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A life cycle approach for the use of hydrogen as a marine fuel: Analysis and results

Diploma Thesis

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Abbreviations

ABBREVIATIONS LIST	
AD-Test	Anderson-Darling test
AFC	Alkaline Fuel Cell
ATR	Autothermal Reforming
BH	Blue Hydrogen
CapEx	Capital Expenses
CCS	Carbon Capture Storage
CDF	Cumulative Distribution Function
CH2	Compressed Hydrogen
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
CO2eq	CO2 Equivalent
COP	Conference Of Parties
DOE	Department Of Energy
EEDI	Energy Efficiency Design Index
EF	Emission Factor
EU	European Union
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
GNH	Green Hydrogen
GWP	Global Warming Potential
IMO	International Marine Organization
IRR	Internal Rate of Return
ISO	International Organization of Standarization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LH2	Liquified Hydrogen
LNG	Liquified Natural Gas
LS_MGO	Low Sulphur Marine Gas Oil
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
NCV	Net Calorific Value
NO2	Nitrogen dioxide
NOx	Nitrogen oxides

NPC	Net Present Cost
NPV	Net Present Value
OpEx	Operational Expenses
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
POX	Partial Oxidation
PSA	Pressure Swing Adsorption
SFC	Specific Fuel Consumption
SLOC	Specific Lubricant Oil Consumption
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cells
SOFC	Solid Oxide Fuel Cell
SOx	Sulphur Oxides
SR	Steam Reforming
WGS	Water-Gas Swift
H2	Hydrogen
YSZ	Yttria-Stabilized Zirconia

Περίληψη

Σκοπός της παρούσας διπλωματικής εργασίας είναι η ανάλυση κύκλου ζωής, περιβαλλοντική και οικονομική, των πλοίων που χρησιμοποιούν υδρογόνο ως καύσιμο για την πρόωση τους, χρησιμοποιώντας τους σχετικούς κανονισμούς των προτύπων ISO για τις αποτιμήσεις κύκλου ζωής. Η μελέτη συμπεριλαμβάνει σύγκριση των αποτελεσμάτων για τους διάφορους τύπους υδρογόνου(γκρι υδρογόνο, μπλε υδρογόνο, πράσινο υδρογόνο), καθώς και σύγκριση ανάμεσα σε υγροποιημένο και συμπιεσμένο αέριο υδρογόνο. Επιπλέον, γίνεται σύγκριση με τα αντίστοιχα αποτελέσματα πλοίων που χρησιμοποιούν συμβατικά καύσιμα, καθώς στόχος της μελέτης είναι να εκτιμήσει τα περιβαλλοντικά οφέλη(ή αντίστοιχα την οικονομική επιβάρυνση) λόγω της χρήσης υδρογόνου. Για την εκπλήρωση της εργασίας και των απαραίτητων υπολογισμών αναπτύχθηκαν προγράμματα σε περιβάλλοντα Excel και Matlab.

Αρχικά, γίνεται ανασκόπηση της σχετικής με το θέμα βιβλιογραφίας, έτσι ώστε ο αναγνώστης να αποκτήσει μια πρώτη επαφή με το πλαίσιο των αποτιμήσεων κύκλου ζωής και των μελετών που έχουν γίνει ως τώρα γύρω από αυτές. Όπως είναι λογικό, η έμφαση δίνεται σε μελέτες κύκλου ζωής σχετικές με το υδρογόνο ως καύσιμο, οι οποίες αναλύουν τις εκπομπές για τον πλήρη κύκλο ζωής του καυσίμου πριν την καύση του σε κάποια μηχανή. Επιπλέον, παρατίθεται μια σειρά από μελέτες σχετικά με το υδρογόνο ως ναυτιλιακό καύσιμο και γίνεται μια πρώτη σύντομη ανάλυση των αποτελεσμάτων τους. Το κεφάλαιο της βιβλιογραφικής ανασκόπησης περιλαμβάνει επιπλέον μια σύντομη αναφορά στην ανάλυση αβεβαιότητας, η οποία αποτελεί επίσης αντικείμενο της παρούσας διπλωματικής εργασίας.

Κατόπιν, η εργασία αναφέρεται στην ποσότητα των εκπομπών στη θάλασσα παγκοσμίως και περιγράφει τα κύρια παραγόμενα αέρια από την καύση ορυκτών καυσίμων, καθώς και τις συνέπειες τους τόσο για την ανθρώπινη υγεία, όσο και για το περιβάλλον. Επιπλέον, γίνεται επεξήγηση των βασικών μέτρων περιορισμού των εκπομπών στην ναυτιλία, που έχουν ληφθεί από οργανισμούς όπως ο ΙΜΟ, η Ευρωπαϊκή Ένωση και ΟΗΕ. Πιο συγκεκριμένα, αναλύεται το χρονοδιάγραμμα του ΙΜΟ για την επίτευξη μηδενικών εκπομπών στην ναυτιλία ως το 2050, καθώς και η πολιτική της Ευρωπαϊκής Ένωσης γύρω από το θέμα των εκπομπών, απότοκος της οποίας είναι η καθιέρωση του φόρου εκπομπών από το 2024. Στόχος των παραπάνω είναι να κατανοήσει ο αναγνώστης την ανάγκη για ενεργειακή μετάβαση και υιοθέτηση χρήσης εναλλακτικών καυσίμων στην ναυτιλία.

Στη συνέχεια, η εργασία εμβαθύνει στο υδρογόνο δίνοντας τα βασικότερα στοιχεία του θεωρητικού του υποβάθρου, ώστε ο αναγνώστης να αποκτήσει μια πρώτη επαφή με έννοιες που θα χρησιμοποιηθούν στην ανάλυση κύκλου ζωής. Έτσι περιγράφονται οι βασικές αρχές του υδρογόνου ως καύσιμο, ενώ γίνεται μια σύντομη ανάλυση των δύο κύριων μεθόδων παραγωγής του: παραγωγή με χρήση

ορυκτών καυσίμων και παραγωγή με χρήση ανανεώσιμων πηγών ενέργειας. Επιπλέον, γίνεται σύντομη αναφορά στις διάφορες κατηγορίες του υδρογόνου(μαύρο, γκρι, μπλε, πράσινο κλπ), ενώ περιληπτικά περιγράφεται και το ζήτημα της αποθήκευσης του υδρογόνου. Ξεχωριστή αναφορά γίνεται στην υγροποίηση του υδρογόνου και στα πλεονεκτήματα/μειονεκτήματα της, καθώς σύμφωνα με πολλούς συγγραφείς είναι απαραίτητη πριν την μεταφορά και αποθήκευση του υδρογόνου σε μεγάλες ποσότητες. Για το κομμάτι της μεταφοράς του υδρογόνου γίνεται συνοπτική περιγραφή της μεταφοράς μέσω αγωγών ή με χρήση φορτηγών, εξετάζοντας τόσο την περίπτωση υγροποιημένου υδρογόνου, όσο και την περίπτωση αέριου συμπιεσμένου υδρογόνου . Οι βασικές αρχές γύρω από την λειτουργία των κυψελών καυσίμου αναφέρονται επίσης, καθώς στο πλαίσιο της παρούσας εργασίας θεωρείται ότι το υδρογόνο καίγεται αποκλειστικά σε κυψέλες καυσίμου και όχι σε μηχανές εσωτερικής καύσης. Επομένως, παρατίθενται οι κύριοι τύποι κυψελών καυσίμου, με τις κυψέλες τύπου PEMFC και SOFC να αναλύονται περισσότερο, ενώ γίνεται απαρίθμηση των πλεονεκτημάτων και των μειονεκτημάτων γύρω από τη χρήση κυψελών καυσίμου στη ναυτιλία.

