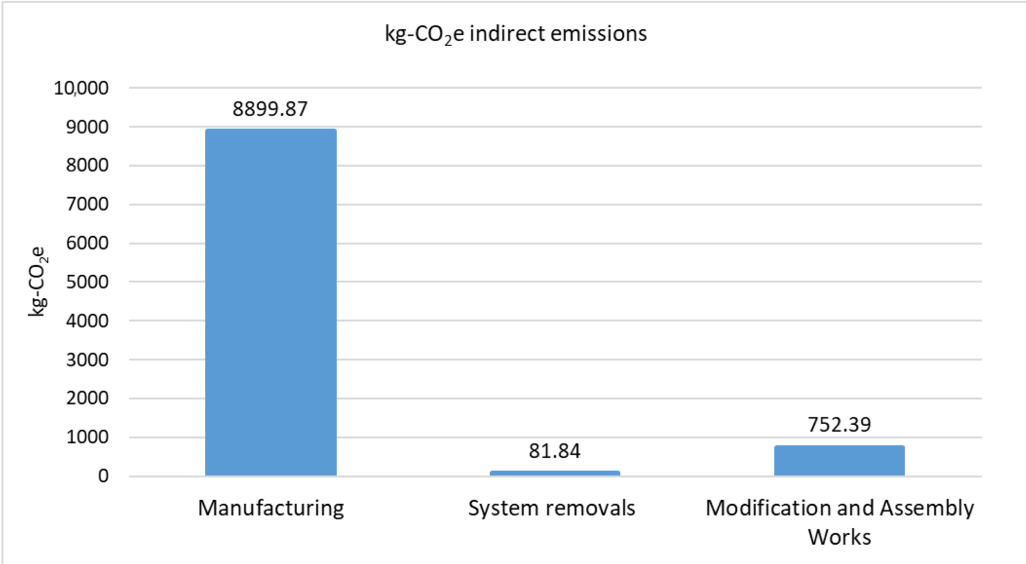

Figure 19. Indirect (Scope 2) GHG emissions by retrofit stages.

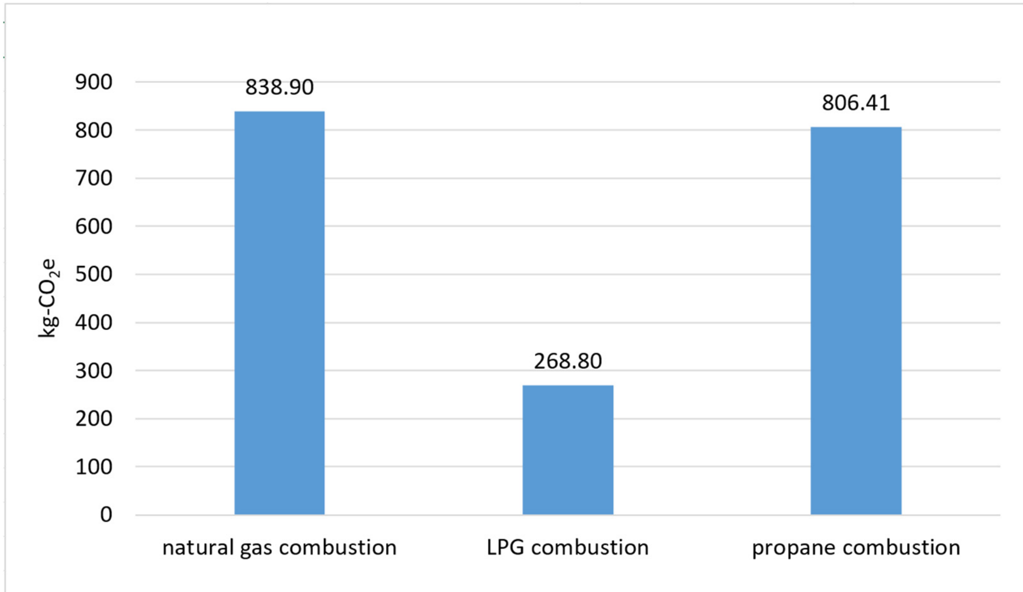

Figure 20. Main fuel sources of the direct emission (scope 1) in the GRS retrofit project.

