THE EFFECT OF LNG AND DIESEL FUEL EMISSIONS OF MARINE ENGINES ON GHG-REDUCTION REVENUE POLICIES UNDER LIFE-CYCLE COSTING ANALYSIS IN SHIPPING

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ABSTRACT

The fuel life cycle involves different phases of extraction/refinery (well to tank: WtT), transport (tank to propeller: TtP), and storage where each of these processes can add a specific amount of emissions to the overall LCCA inventory. During the extraction or operation of machinery on the raw material, the released amount of GHG components is undergoing a change in the generated emissions per functional unit of the consumed fuel. As a result, the machinery efficiency, electricity share, and resources mix during the extraction or refinery would impact the emission factor and subsequent carbon credit plans. Additionally, the transportation characteristics such as the traveled distance, multi-model transportation share, and ship engine fuel efficiency can make difference in the emitted GHGs into the atmosphere. The GHG credit rate and duration under different carbon allowance scenarios in the LNG-powered vessel are considered for the current life-cycle carbon emission cost analysis. For the life-cycle costing, the inflation rate, and the discount rate along with the emission reduction incentives are going to be emphasized in the project's feasibility indicators and its profitability. The results have shown to what extent the LNG use in marine transportation can favor green shipping and how the legislated carbon incentives encourage the shipping industry for the LNG infrastructure development. The methane slip (evaporation) during the liquefaction of LNG will also be addressed, i.e., during the LNG production phase, and its effect on the emission factor of GHGs to have a better understanding of the challenges and outlook on the LNG production industry and its utilization in shipping.

Keywords: Emission factor, GHG reduction revenue, LCCA, LNG, Process modification

1. INTRODUCTION

There are ongoing efforts towards decarbonization in shipping industry since the sea-transport makes 1.1 GtCO2 emission annually that constitutes 3% of the worldwide emission [1]. The international maritime organization (IMO) has declared the greenhouse gas (GHG) ambitions for international shipping to establish 50% GHG reduction by 2050 compared to 2008 to address the emission threat [2]. Decarbonization can be accomplished using renewable energy like the electrification of naval fleet, using energy efficient methods in the powertrain of ships or the use of alternative fuels. Heavy fuel oil (HFO)and marine diesel oil (MDO) are the main currently used fuels in the marine sector [3] that have a high carbon ratio in their composition and the combustion of these fuels release high carbon emission to the atmosphere. Among alternative fuels, Liquified Natural Gas (LNG) is promising due to its 30% potential for CO2 reduction and cost-effectiveness in the market [4].

An investigation on the fuel Lifecycle cost assessment (LCCA) in the shipping industry has gained attention but facing many challenges in terms of lacking enough research on the energy production, supply and demand, consumption, and emissions. A majority of the research studies indicating the emission differences with different fuels and fail to consider the upstream process of the fuels but focus instead on the end user of the fuels [5,6]. Moreover, several studies have only concentrated on the released emissions because of the energy consumption differences, but not the emission factors influenced by the fuel lifecycle [7]. For different alternative fuel lifecycles, although the amount of the emission disparity is reported in [8-10], the production stage of the fuel and possible variety in technical parameters have not been dealt with properly. Park et al. [11] recently engaged in a live-LCA method for the clean maritime economy to determine the effect of carbon-free fuels on global warming potential (GWP). The results of their method reaffirmed the dependency of the emissions on the fuel/energy production approach with relevant energy resources during the production pathway. Balcombe et al. [12] discussed the LNG-powered ship viability plan to achieve the decarbonization policies from the financial and environmental aspects. The reported results suggest that LNG enhances air quality and costs, hence ship energy efficiency can be upgraded 35% to fulfill the decarbonization ambitions. Methane slip is a serious problem from marine engines, and it can be concluded that it is beyond the acceptable threshold in some situations, noting that LNG-operated engines can ideally diminish 28% GWP in a combination with the fuel supply chain. Bui et al. [13] analyzed the LCCA of a dual-fuel LNG-diesel engine where a 33% CO2 reduction possibility is reported. In the research, the carbon pricing has also been emphasized with a basic diesel engine and dual-fuel LNG-diesel engine while the carbon cost reduction by a dual-fuel engine under different pricing scenarios is contrasted. This study is an effort to consider the LNG fuel lifecycle modification during the production and transportation process and to observe the emission factors of GHG components. The emission factors, GWP, and fuel consumption in a vessel can be used to calculate the amount of generated emissions t and the cost associated with such emissions. The economic evaluations of LNG emissions compared to diesel are analyzed in two ways of lifecycle carbon emission costing and GHG reduction revenue in different LNG LCCA pathways. The workflow procedure of the emission economy by the LNG lifecycle modification compared to diesel is illustrated in Fig. 1.