Στη συνέχεια της εργασίας εξηγείται αναλυτικά το πλαίσιο εφαρμογής των αποτιμήσεων κύκλου ζωής, το οποίο υποδεικνύεται από σχετικά πρότυπα ISO, αλλά και από άλλες σχετικές μελέτες. Με βάση το συγκεκριμένο πλαίσιο αναπτύσσεται κατόπιν αναλυτικό υπολογιστικό μοντέλο για την ακριβή αποτίμηση του κύκλου ζωής ενός πλοίου με υδρογόνο, ενώ παράλληλα αναπτύσσεται και αντίστοιχο μοντέλο για πλοίο με συμβατικά καύσιμα, προκειμένου να γίνουν οι σχετικές συγκρίσεις. Οι εξισώσεις των δύο μοντέλων παρουσιάζονται αναλυτικά και προέρχονται από τη διεθνή βιβλιογραφία και από άλλες σχετικές μελέτες. Ο δείκτης απόδοσης(KPI) που χρησιμοποιείται για την περιβαλλοντική ανάλυση είναι ο GWP_{100}, που μετρά την υπερθέρμανση του πλανήτη σε βάθος 100 ετών και μετριέται σε μονάδες ισοδύναμου διοξειδίου του άνθρακα(CO_{2eq}). Για την οικονομική ανάλυση του κύκλου ζωής, από την άλλη, αθροίζονται όλα τα κόστη του κύκλου ζωής του πλοίου και γίνεται αναγωγή τους στο παρόν, με χρήση της μεθόδου της καθαρής παρούσας αξίας(ή καθαρό παρόν κόστος στην συγκεκριμένη περίπτωση). Το παραπάνω μοντέλο εφαρμόζεται τελικά σε 5 περιπτώσεις πλοίων: επιβατηγό/οχηματαγωγό, πλοίο μεταφοράς ξηρού φορτίου χύδην, πλοίο μεταφοράς πετρελαίου χύδην, πλοίο μεταφοράς εμπορευματοκιβωτίων και κρουαζιερόπλοιο. Στόχος του παραπάνω είναι να διαπιστωθεί κατά πόσο ο διαφορετικός τύπος πλοίου επηρεάζει τα τελικά αποτελέσματα της ανάλυσης κύκλου ζωής. Τα αποτελέσματα των προσομοιώσεων παρουσιάζονται σε πινακοποιημένη μορφή και σχολιάζονται εκτενώς, ενώ γίνεται και σύγκριση τους με άλλες αντίστοιχες μελέτες της βιβλιογραφίας.

Η μελέτη περιλαμβάνει επιπλέον μια οικονομική ανάλυση κύκλου ζωής υπό καθεστώς αβεβαιότητας, στην οποία λαμβάνεται υπόψιν η μεταβολή της τιμής των καυσίμων και του φόρου εκπομπών(για την περίπτωση πλοίου με συμβατικά καύσιμα). Για την ανάλυση αυτή χρησιμοποιούνται πραγματικές τιμές καυσίμων

και εκπομπών για τα τρία προηγούμενα έτη(Σεπτέμβριος 2021-Σεπτέμβριος 2024).Η μεθοδολογία που επιλέχτηκε για την εκτίμηση των κατανομών που ικανοποιούν καλύτερα τα διάφορα δεδομένα είναι το Anderson-Darling Test, το θεωρητικό υπόβαθρο του οποίου αναλύεται συνοπτικά. Η πιθανοθεωρητική αυτή προσέγγιση στοχεύει στην εκτίμηση της κατανομής που ακολουθεί το καθαρό παρόν κόστος, καθώς και των πιθανοτήτων να είναι επικερδής μια επένδυση σε πλοίο με υδρογόνο, συγκριτικά πάντα με την επένδυση σε συμβατικό πλοίο. Τέλος, αναλύονται τα συμπεράσματα του συνόλου της μελέτης και γίνονται προτάσεις για περαιτέρω έρευνα γύρω από το θέμα της ανάλυσης κύκλου ζωής πλοίων με υδρογόνο.

Στο 1ο κεφάλαιο, μέσω της βιβλιογραφικής ανασκόπησης, γίνεται μια εισαγωγή στο πλαίσιο των αποτιμήσεων κύκλου ζωής και αναφέρονται σχετικές μελέτες άλλων συγγραφέων, καθώς και τα βασικά συμπεράσματα στα οποία αυτές κατέληξαν.

Στο 2ο κεφάλαιο παρατίθενται στατιστικά για τις εκπομπές στο θαλάσσιο περιβάλλον, αναλύονται οι κύριες εκπομπές των ορυκτών καυσίμων και οι συνέπειες τους και αναφέρονται τα μέτρα των διαφόρων οργανισμών για τον περιορισμό των αερίων εκπομπών στην ναυτιλία.

Στο 3ο κεφάλαιο επεξηγείται το θεωρητικό υπόβαθρο γύρω από το υδρογόνο, την παραγωγή του και τις διάφορες διεργασίες του. Οι κυψέλες καυσίμου επεξηγούνται επίσης σύντομα.

Στο 4ο κεφάλαιο περιγράφεται αναλυτικά το πλαίσιο του ISO για τις αναλύσεις κύκλου ζωής.

Στο 5ο κεφάλαιο περιγράφονται αναλυτικά τα υπολογιστικά μοντέλα της περιβαλλοντικής και της οικονομικής ανάλυσης κύκλου ζωής. Οι χρησιμοποιούμενες εξισώσεις, καθώς και οι τιμές που επιλέγονται για τα διάφορα μεγέθη, αναφέρονται αναλυτικά.