As can be seen in Figure 21, around 56% of the total direct GHG emissions in the retrofit project were generated during the CRS removal, hull system modification, and assembly of the GRS system, primarily as a result of the oxyfuel cutting process, which led to the release of 1075.21 kg CO_2e as a result of propane and LPG combustion. The manufacturing operations contributed to 44% (equivalent to 838.9 kg CO_2e) of the overall direct GHG emissions. These emissions were primarily a result of the heating processes involved in the forging of propeller shafts and rudder stocks, carried out using a natural gas-fired heating furnace.

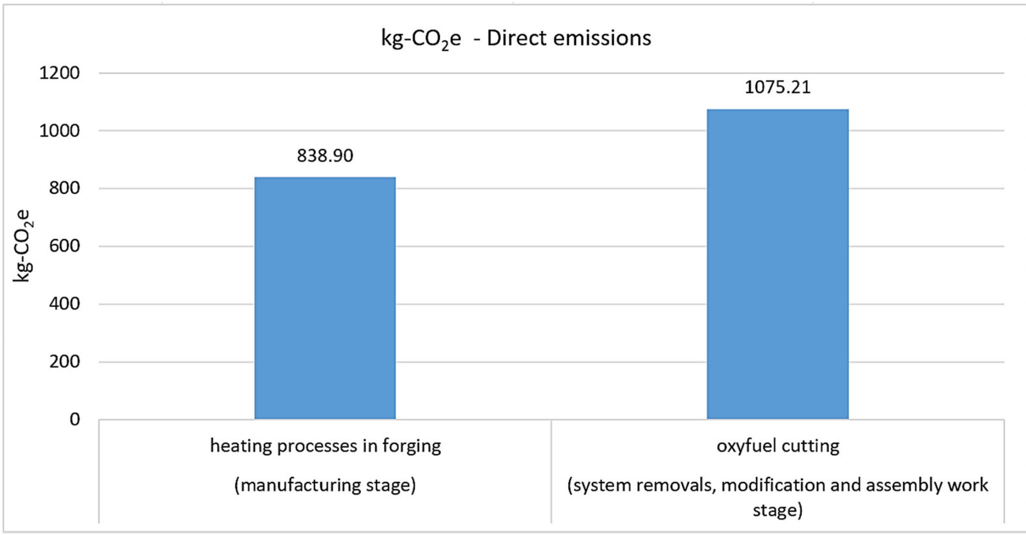

Figure 21. Comparison of direct GHG emissions in the main retrofit activities of manufacturing and system removals, modification, and assembly work stages.

5. Discussion

The results presented in Section 4 demonstrated an overall consumption of 19,507.21 kWh of electricity and 8881.3 kWh of thermal energy based on fuel use in the GRS retrofit of MV ERGE. The fuel usage for thermal energy consumption was 90 kg of LPG, 270 kg of propane, and 443.5 m^3 of natural gas. Additionally, the overall direct and indirect GHG emissions were 1914.1 kg CO_2e and 9734.1 kg CO_2e, respectively, resulting in a total of 11,648.2 kg CO_2e.

Regarding the breakdown of the above-stated consumption figures for various stages of the retrofitting process, the manufacturing stage was the most energy-intensive stage of the GRS retrofit application. Manufacturing activities were responsible for approximately 91.4% of total electricity consumption and 46.7% of total thermal energy consumption through fuel combustion. The stage of the CRS removal was the most significant thermal energy user, accounting for about 53.3 % of the total, while it was the least electricity consumer, with less than 1% of the total electricity use. The hull system and S/G room modification and the GRS assembly stages only accounted for 7.7% of the total electricity consumption and no thermal energy use.

The quantity of the indirect GHG emissions stemming from the electricity consumption was dependent on the electricity consumption and the electricity CO_2e emission factor. The electricity consumption was related to processes, while the emission factor was related to the electricity used. Because MV ERGE's home base is in Türkiye, the retrofit activities were carried out in factories and a shipyard in Türkiye, which is powered by grid electricity. The reduction of the indirect GHG emissions stemming from electricity consumption is more effortless than reducing the direct emissions from fuel combustion. A factory or shipyard can reduce electricity consumption-related GHG emissions by using renewable energy sources such as solar PV electricity through onsite generation. The leading author of this study previously demonstrated in another study that manufacturing plants where the various casted structural elements for rudder blades, rudder trunks, hydraulic nuts for propeller shafts, and rudders were produced can be entirely supplied by renewable electricity through a hybrid renewable energy system application [26]. In such a case, the indirect GHG emissions of the casted components would be significantly eliminated.