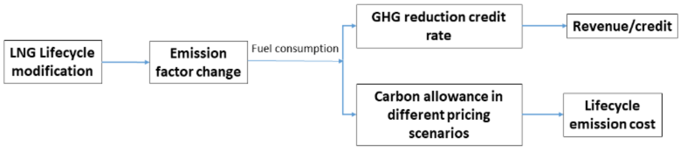

FIGURE 1: The step-by-step process diagram to calculate the emission economy

2. MATERIALS AND METHODS

In this study, the lifecycle cost assessment (LCCA) of two fuels i.e., LNG and low sulfur diesel (LSD) are considered. Firstly, the process of LNG LCCA is modified in two aspects of the stationary process and transportation process of the pathway and the subsequent emission factor changes are monitored. These emission factors along with fuel consumptions/distances of a selected ship that accounts for GHG emissions. Secondly, the amount of emission reductions in relation to diesel is tracked to observe the economic implications or reduction of revenue under different scenarios. The various cases of LNG LCCA modifications are categorized in Table 1 with S and T denoting the change in the stationary or transportation processes of the fuel pathway.

TABLE 1: Designed cases for the LCA modification and emission cost analysis

Scenarios	Comments
S1	CH4 coproduct decrease to 15.8 g + LNG losses decrease to 10% i.e., CH4 evaporation
S2	CO2 sequestration from H2 gas production from NG: carbon capture
S3	Electricity shares increase to 10% in the liquefaction mix
S4	Large gas turbine efficiency decreases to 90%
T1	Barge (LNG90 diesel10) & Tanker (LNG90 diesel10) with corresponding brake specific fuel consumption (BSFC) modification
T2	Avg. speed 50% increase compared to the base case
T3	load factors decrease to 0.75

S: stationary process, T: transportation process

2.1 Lifecycle assessment of fuels

The LCCA is composed of many steps, such as end-use, transportation, distribution, and production. In the proposed model, each stage is represented as a stationary or transportation process. At each process step, the respective emissions can be emitted in several ways: (a) combustion of process fuels that provide heat and energy for the process, and (b) leakage which is usually associated with the storage and transportation of volatile fuels. To account for energy inputs to a process, a list of resources is considered (associated amounts). To account for process emissions, an integration among various technologies is considered. Each resource is used in a process that can be allocated to one or more technologies. To model the entire lifecycle, the processes can be combined into pathways. The pathway of two fuels, namely LNG and low sulfur diesel (LSD) with the chain of processes including stationary (blue boxes) and transportation (pink boxes) are illustrated in Fig. 2.

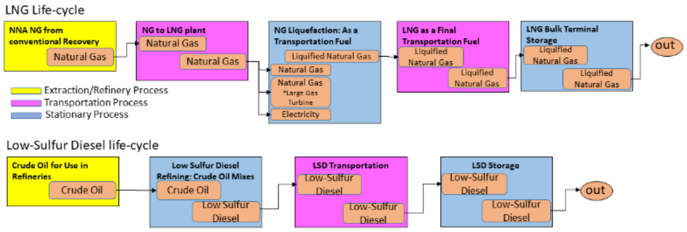

FIGURE 2: The lifecycle of LNG and LSD fuels with associated resources and technologies

2-2 The Greenhouse Gas (GHG) Emission Reduction

The proposed model estimates the GHG reduction (mitigation) potential of LNG use in marine engines with compared to fossil fuel of diesel. The model calculates the GHG emission profile for a base case (diesel engine operation as the baseline case), and for the proposed case (clean energy project: LNG with gas-powered engine). The GHG emission reduction potential is obtained by combining the difference of the GHG emission factors with annual fuel consumption in a selected marine engine. The model uses carbon dioxide, the most common GHG, as a common currency: methane and nitrous oxide emissions are converted into their equivalent carbon dioxide emissions according to their "global warming potential" (GWP). International scientific committees such as the International Panel on Climate Change [IPCC, 1996] [14] have proposed GWP factors for these gasses.