Στο 6ο κεφάλαιο περιλαμβάνονται οι 5 περιπτώσεις πλοίων στις οποίες εφαρμόζεται το μοντέλο. Τα αποτελέσματα της κάθε περίπτωσης παρουσιάζονται αναλυτικά σε μορφή πινάκων και διαγραμμάτων, ενώ γίνεται σύγκριση τους και με άλλες αντίστοιχες μελέτες της βιβλιογραφίας.

Στο 7ο κεφάλαιο περιλαμβάνεται η οικονομική ανάλυση κύκλου ζωής υπό καθεστώς αβεβαιότητας, για την οποία χρησιμοποιούνται πραγματικές τιμές καυσίμων από την ευρωπαϊκή αγορά.

Στο 8ο κεφάλαιο συνοψίζονται τα βασικά συμπεράσματα της μελέτης και συμπεριλαμβάνονται προτάσεις για μελλοντική έρευνα.

Abstract

The aim of the present thesis is to perform a Life Cycle Assessment (LCA) and a Life Cycle Cost Assessment (LCCA) for hydrogen-fueled ships, using the relative International Organization for Standardization (ISO) framework for Life Cycle approaches. The results for the hydrogen-fueled ships are being compared with equivalent results of ships using conventional fuels to precisely evaluate the benefits due to the adoption of hydrogen as a marine fuel. The whole study has been accomplished by using Excel and MATLAB softwares.

Initially, the most significant shipping emissions and their consequences for the environment and human health are described. The measures framework towards GHG emissions reduction is also briefly analyzed, so as to make clear the need for transition to alternative and “cleaner” fuels. The study is then focusing mainly on hydrogen as a fuel, describing shortly its basic principles and production methods, as well as the main procedures needed before hydrogen is combusted. The basic principles and types of fuel cells are also explained, since the scenarios in this thesis assume that hydrogen is combusted only in fuel cells. Additionally, the Life Cycle approaches (LCA,LCCA) framework is analyzed, following the ISO guidelines, as well as other relative studies. Afterwards, the equations used for the development of the LCA,LCCA models are thoroughly presented. The model includes Life Cycle approaches for both hydrogen-fueled and conventional-fueled ships, since the scope of the study is to compare the two cases. The LCA,LCCA model is finally applied in five case studies: a Rop-ax ship, a bulk carrier, a tanker, a containership and a cruise/passenger ship, so as to determine whether the ship type influences the final results. Moreover, the thesis includes a LCCA under uncertainty, in which the fluctuation of fuel and carbon prices are taken into account. Aim of the uncertainty analysis is to estimate the chance of a hydrogen-fueled ship investment to be economically beneficial compared to a conventional-fueled ship. Finally, conclusions and recommendations for further research are mentioned.

Chapter 1 includes the literature review, through which the guidelines for Life Cycle Approaches are analyzed. Additionally, other Life Cycle studies focused on hydrogen-fueled ships are mentioned.

Chapter 2 introduces the reader to the harmful effects of GHG emitted from fossil fuels. The measures framework is analyzed, explaining briefly the measures of IMO, European Union (EU) and United Nations (UN) towards GHG limitation.

Chapter 3 is dedicated to the theoretical background of hydrogen, analyzing the basic principles of hydrogen as a fuel and including also information

about its production methods and the following procedures before its combustion in a ship. Fuel cells are also briefly analyzed.

Chapter 4 describes the guidelines for two Life Cycle Approaches (LCA and LCCA), given by the ISO framework.

Chapter 5 illustrates the LCA and LCCA simulation models for both hydrogen and conventional-fueled ships. The equations used for the development of the models are analytically mentioned in this chapter.

Chapter 6 describes the five case studies applied for the simulation. The results of each case are analyzed and compared to other relative studies.

Chapter 7 is dedicated to performing a LCCA under uncertainty, using actual market prices for the fuels.

Chapter 8 includes the final conclusions of the study, as well as recommendations for further research.

1) Literature review

The first chapter of this thesis is dedicated to the analysis of relative literature. The historical background of life cycle approaches is initially given, along with a number of studies carried out in the field. Since the thesis refers to the life cycle analysis of hydrogen as a maritime fuel, the emphasis is mainly put on LCA and LCCA studies carried out for hydrogen-fueled ships. Moreover, uncertainty analysis and relative studies are briefly discussed, since chapter 7 is fully dedicated to performing LCCA under uncertainty.

The idea of LCA was first conceived in the decade of 1960, when environmental issues started creating concerns. After stagnation in the 1970s, the method was further developed in the 1980s and 1990s and started gaining ground in the scientific community and the universities. Afterwards, the LCA methodology was applied to a wide range of products and systems to measure their environmental impact during their complete life cycle. Studies were conducted by both governments or industry and the results were presented through academic papers or government reports (Bjørn, 2018). Since 2006, the LCA framework is standardized by ISO guidelines (ISO 14044, 2006), (ISO14040, 2006). According to these guidelines, the LCA process is divided into four main steps: Goal and scope definition, inventory analysis, impacts assessment and interpretation. As far as the maritime sector is concerned, the application record of LCA is short so far, since the whole ship system is considered complex and makes such analyses difficult. In 2010s ,however, the concept of LCA in shipping started gaining interest, with several studies being conducted on the field. For example, Chatzinikolaou and Ventikos conducted a LCA for the case of a Panamax tanker, in which they calculated the life cycle emissions including the phases of shipbuilding, operation, maintenance and recycling (Chatzinikolaou, 2015). Diamantakis carried out a comparative LCA for LNG and Low Sulphur Oil using the case study of a Ro-pax ship, in which he calculated the values of CO_{2eq}, SO_{2eq} and PM_{eq} for the ship's life cycle and stated that SO_{2eq}, PM_{eq} are intensely reduced in the case of LNG, whereas CO_{2eq} was only slightly reduced (Diamantakis, 2014).

LCCA, on the other hand, was first developed in the 1930s, as a tool to count the impacts on the production of goods due to the increasing prices and limited energy resources (Panagiotopoulou, 2016). In principle, LCCA can be defined as a procedure used to compare different alternatives for a system's design, considering its entire life cycle (Bui, 2021). The LCCA can be conducted individually, however, in many studies it is carried out together with a LCA. The LCCA framework follows generally the structure of the LCA framework, however, the exact structure followed in this thesis is obtained from the study of Ventikos et al. (Ventikos, 2023). In this study, the economic life cycle of a system is divided into four phases: construction phase, operation phase, maintenance phase and

disposal phase. In the aforementioned study, the authors examined the case of a ship equipped with a foil thruster and tried to estimate the possible economic benefits under uncertainty, as they also took into account the fluctuations of fuel price, carbon tax, discount and inflation rate etc. Panagiotopoulou conducted a LCCA study for the complete life cycle of a conventional marine engine, including multiple fuel scenarios (Panagiotopoulou, 2016).