The study indicated that the manufacturing stage activities, which included the manufacturing of the GRS components and supporting elements, accounted for a significant share of the retrofit electricity consumption. The manufacturing stage contributed significantly to the overall electricity consumption, accounting for approximately 91.4%. The manufacturing of the main GRS retrofit components, such as the propeller, shaft, rudder stocks, and rudder trunks, was responsible for about 81.4% of the manufacturing-related electricity consumption, whereas the manufacturing of the supporting elements was responsible for about 18.6%. Furthermore, the manufacturing stage was the primary source of indirect GHG emissions because of the significant amount of electricity consumed, particularly due to the casting process, which was essential for the manufacturing of the GRS components such as the propeller.

Among the manufacturing processes, casting was the most significant electricity consumer, accounting for 41.3% of the overall GRS retrofit project electricity consumption and associated indirect GHG emissions. All the casting components, apart from the propeller and stern tube, were produced using the same material (i.e., GS45) in the same foundry, and their total energy consumption was 5889 kWh of electricity. Melting is the most energy-intensive process in a casting facility and requires special consideration in terms of energy efficiency. The lead author of this paper previously conducted an energy audit of the foundry that produced the casting components for the retrofit project, to assess its energy consumption and efficiency potentials [26]. The author found that the casting energy consumption of the foundry due to the casting processes, including melting, grinding, and shot blasting, could be reduced by about 14.5% through improved melting practices, including the use of clean scrap and efficient furnace management. Bearing this in mind, there is a potential 14.5% reduction in electricity consumption and associated GHG emissions in the manufacturing of those cast components, including the structural elements for rudder blades, rudder trunks, hydraulic nuts for propeller shafts, and rudders. This corresponds to an approximate 4.3% saving in the entire electricity consumption of the GRS retrofit together with associated indirect GHG emissions. Furthermore, the structural design of the rudder blades necessitated the welded assembly of various sub-components, including the 2611 kg cast elements. By optimising the structural design of the blades (structural reconfiguration), it is possible to eliminate the energy-intensive cast components and use materials that necessitate less energy-intensive manufacturing processes, such as machining from metal billets, in future applications, taking the material and machining cost into account.

Plasma cutting was another major energy user, contributing 12.6% to the aggregate electricity consumption and related indirect GHG emissions of the GRS retrofit. The cutting of steel plates for the fabrication of the moulds was responsible for approximately 46.3% of the plasma cutting electrical consumption (see Figure 16). These moulds may be employed in future GRS retrofit applications of comparable size with the GATERS project. Consequently, the indirect GHG emissions of 571.35 kg CO_2e and 1145 kWh of electricity will be avoided by reusing the moulds in future applications. This corresponds to about a 6% reduction in total electricity consumption and associated indirect GHG emissions in future GRS applications of similar size, given that the same manufacturing facility carries out the manufacturing of the rudder blades.

The forging processes used to manufacture the propeller shaft and rudder stocks accounted for about 14.1% of the total electricity consumption and indirect GHG emissions in the retrofit project. The electricity consumption in the forging processes was due to the operation of the forging press and the execution of auxiliary forging processes such as cutting and finishing. Because no data were available regarding the specifications of these processes, an evaluation of their energy consumption was recommended. Nevertheless, there is room for energy savings through reusing the existing shaft. The situation on the target vessel, MV ERGE, necessitated the replacement of her shaft. Reusing the existing shaft in the retrofit could prevent the consumption of 2118 kWh of thermal energy and 1412 kWh of electricity. This translates into considerable savings of about 14% of the total natural gas-related thermal energy use and 7.2% of the total electricity use in the retrofit project.

The machining of the forged shaft and rudder stocks using a manual horizontal lathe accounted for approximately 10% of the GRS retrofit's total electricity consumption. The energy consumption of the machining process depends on the efficiency of the machine tool and the material removal rate. The manual lathes used for machining the forged steel in the project were quite old. Several studies [26,40–42] have demonstrated that the age of the machine tool can adversely affect the energy consumption of machining processes. For instance, [26] demonstrated that a 4-year-old CNC vertical lathe utilised approximately 45% less electricity than a 30-year-old lathe for the same machining task. Therefore, using new and efficient machine tools to conduct the machining operations has the potential to decrease the consumption of electricity in future GRS retrofit applications. Furthermore, by forging the rudder stocks and shafts to near-final dimensions, the need for machining can be minimised, resulting in a reduction in electricity consumption during the machining process.