The GHG emission factors for the base diesel case and the proposed LNG are estimated as:

$$e_{base:diesel} = (e_{CO_2} GWP_{CO_2} + e_{CO_2} GWP_{CO_2} + e_{CO_2} GWP_{CO_2})_{diesel} \quad (1)$$

$$e_{proposed:LNG} = (e_{CO_2} GWP_{CO_2} + e_{CO_2} GWP_{CO_2} + e_{CO_2} GWP_{CO_2})_{LNG} \quad (2)$$

The GHG reduction amount (Δ_{GHG}) equals:

$$\Delta_{GHG} = e_{base:diesel} FC_{diesel} - e_{\mathrm{proposed}:LNG} FC_{LNG} \quad (3)$$

Where *e* represents the emission factor and FC is the fuel consumption of the vessel annually, *GWP* is the global warming potential, where the following values are considered $GWP_{CO2} = 1$, $GWP_{CH4} = 28$, and $GWP_{N2O} = 265$ [15].

GHG emission reduction revenue (GRR):

The GHG reduction (in tons) can be quantified by the GHG emission reduction revenue (GRR) [16]:

$$GRR = -\frac{ALCS}{\Delta_{GHG}} \quad (4)$$

The annual life cycle savings (ALCS) is the levelised nominal yearly savings.

The fuel consumption of a ship depends on the fuel's lower heating value (LHV), i.e., to maintain a fixed power and load to be able to compare the fuel efficiency. In this study, for a selected vessel, the vessel characteristics and fuel specifications are summarized in Table 2. According to values in Table 2, LNG has a lower fuel consumption since it has a higher heating value and energy intensity. Therefore, higher emissions are expected from diesel rather than LNG which has to be considered in addition to the emission factor.

TABLE 2: Ship characteristics and fuel specifications

Ship speed (kn)	8.0
Engine speed (rpm)	650
Main engine power (kW)	1346.8
Avg. fuel consumption: diesel (ton/day), BSFC (g/kWh)	5.26, 181.1
Avg. fuel consumption: LNG (ton/day), BSFC (g/kWh)	3.77, 137.0
LHV: diesel (MJ/kg)	42.7
LHV: LNG (MJ/kg)	48.0

3. RESULTS AND DISCUSSION

The obtained results are categorized into three sections: the emissions, economic consequences of the emissions that fall into GHG revenue and lifecycle carbon emission costing.

The lifecycle of LNG and LSD fuels are considered and the emissions per gram are assessed for the functional energy unit of 1 MJ. In this sense, the emission factors of three main GHG components of CO2, CH4, and N2O are obtained. The first phase of this study concerns the estimation of the emission factors of the annual gross GHG emissions for each designed LCCA of the LNG. Based on this amount (in unit of equal ton of CO2), the emission reduction credit or carbon emission cost can be calculated. For the changes in the lifecycle pathway, the stationary process and transportation blocks are modified. In the stationary process, the liquefaction stage of the LNG production is chosen, and the corresponding cases are represented by "S". For the transportation process, the tanker and barge shipping characteristics are of the interest of this study and the cases related to transportation are represented by "T". The flowchart diagram of the LCA modification and the final LCC of carbon emission (GHG revenue) is demonstrated in Fig. 3.

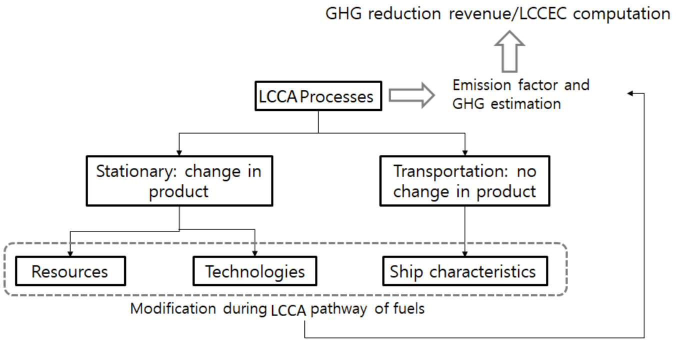

FIGURE 3: The LCCA and emission cost/credit link

The variation of emissions for different cases are shown in Fig. 4 where the lowest amount of each emitted gas for the pertained case of LCCA can be monitored and detected. These emissions are illustrated under their corresponding global warming potential (GWP) coefficients and added together to constitute the GHG amounts. The lowest CO2 amount pertains to S2 with 11.173 g/MJ that is well below the base LNG lifecycle (13.7%). The case of S2 deals with the carbon capture technology added to the natural gas resource by CO2 sequestrations from gaseous hydrogen (G H2) of natural gas (NG) by the ratio of 40%. On the contrary, the highest CO2 amount is emitted by S4 where the gas turbine efficiency has been decreased. If the efficiency of the turbine decreases, the combustion process has not completed, and it is expected that the CO2 amount increases accordingly. As a result, the CO2 emission factor compared to the base case increases. The lowest CH4 emission occurred for the S2 situation in which there have been actions taken to reduce the methane leakage and CH4 coproduct reduction by using a less evaporation of 10%