As far as hydrogen is concerned, the first environmental studies were focused on estimating the emissions due to hydrogen production. Spath and Mann conducted a LCA study to estimate the emissions of hydrogen production via conventional SMR, ending up to a GWP equal to 11,888 $\frac{kg\ CO_{2eq}}{kg\ H2}$ (Spath, 2000). The approach included the emissions from natural gas production and distribution, electricity generation, construction and decommissioning of the plant and the production plant operation. The same authors conducted another LCA study for hydrogen production via wind electrolysis (Mann, 2004). The study included the stages of wind turbine production and operation, electrolysis production and operation, as well as hydrogen compression and storage. The study concluded that GWP was only 0,97 $\frac{kg\ CO_{2eq}}{kg\ H2}$. Koroneos et al. studied the hydrogen production LCA for SMR and electrolysis using energy from renewable sources (Koroneos, 2004). The study's result demonstrated a GWP equal to almost 10 $\frac{kg\ CO_{2eq}}{kg\ H2}$ for SMR hydrogen, while hydrogen produced via wind electrolysis was found with a GWP equal to 0,96 $\frac{kg\ CO_{2eq}}{kg\ H2}$. Cetinkaya et al. conducted a comprehensive LCA study for various hydrogen production methods, including SMR, Coal gasification, Water electrolysis via wind energy, Water electrolysis via solar energy and Thermochemical water splitting via Cu-Cl cycle (Cetinkaya, 2012). The boundaries for the SMR and the wind electrolysis case respectively followed the structures of the studies of Spath and Mann. The GWP value was calculated equal to 11,893 $\frac{kg\ CO_{2eq}}{kg\ H2}$ for the SMR and 0,97 $\frac{kg\ CO_{2eq}}{kg\ H2}$ for water electrolysis via wind energy case. Hermesmann and Muller conducted a LCA study for hydrogen production via SMR, SMR with CCS, Methane pyrolysis and water electrolysis, using electricity from current German grid (Hermesmann, 2022). SMR resulted to a GWP equal to 11,57 $\frac{kg\ CO_{2eq}}{kg\ H2}$, while SMR with 90% CCS ended up with 3,97 $\frac{kg\ CO_{2eq}}{kg\ H2}$, that is 66% reduction compared to the SMR case. Alghool et al. published a LCA for green hydrogen supply network pathways, estimating the total emissions during the fuel's well to wake phase, including production, storage, liquefaction or compression and reconditioning (Alghool, 2024). The electrolysis was assumed to be completed with solar energy produced from standard PV panels, PV-T collectors or CPV-T collectors. Between compressed and liquified hydrogen, the authors observed a 28%-32% fewer emissions in the compressed hydrogen case.

As far as hydrogen-fueled ships are concerned, several LCA and LCCA studies have been conducted. Alkaner and Zhou were pioneers in hydrogen-fueled ship LCAs, as they carried out a comparative LCA between a diesel engine and Molten Carbon Fuel Cell(MCFC) using grey hydrogen (Alkaner, 2006). The authors analyzed the complete life cycle of the two systems, including manufacturing, operation, maintenance and recycling phases. The GWP ($kg\ CO_{2eq}/kWh$)calculated was 1,06 for the MCFC case and 0,64 for the diesel engine case, that is 65% increase of emissions when grey hydrogen is used. Percic et al. performed a comparative LCA and LCCA study, which was applied in 3 small ro-ro passenger ships equipped either with PEMFC or SOFC for their propulsion (Perčić, 2022). The cases of liquified grey, blue and green hydrogen were examined and the results were compared with the case of diesel-powered ships. GWP values were found to rise up to 53% for grey hydrogen, whereas a decrease of almost 75% and 94% was observed for blue and green hydrogen respectively. It should be noted that LCA boundaries include the manufacturing stage as well as hydrogen production, liquefaction and transportation. The electricity needed for the preheating of the fuel cell is also taken into account and, indeed, the authors examine the cases of shore electricity or onboard batteries. NPC values, on the other hand, were found to increase up to 95%, 125% and 227% for grey, blue and green hydrogen respectively. The final NPC values calculated contain both CapEx (PEMFC system and additional equipment cost) and OpEx (fuel cost, electricity cost, maintenance and replacement costs). Guven and Kayalica conducted another LCA study for hydrogen-powered ferries, in which they studied three types of electrolysers (AEC,PEMEC,SOEC)and two types of fuel cells (PEMFC,SOFC) and compared their life cycle results with MDO conventional marine engine (Guven, 2024). Their case study was a ferry line in Marmara Sea and the scenarios of three different electricity mixes were examined. The conventional MDO engine was found to be the eco-friendlier option regarding the GWP value. Wang et al. carried out a LCA and LCCA study, using a mainland ferry, a pelagic trawler, a large tug ship and an interisland ferry as case studies (Wang, 2023). The study assumed green hydrogen for the propulsion of ships and the results were compared directly with the MDO case. According to their results, the adoption of hydrogen was found environmentally as well as economically beneficial. A team of Spanish and British researchers carried out a comparative LCA study, in which they estimated the GWP/kWh for the cases of a Diesel ICE, a PEMFC and a H_2 ICE (Fernández-Ríos, 2022). The study resulted that SMR hydrogen combusted in a PEMFC would increase GWP by 7% compared to the Diesel ICE, whereas blue hydrogen would decrease GWP by 81%. The H_2 ICE was found to be much more environmentally beneficial compared to the PEMFC, however, the authors mention that this technology is hardly studied in the relative literature from an environmental point of view. Another team of Korean researchers studied the LCA of a 170 GT nearshore ferry, comparing MDO,LNG and grey hydrogen produced via SMR (Lee, 2022). Their results showed that grey hydrogen increased GWP by almost 10% compared to MGO. Jang et al. applied a parametric LCA study to 1932 ships with

500 GT or less, assuming various hydrogen production methods and fuel cell types (Jang, 2022). Their goal was to correlate the life cycle GWP of a certain hydrogen production method or a fuel cell type with the total power of the ship.

Uncertainty analysis was first found in engineering literature back in 1953, when Kline and McKlintock proposed a framework for statistical interference to estimate uncertainty in single-sample experiments (Kline, 1953). Over the years, uncertainty analysis became popular in research experiments and was established as a diagnostic tool for the development of experiments (Moffat, 1988). Uncertainty analysis was afterwards used in a wide range of applications, including engineering design, quality control, environmental studies and economics etc. The acceptance of uncertainty analysis method led to its standardization by ISO, known as Guide to the Expression of Uncertainty in Measurement (GUM), which aimed to provide a structured approach to estimating and expressing uncertainty in measurement (ISO, 1993). Goodness of fit tests also play an important role in uncertainty analysis, as they assist modelling uncertainty by deciding whether a sample of observed data fits a certain distribution. Popular goodness-of-fit tests are Kolmogorov-Smirnov test, Chi-square-test and Anderson-Darling test. In this thesis, Anderson-Darling test is used for the analysis and its basic theoretical background is analyzed in Section 7.2.