Grinding processes using angular grinders accounted for approximately 10.9% of total electricity consumption and indirect GHG emissions. About 84.6% of the total grinding process electricity consumption was due to the manufacturing stage, which is 1806 kWh of electricity, whereas the CRS removal, modification, and GRS assembly stages accounted for 328 kWh. Reducing the workload on grinding by achieving cleaner and more precise steel cuttings, especially oxyfuel cuttings, can lessen the need for secondary grinding processes and, consequently, power consumption. Similarly, better weld seams with fewer finishing tasks can reduce grinding energy consumption. Future GRS retrofit applications should consider these factors. Besides, it was estimated that about 80% of the total electricity use in the grinding process in the manufacturing stage was due to the manufacturing of the moulds. Similar to the plasma cutting process, reusing these moulds can provide an 867.2 kWh reduction in future GRS retrofit applications.

The welding processes accounted for approximately 7.3% of the overall electricity consumption, totalling 1438 kWh. The fabrication of gate rudder blades, trunks, and moulds at the factory accounted for 543 kWh of welding process electricity use, while the rest of the electricity consumed was for the hull system modification and assembly activities at the shipyard. The ACAG used for welding preparations in the modification and assembly stage was responsible for 449 kWh of electricity consumption. There are various factors affecting the power consumption of a welding process, including the efficiency and duty cycle of the welding equipment power source, the skills of the welder, and operation parameters such as welding speed and amperage values. These factors should be considered during welding processes. The manufacturing of the moulds consumed around 60% of the total welding process electricity consumed in the manufacturing stage. By utilising these moulds again in future GRS applications of comparable dimensions, it is possible to avoid the use of approximately 323 kWh of electricity consumption and the release of 162.5 kg CO_2e of indirect GHG. This results in approximately a 1.5% decrease in overall electricity usage and the resulting indirect GHG emissions from the GRS retrofit.

When it came to thermal energy consumption, the oxyfuel-cutting process was the only thermal energy consumer and the primary source of direct GHG emissions in the stages of CRS removal, hull system modification, and assembly. Through using LPG and propane, the oxyfuel cutting process contributed to approximately 53.3% of the total thermal energy consumption and 56% of the total direct GHG emissions in the retrofit project. During the manufacturing stage, the heating processes involved in the forging processes were the primary thermal energy consumers. The preheating and heat treatment processes carried out in natural gas-fired furnaces were responsible for about 46% of the overall thermal energy use and 44% of the direct GHG emissions.

The direct GHG emissions can be substantially reduced through electrification. For example, if the heating processes within the forging of the shaft and rudder stocks were carried out in an electric heating furnace (with an efficiency of 85%), the GHG emissions would be 1462 kg of indirect GHG emissions, compared with the onsite release of 839 kg of direct emissions from the natural gas-fired furnace. The high cost of electricity significantly hinders the use of electric furnaces. Nevertheless, if the electric furnace is powered by a cost-effective, clean electricity source, the indirect emissions could be substantially minimised.

In addition, plasma cutting can be considered to replace emission-intensive oxyfuel cutting. Plasma cutting uses electric power and produces no direct emissions from fuel combustion, whereas oxyfuel cutting does. Furthermore, compared with oxyfuel cutting, plasma cutting provides superior cut edges of high quality with fewer slag occurrences [43]. This can eliminate the need for additional finishing processes, such as angle grinding, and further reduce energy use. However, the plasma-cutting process has some drawbacks, including the higher cost of electricity compared with fuels and the higher initial investment costs of plasma-cutting machines. In addition, oxyfuel cutting torches have better portability and mobility than plasma [43]. After evaluating these economic and operational aspects, plasma cutting's potential for future GRS retrofit applications to effectively eliminate direct GHG emissions can be considered.

It is clear that energy consumption and associated GHG emissions can be reduced through various strategies in future applications of GRS retrofit. These include energy efficiency, clean electrification, tool and mould reuse, product reconfiguration, and reconditioned component reuse. For example, reusing the GATERS project's moulds in future GRS retrofit applications of similar size can save about 2335.2 kWh of electricity and 1165.26 kg of indirect GHG emissions. This represents a significant 12% reduction potential in total electricity use and associated GHG emissions in the GRS retrofit. Notably, the manufacturing of GRS components accounts for a significant portion of energy consumption. The potential of reusing the target ship's existing components, such as the propeller shaft or other components, through reconditioning should be investigated to save energy and emissions. In addition, the energy efficiency of the production system and equipment should be evaluated. These aspects should be part of the strategic planning for any future GRS retrofit projects.