compared to the base case having more methane evaporation. Other cases involving stationary or transportation calculations in the LCA process do not affect the CH4 emissions, drastically. It can be admitted that the best strategy to reduce the N2O emission is adopting a higher share of the electricity mix by 10% (S3 case). In this way, in addition to N2O, tCO2 can also be decreased by giving more electrical power for the liquefaction of CH4.

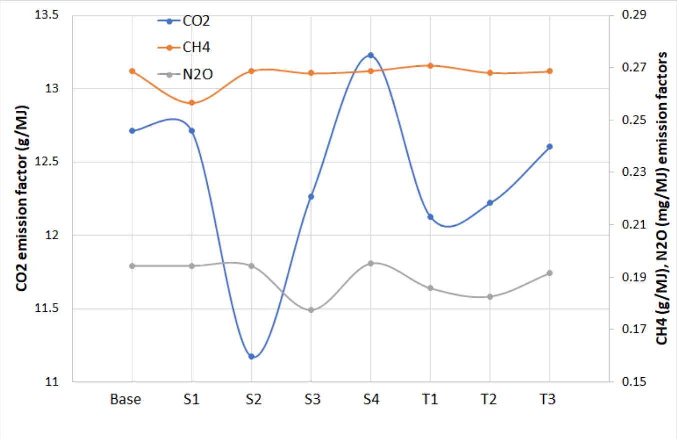

FIGURE 4: The variation of main GHG components based on emission factor: CO2, CH4, and N2O

The GHG reduction by different cases of the LCCA for LNG compared to diesel (LSD) is displayed in Fig. 5. The highest GHG reduction can be implemented by S2, while T1 ranks the second optimal scenario to reduce the GHG emissions. The case of T1 governs the transportation block modifications, where the fuel mix of LNG90Diesel10 (90% LNG with 10% pilot diesel)is used instead of the pure diesel fuel in a marine engine of a selected vessel. In this manner, the BSFC of the vessel also decreases since the LNG-powered engine consumes lower LNG fuel. As a result of cleaner gas fuel use in the engine, there will be lower CO2, and N2O versus diesel transport, leading to a 18% GHG reduction. This shows that by selecting proper technologies during the fuel production phase more emission reduction is plausible.

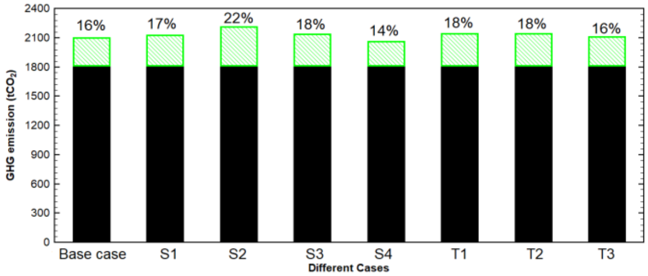

FIGURE 5: The GHG-100 emission reduction by using different LNG lifecycle modifications instead of diesel

In this study, only carbon emission costing is emphasized that is directly linked to the respective emissions produced during the Lifecycle of the fuel. Two different approaches for the financial assessment of the LNG fuel are considered. The first approach governs the credit or revenue of the emission control policies that encourage the policy makers to reduce the respective emissions. The second approach considers the emission generation as a cost payment that must be paid per 1 ton of the generated equal CO2.

The values of GHG reduction credits, per equivalent tons of CO_2 (tCO_2), changes drastically based on how that is priced and will be delivered. Other factors which have an impact on the price may include various measures: voluntary or mandatory emissions reduction requirements; private or public purchase of credits; credits traded within, for example, the European Union Greenhouse Gas Emission Trading Scheme (EU ETS), other national, transnational, or regional schemes; type of technology used to generate the emissions reductions; and others. As of May 2014, the prices (including rates for carbon taxes) varied between $US 1 to $US 168 per tons of CO_2 [World Bank Group/ECOFYS, 2016] [17]. However, for this research, the values used for crediting the emission reduction calculations are based on the case under study for the marine technology as per mentioned in Table 3. The emission from which industry like the power plant, marine industry, boilers, etc., can be assigned to different GHG credit rate. The credit rate mentioned in Table 3 is for use of engine in marine use application.