Several uncertainty studies have been conducted on hydrogen costing field. Yates et al. tried to estimate the Levelized Cost Of Hydrogen (LCOH) of hydrogen electrolysis from off-grid stand-alone photovoltaics, using a Monte-Carlo analysis (Yates, 2020). De Andrade et al. implemented a stochastic model using Monte-Carlo simulation to evaluate green hydrogen investments in Brazil and Germany (de Andrade, 2024). Lee et al. also used Monte-Carlo simulation method to evaluate hydrogen production from high pressure PEM water electrolysis (Lee, 2017). The authors took into account the price fluctuation in hydrogen production equipment, construction, electricity and labor and performed the simulation for various price range limits. Unfortunately, hydrogen-fueled ships LCA,LCCA under uncertainty are rarely found in literature and hence they are not mentioned in the present chapter.

2) Shipping Emissions and relative measure

2.1) Introduction

Sea transportation represents the most significant portion of the transportation sector with a 90% share of global trade (Deniz, 2016), while on the other hand it is reported from IMO that shipping is responsible for only 2,89% of global anthropogenic GHG emissions (Perčić, 2022). However, emissions from shipping are expected to grow between 50% and 250% by 2050, since world population is increasing, and global trading is expected to grow accordingly (Figure 1). This would potentially increase shipping's emissions to up to 17% of the total GHG emissions if no measures are taken (Timoleon, 2019). Hence, IMO MEPC 80 set the target of complete decarbonization of the shipping industry by 2050; a goal that can only be accomplished by the adoption of alternative fuels with zero environmental footprint. Carbon Dioxide (CO2) , Hydrocarbons i.e. Methane (CH4), Carbon Monoxide (CO) , Sulphur Oxides (SOx) ,Nitrogen Oxides (NOx) and particulate matter (PM) are the most significant byproducts of fossil fuels combustion in internal combustion engines. The task of this chapter is to analyze the negative effects of these byproducts for the environment and human health, which are even greater in regions near ports or close to busy trading routes(Figure 2). Moreover, the measures taken towards the decarbonization of shipping industry are going to be summarized and briefly analyzed.

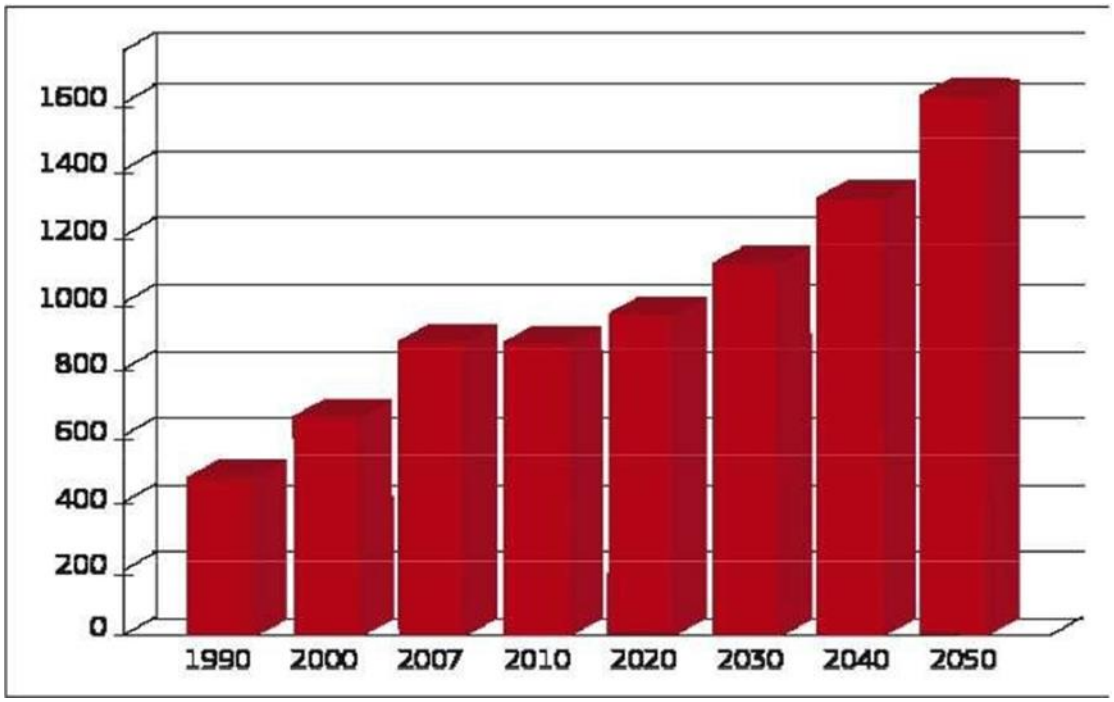

Figure 1:Estimated CO 2 emissions in million tonnes per year (Sources: 2nd IMO GHG study 2009 for emissions until 2007; MEPC 63/INF 2 for average scenario projections 2010-2050)