6. Conclusions

This study provided a detailed assessment of the energy consumption and associated GHG emissions during retrofitting of a ship with a new propulsive EDS. The study was based on the successful application of a novel ESD, the GRS, to a general cargo ship (MV ERGE) as the first retrofit application of the GRS as part of the EC's H2020 Innovation Action project GATERS. This paper presented a systematic and customised methodology framework that offers novel insights into the analysis and assessment of energy consumption and related carbon emissions in GRS retrofitting. The study shed light on the energy consumption and associated carbon emissions during the novel ESD retrofitting stages, which include manufacturing, existing system removal (CRS), and modification of the hull system. Also, some potential state-of-the-art strategies to reduce energy use and emissions in future GRS retrofit applications were discussed.

The following are the major conclusions of the study:

(1) The total energy consumption during the major stages of the GRS retrofit application to the 90 m target coastal general cargo vessel was 19,507.21 kWh of electricity and 8881.3 kWh of thermal energy through fuel combustion. Therefore, the GRS retrofit was an electricity-intensive process. The fuel consumption for thermal energy generation was 90 kg of LPG, 270 kg of propane, and 443.5 m^3 of natural gas. The direct GHG emissions were 1914.1 kg-CO_2e, and the indirect GHG emissions were 9734.1 kg-CO_2e, resulting in a total of 11,648.2 kg-CO_2e.

(2) The manufacturing stage of the GRS main components was the most significant energy consumer in the retrofit project, accounting for approximately 91.4% of electricity consumption and 46.7% of thermal energy consumption. Additionally, manufacturing activities accounted for about 91.4% of the indirect GHG emissions (Scope 2) and about 44% of the direct GHG emissions (Scope 1). The existing system (CRS) removal stage was the most important thermal energy consumer, contributing to about 53.3% of the overall thermal energy use through fuel combustion and 56% of the total direct carbon emissions. The total electricity consumption during the hull system and

S/G modification and assembly stage was around 7.7% of the overall retrofit project electricity use.

(3) Casting, plasma cutting, forging, grinding, and machining are the major energy consumers in the manufacturing stage. Their contributions to the overall electricity consumption were 41.3% for casting, 14.1% for forging, 12.6% for plasma cutting, 10.9% for angle grinding, and 10% for machining. The heating process of the forging process was the only significant thermal energy user in the manufacturing process.

(4) A total of 81.4% of electricity consumption and 100% of fuel consumption (i.e., natural gas) within the manufacturing stage were attributed to the production of new components, whereas 14.3% of the electricity consumption was used in mould manufacturing. Therefore, the reuse of the ship's existing components in the GRS retrofit through reconditioning can be considered for energy and emissions savings. Also, the reuse of the moulds in future GRS retrofit applications of similar size can prevent a considerable 12% of total electricity consumption and associated emissions.

(5) Additionally, implementing clean electricity based on low-carbon renewable energy sources like solar PV generation onsite the plant can significantly reduce the indirect emissions associated with electricity consumption. The direct emissions from fuel combustion can be reduced by increasing energy efficiency as well as transitioning to electrification, such as from a gas-fired furnace to an electric furnace and from oxyfuel cutting to plasma cutting, provided that the cost of electricity is taken into account.

This study provided valuable insights regarding energy consumption and related GHG emissions during the manufacturing, existing (CRS) system removal, hull system modification, and assembly stages of a GRS retrofit, along with the reduction potentials. The findings of this study can guide the implementation of strategies to reduce energy consumption and emissions in future GRS retrofits and other complex propulsive ESD applications. Future GRS retrofitting projects can utilise the methodology framework that this study developed for strategic planning and life cycle cost assessments. The findings are invaluable for practitioners, scholars, and decision-makers.

The present study focused solely on the energy consumption and associated GHGs that resulted from the activities conducted during the retrofit stages. The authors are planning to extend this study to a more comprehensive GHG assessment covering the emissions from other sources, such as processes, transportation, and embodied emissions in the raw materials.

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Conflicts of Interest: Author Osman Gürsoy was employed by the company GÜRDESAN Ship Machinery Inc. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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