TABLE 3: Parameters assumed for the GHG reduction revenue for the LNG use instead of diesel

parameter	value
GHG reduction credit rate (€/tCO2) [18]	100
GHG reduction credit duration (yr)	4
GHG reduction credit escalation rate (%)	2
GHG credits transaction fee (%)	1
LNG fuel consumption (MWh)	20,384
Diesel fuel consumption (MWh)	23,152

For the calculation of the extent of the credit or emission reduction revenue, it is important to have the amount of fuel consumption in the ship and the annual distance that the vessel is traveled. The fuel consumptions for both LNG and diesel are available in Table 2. The fuel consumption multiplied by the GHG emission factors gives the GHG emission per equal tons of CO2. The differences of GHG emissions of LNG and diesel yield the gross annual GHG emission reduction and by applying the GHG credits transaction fee, where the net annual GHG emission reduction is achieved. For different cases in this study, the fuel consumption, and the traveled distance (100,197 km) are constant but the emission factors of the LCCA vary according to the modifications in the stationary/transportation processes. The variations of GHG reduction revenue for different cases of the LNG Lifecycle is shown in Fig. 6. The CO2 sequestration technology incorporation of S2 results in the highest GHG reduction with the respective profitability. Furthermore, this technology installment and equipment cost must be considered in the final LCC evaluation to observe if it is economically viable. The electrification of the LNG liquefaction process can also reduce the respective emissions and gives a 32,352 € revenue income.

For the stationary processes of S3 and S4, the extent of electricity share and gas turbine efficiency change on the final GHG reduction revenue. That is an interesting outcome and is plotted in Fig. 7. The economic changes of these factors are compared with the level of the reference LNG case (default LNG lifecycle available in GREET model: LNG as a transportation fuel from non-north American NG). The increase of electricity share from 2% to 5% and 10% resulted in a higher GHG revenue than the reference case of LNG. On the other hand, the GT efficiency is reduced to 90% and 85% resulted in a lower GHG reduction income. The lower the efficiency of the gas turbine, the more power input is required, and higher emissions are generated thus the GHG reduction price has dropped by 19.61% for η_{GT} = 85% compared to the reference case (isentropic gas turbine operation).

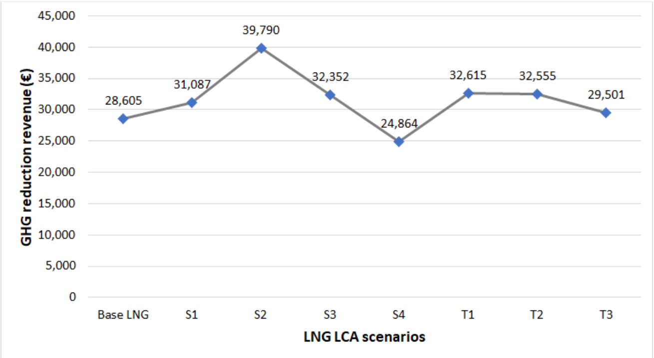

FIGURE 6: The GHG reduction revenue for different cases of the LNG lifecycle modifications

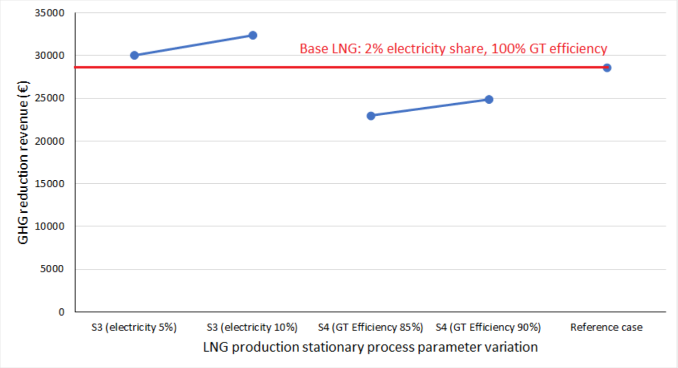

FIGURE 7: The case-sensitive variations of electricity share and gas turbine efficiency and their impact on the GHG reduction revenue

This approach considers a penalty on the equal tons of emitted CO2 and is signified with lifecycle carbon emission cost (LCCEC). These costs regard the carbon allowance during different years for different EU policies (these factors are gathered in Table 4). These factors are multiplied by the equal tons of CO2 emission and resulted the LCCEC. The LCCEC criteria are calculated for each case of the LNG lifecycle according to the following equation [19]:

$$LCCEC = \sum_{i=1}^{20} EqCO2_i \times CA_i \tag{5}$$

Wherein the *CA* signifies the carbon allowance and i subscript denotes the year in the ship's lifetime. In this study, the carbon allowance values of different policies for the LCCEC are calculated for the year 2040, mentioned in Table 4.