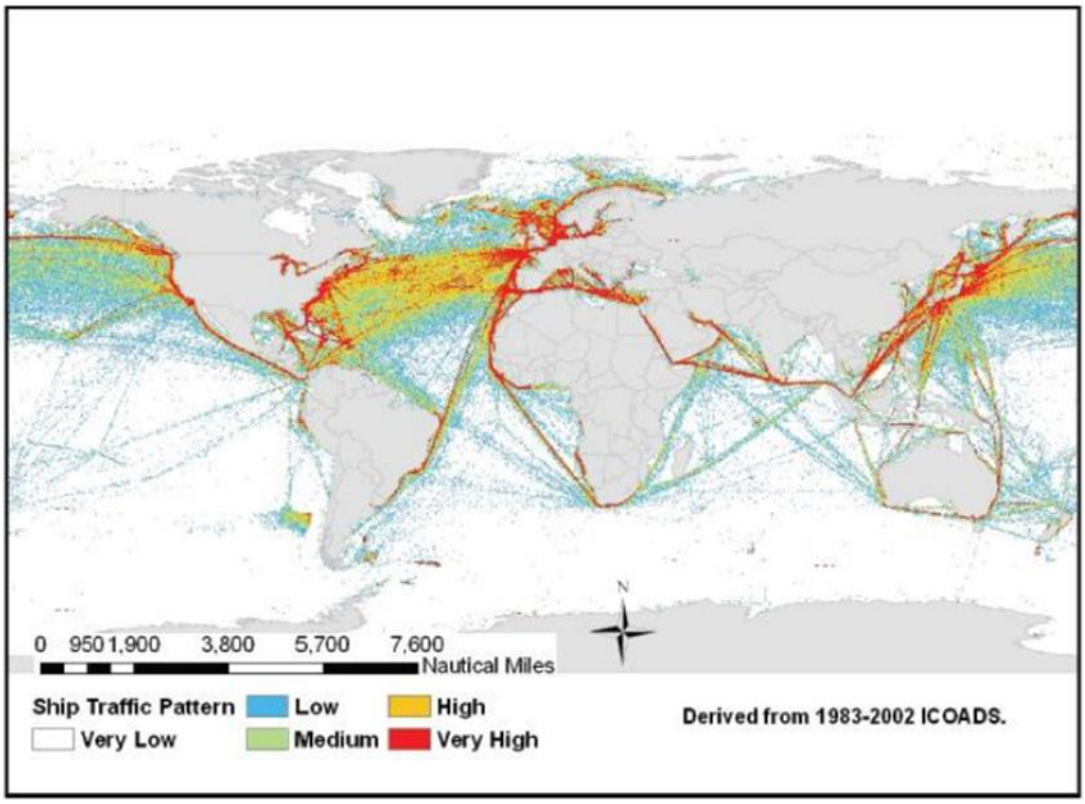

Figure 2: distribution of global marine traffic

2.2) Fossil fuels emissions

Fossil fuels emissions are considered to be really harmful for the environment and human health, while they are also responsible for the planet's overheating. This section is devoted to analyzing the main fossil fuels byproducts and their consequences.

- CO2 is the most significant GHG produced by fossil fuels combustion and an increase of its concentration in the atmosphere is expected to accelerate global warming (Perčić, 2022). By 2018, the maritime sector was responsible for 2,89% of global CO2 emissions, which meant 740 million tones in total. Besides all IMO measures for a lower carbon footprint, such as EEDI, CO2 emissions of the shipping sector are expected to rise in the next years (IMO, 2020), making the need for stricter measures even more intense.
- SOx are byproducts of maritime fuels, which contain sulphur, i.e. fuel oil and diesel oil. SOx are harmful for the environment, as they cause acid rain, but also for the human health, as they are related with problems in the lungs (Diamantakis, 2014). Maritime fuels contain increased sulphur in

comparison to other fuels and hence, IMO has implemented strict measures to contain SOx emissions.

- NOx are produced by the operation of internal combustion engines in high temperatures and pressures. The mayor nitrogen oxide is nitrogen dioxide (NO2), which is considered responsible for the acid rain and smog phenomena. It is also harmful for the maintenance of ancient monuments made of marble, because it is correlated with increased corrosion. As far as health problems are concerned, NO2 is associated with lung's problems and asthma.
- CH4 emissions are caused by imperfect combustion of fossil fuels in ship's engines. As far as shipping is concerned, CH4 emissions are mostly related to LNG. CH4 is a greenhouse gas and has a significant implication in greenhouse effect (Diamantakis, 2014).
- CO is produced by imperfect combustion of hydrocarbons due to the lack of oxygen. Although it is not observed in high concentrations, it is very dangerous for people health, as it is toxic and its inhalation can even lead human to death (Timoleon, 2019).
- PM is a mixture of solid and liquid particles found in the air, which is produced by combustion of fossil fuels. Particle pollution includes PM10 (diameter 10 micrometers or smaller) and PM2,5 (diameter 2,5 micrometers or smaller). Increased concentration of PM in the atmosphere can cause serious health problems, such as lung problems or even cancer, while it is also associated with less serious consequences, such as smog and reduced visibility (EPA, 2024).

2.3) Measures framework

This section is dedicated to analyzing the measures framework towards GHG emissions reduction in the maritime sector. Measures have been taken from various organizations, including the EU and UN except for IMO.

The UN climate change conference (COP21) , which took place in Paris in 2015, met an agreement about the clime and the efforts needed to reduce the impacts of climate change. This agreement, mostly known as the Paris agreement, is a legally binding international treaty on climate change, which primary goal is to maintain the average global temperature increase to 1,5 °C by the end of the century. To achieve this goal, GHG emissions should maximize before 2025 and decline by 43% in 2030 (COP21, 2015).

IMO itself decided to set climate measures for the first time in 2011. Back then IMO established EEDI, aiming to improve ship's efficiency. By 2018 IMO decided to take additional action to reduce shipping GHG emissions and adopted the initial IMO GHG strategy. However, the acceleration of global warming and the

increasing climate change impacts led to a revised IMO GHG Strategy, which was adopted by MEPC 80 in July 2023 (

Figure 3).

The IMO 2023 GHG strategy set as a primary goal to reach net zero GHG emissions in shipping by or around 2050. In the interval, the mid-term targets are the following:

- 2030: 40% reduction of CO2 per transport work and 20% reduction of total annual GHG, striving for 30%.
- 2040: 70% reduction of total annual GHG, striving for 80% (IMO MEPC 80, 2023).

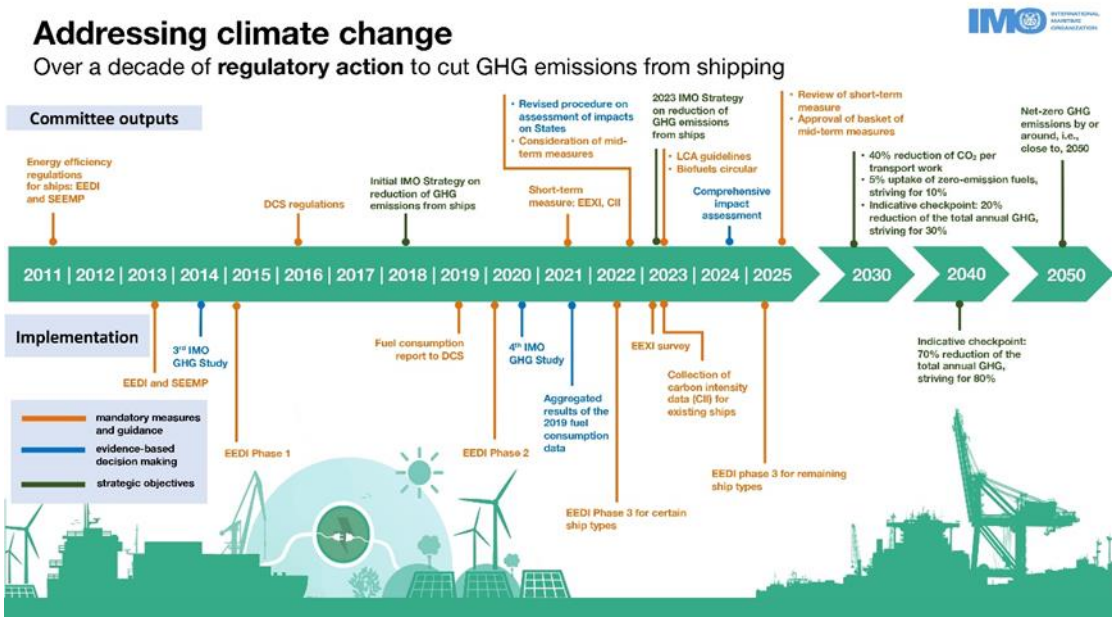

Figure 3: IMO GHG strategy

The EU has implemented the EU Emissions Trading System (EU ETS) since 2005, which is the world's first carbon market and requires the polluters to pay for their greenhouse gas emissions. The EU ETS was first launched for sectors such as electricity and heat generation or industrial manufacturing and operates in all EU countries. From 2024 EU ETS is also applied in maritime transport. More specifically, ship holders will have to pay for 50% of emissions for voyages starting or ending outside of the EU and 100% of emissions for voyages between two EU ports or for ships within EU ports. The ambition of the EU is to reach net zero GHG emissions by 2050, while the mid-term target is to bring emissions down by 62% by 2030, compared to 2005 levels.

The decision for a zero-carbon shipping until 2050 is surely going to provoke major changes to the shipping sector. It is clear that net zero cannot be achieved with fossil fuels being the main choice for the propulsion of the ships and, as a result, alternative fuels should start playing an important role in the next years.

According to a study contributed by Bouman (Bouman, 2017) the replacement of fossil fuel by alternative ones may lead to a significant decline of GHG. Hydrogen is considered to be one of the most eco-friendly alternative fuels and the analysis of its environmental footprint will be the main object of this thesis.

3) Hydrogen Fuel: A theoretical background

3.1) Introduction

Hydrogen is the first element of the periodic table with an atomic number equal to 1. Although it is found in abundance in nature, it is hard to detect it free, as it is usually found bonded with other chemical elements. It is mostly found in water (bonded with oxygen) or in hydrocarbons (bonded with carbon), thus its isolation requires chemical processes. Hydrogen is considered one of the strongest candidates for being the fuel of the future, since its combustion is carbon-free and doesn't contribute to global warming. However, production of hydrogen is not carbon-free at all , as around 96% of hydrogen today is produced via hydrocarbons (coal, natural gas etc.) and from this point of view, the production phase of hydrogen should be taken into consideration (FRANTZIS, 2022).The production methods of hydrogen will be briefly analyzed in this chapter, along with issues such as hydrogen liquefaction, storage, distribution and combustion.

3.2) Hydrogen production methods

In this section the main hydrogen production methods are going to be presented. Hydrogen production methods are divided into two main categories: hydrogen production from fossil fuels and hydrogen production from renewable energy sources. It is noted that many hydrogen production technologies found in relative literature are still in an experimental stage and are not going to be mentioned in this thesis.

3.2.1) Hydrogen production from fossil fuels

Hydrogen is most commonly produced by fossil fuels, as nearly 96% of its quantity worldwide is produced using natural gas, heavy oils and naphtha and coal (48%,30% and 18% accordingly). Even though hydrogen production from fossil fuels is not always environmentally friendly, these methods are dominant in the hydrogen market, since the production price remains in acceptable levels (Nikolaidis, 2017). The most common technologies used are reforming and pyrolysis and will be shortly analyzed in the following paragraphs, with information obtained from Nikolaidis and Poullikkas publication (Nikolaidis, 2017).

In general, hydrocarbon reforming is a process that takes place in a suitable reforming plant and converts hydrocarbon fuel into hydrogen, using different reforming techniques. Except for the hydrocarbon, another reactant is also used, which can be either steam or oxygen. The three main reforming methods are considered to be Steam Reforming(SR), Partial Oxidation(POX) and Autothermal Reforming(ATR).

SR is an endothermic reaction, which converts hydrocarbon and steam to hydrogen and carbon oxides. SR method includes three main stages:

1. *Reforming or synthesis gas (syngas) generation*
   In this stage, the hydrocarbon reacts with water and produces hydrogen and CO. The process takes place at high temperatures and pressures (up to 3,5MPa) and with a steam to carbon ratio equal to 3,5, in order to avoid the coking formation of the catalyst. Since the catalyst is usually made of nickel, a desulphurization step has to be made prior to the reforming reaction if the raw material contains sulphur, in order to prevent poisoning of the catalyst.

2. *Water-gas shift (WGS)*
   When the reforming stage is completed, the gas mixture heads to a WGS reactor. The CO reacts with steam inside the reactor and produces additional H2 and CO2. CO2 emissions produced at this point can be restricted by the use of carbon capture and storage technologies (CCS), which can capture even up to 90% of the CO2 emitted.

3. *Methanation or gas purification*
   In this final stage of the SR process, the gas mixture passes through methanation or pressure swing adsorption (PSA), leaving hydrogen of great purity, which even approaches 100%.
   The three stages of the SR method are described through the following chemical reactions:
   - Reformer: $C_nH_m + nH_2O \rightarrow nCO + (n + \frac{1}{2}m)H_2$
   - WGS reactor : $CO + H_2O \rightarrow CO_2 + H_2$
   - Methanator: $CO + 3H2 \rightarrow CH4 + H2O$

   The most commonly used raw materials in a steam reforming method are CH4, natural gas or other methane containing gases. Steam methane reforming (SMR) is the most mature H2 production method, also suitable for large-scale hydrogen production. SMR method is characterized by a high efficiency of 74%-85% and high-quality hydrogen(99,999%), as PSA is applied to separate hydrogen from the other components of the gas mixture.

Partial Oxidation Method involves the conversion of hydrocarbons along with steam or oxygen into hydrogen and carbon oxides. The process can be accomplished either using a catalyst(catalytic process) or without using a catalyst(catalytic process). The catalytic process takes place in lower temperatures and is more suitable for feedstock ranging from methane to naphtha, while on the other hand, non-catalytic reaction can take place using hydrocarbons like heavy oils and coal. The stages of the POX method are similar to those discussed for the SR method and are described from the following chemical reactions:

- Reformer: $C_nH_m + nH_2O \rightarrow nCO + (n + \frac{1}{2}m)H_2$ (non-catalytic)

  $C_nH_m + \frac{1}{2}nO_2 \rightarrow nCO + \frac{1}{2}mH_2$ (catalytic)
- WGS reactor : $CO + H_2O \rightarrow CO_2 + H_2$
- Methanator: $CO + 3H2 \rightarrow CH4 + H2O$

The most commonly used raw materials in a POX method are heavy oil residues and coal. When coal is used the process is mentioned as coal gasification and constitutes a major hydrogen production method, which, however, is considered to be harmful for the environment (analysis follows in next chapters). Drawbacks of the method are the low H2/CO ratio in the syngas and the high operating temperatures, which can even reach 1100-1500 °C in the non-catalytic process (Carapellucci, 2020).