TABLE 4: CO2 price scheme according to the European Union policies for the carbon emission life-cycle cost [20]

	2025 CO2 price (€/ton)	2040 CO2 price (€/ton)
Current policies (CP)	20	34
New policies (NP)	22	38
Sustainable development (SD)	56	125

The equal tons of CO2 for diesel, the base case of the LNG, and modified cases of the LNG lifecycle are shown in Fig. 8. As depicted in this plot, diesel has higher emissions compared to all LNG cases since it has higher CO2 emissions and carbon chain (in chemical composition of fuel)but lower CH4 emissions. The CH4 leakages or CH4 evaporations of the LNG fuel during the liquefaction are addressed in case S1. By applying case S2, the CO2 amount decreases from 1800 tCO2-eq to 1400 tCO2-eq from LSD to LNG and this reduction leads to a significant cost reduction, especially to support the sustainable development policies. As shown in Fig. 9, the associated amount of a cost reduction in this scenario is about 50,237.5 €. Using the transportation processes of engine load reductions, LNG as a replacement in the fuel mix in a marine engine, and avg. speed increase are feasible scenarios to reduce the respective emissions and have the LCCEC reductions as demonstrated in Fig. 9.

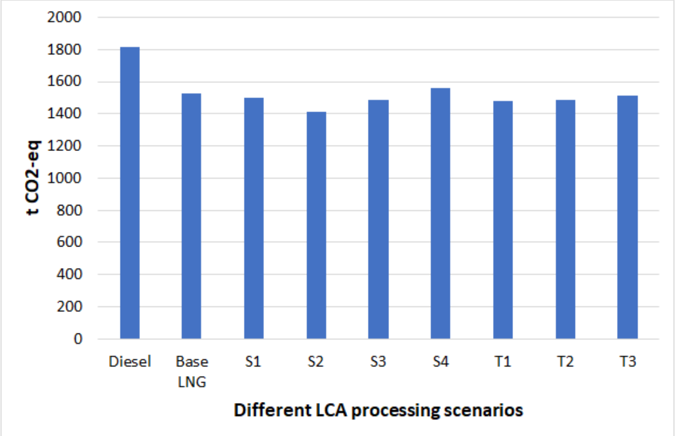

FIGURE 8: The equivalent tons of CO2 production for diesel, base LNG, and modified LNG during the fuel lifecycle

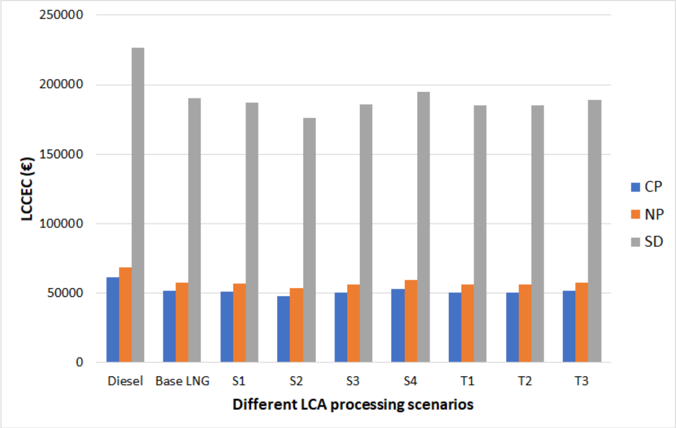

FIGURE 9: The LCCEC variation for different scenarios

In the end, the combination mode of the stationary process of S2 with the transportation process of T1 is the optimal LNG lifecycle pathway (S2+T1). In this hybrid case, a 25% GHG reduction is possible compared to diesel and the GHG reduction revenue reaches up to 43,984 € while the LCCEC based on SD policy amounts to the lowest 170962.5 €.

4. CONCLUSION

In this work, the lifecycle processes of the LNG fuel are modified to have the lowest emission factor. The emission factors along with the fuel consumption per year determine the equivalent CO2 reduction and therefore the emission cost/credit can be calculated. The results indicate that by a combination of the change in stationery and transportation (S2+T1), the GHG reduction from the base case of 16% increases to 25%, and a positive income because of GHG reduction increases up to 43.9 k€.

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