Autothermal reforming method(ATR) is a combination of both SR and POX methods, using the exothermic partial oxidation to provide the heat and endothermic steam reforming to increase hydrogen production. This reforming process is described by the following chemical reaction:

$$C_nH_m + \frac{1}{2}nH_2O + \frac{1}{4}nO_2 + nCO + (\frac{1}{2}n + \frac{1}{2}m)H_2$$

The process is thermally neutral, because the heat generated by the exothermal reaction exactly meets the energy requirement of SMR. The average system temperature is also lower in comparison with POX method (Carapellucci, 2020).This method has significant lower equipment cost than SMR and coal gasification and leads to cheaper H2 production.

Hydrocarbons pyrolysis is a chemical process, in which hydrogen is produced by the thermal decomposition of hydrocarbons. The process is described through the following general reaction:

$$C_nH_m \rightarrow nC + \frac{1}{2}mH_2$$

CH4 is the main hydrocarbon used for pyrolysis and the whole process takes place at above 800°C when nickel is used as a catalyst, whereas temperature rises at

1000°C when no catalyst is used (Schneider, 2020). Despite the fact that pyrolysis of natural gas has not yet been commercialized as hydrogen production method, it is very promising as it is considered less energy consuming and more cost-efficient than SMR method (Nikolaidis, 2017). Moreover, the main product of the process, except for hydrogen, is solid carbon, which is more advantageous over gaseous CO2 from SMR, as it can be more easily disposed i.e. in former cole mines (Schneider, 2020). The major drawbacks of the method are the obstacle of separating the hydrogen due to low H2 partial pressures and the diminishing durability of the membrane because of the high temperatures required (Nikolaidis, 2017).

3.2.2) Hydrogen production from renewable sources

As mentioned before, only a small share of the hydrogen market is produced from renewable sources, since almost 96% of global hydrogen is produced via fossil fuels. The use of renewable sources will, however, increase in the near future and is expected to prevail in long term, if environmental measures continue to exist. The major methods for producing hydrogen from renewable sources are biomass processes or other processes based on water splitting (Nikolaidis, 2017).

Biomass is a renewable energy source derived from dead animal and plants materials. Biomass is organic matter, which stores the sun's energy of sun using photosynthesis. CO2 is emitted when biomass is utilized, however, the quantity is negligible and is equal to the amount of hydrogen the organism absorbed when it still was alive. As far as hydrogen is concerned, it can be produced from biomass either via thermochemical methods or via biological processes, which are considered to be more eco-friendly, while on the other hand they are significantly slower and more expensive. Thermochemical methods include mainly pyrolysis and gasification, whereas the main biological processes are direct and indirect biophotolysis, photo and dark fermentations and multistage or sequential dark and photo-fermentation. The production methods mentioned above will not be further analyzed, as this would be out of the scope of this thesis.

Water is an abundant raw material in earth and for this reason water-splitting processes are considered ideal for hydrogen production. Electrolysis, thermolysis and photo-electrolysis are the main water splitting methods, which can be totally carbon-free, if the required energy input is produced from renewable sources. Electrolysis is considered the most mature and effective water-splitting method and will be analyzed further, as it is the most promising method to produce carbon-free hydrogen.

The electrolysis unit, called electrolyzer, consists of an anode and a cathode. When electrical energy is applied, water splits and hydrogen is produced in the cathode. The process is described through the following chemical reaction:

$$2H_2O \rightarrow 2H_2 + O_2$$

The most common technologies for electrolysis are alkaline, Solid Oxide Electrolysis Cells(SOEC) and Proton Exchange Membrane (PEM). In alkaline and SOEC electrolyzers water is introduced in the cathode where it is splits and produces hydrogen, whereas in PEM electrolyzer water is introduced in the anode and splits into protons, which in their turn head to the cathode in order to form hydrogen. Electrolysis in general is capable of producing the cleanest fuel of the history, when the required energy is produced from renewable sources. The drawback of electrolysis is the high electricity consumption, which makes the cost much higher in comparison to other hydrogen production methods.

3.3) Hydrogen Categorization

In the previous section, the most well-known hydrogen production methods were analyzed. However, in relative bibliography hydrogen is further categorized depending on the source used for its production and the carbon footprint. The categorization is shown in the figure below (Figure 4):

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Figure 4: Hydrogen categories

The most significant hydrogen categories mentioned in literature are black/brown hydrogen, grey hydrogen, blue hydrogen and green hydrogen. A brief analysis of each hydrogen type is following:

- Black hydrogen is produced by the gasification of black coal, whereas brown hydrogen is produced by the gasification of lignite. Coal is the most abundant fossil fuel on earth and coal fuels are predominant for gasification. However, black/brown hydrogen is considered to be the most harmful hydrogen type for the environment, as coal has the lowest hydrogen to carbon ratio and therefore, more carbon is produced per mole of hydrogen (Shoko, 2006). Emissions of black/brown hydrogen could be reduced in the future, if carbon capture technologies are further established.
- Grey hydrogen is mostly produced via SMR method using natural gas. Most of the hydrogen produced today is considered to be "grey" and thus, its production contributes to global warming. CCS technologies are expected to reduce the environmental footprint in the future.
- Blue hydrogen is produced in the same way as grey hydrogen, with the difference that blue hydrogen production involves CCS technologies. CO2 is captured and stored in geological sites and is not released in the atmosphere and therefore blue hydrogen is often mentioned as low-carbon hydrogen. Capture efficiencies range from 53% to 95%, while there are hopes that efficiencies may increase if hydrogen demand gets higher in the future (M. Hermesmann, 2022). The drawback of blue hydrogen is that it requires fossil fuels for its production and cannot contribute to the net zero target, however, it could be a transitional fuel for the reduction of global CO2 emissions.
- Green hydrogen is produced via water electrolysis using renewable energy sources, with the most significant being wind, solar and hydro power. Green hydrogen is not dependent on fossil fuels and at a first glance it is totally carbon free, as no GHG emissions are produced directly during its production. However, the plant manufacturing, the infrastructure development and the supply chains of water and electricity have an environmental impact which should be taken under consideration (M. Hermesmann, 2022). Although green hydrogen is an almost clean fuel, there should be put great effort on reducing its price, as today it is significantly more expensive than the other types of hydrogen.

3.4) Hydrogen Storage

There are three main methods to store hydrogen; compressed gaseous hydrogen storage, liquid hydrogen storage and solid hydrogen storage. Although more than 80% of hydrogen refueling stations by 2010 used gaseous compressed hydrogen, liquid hydrogen storage is very promising, while solid hydrogen storage is still under development and might be used in the following years. Compressed

gas is the most simple and mature storage method, while another advantage is the fast filling and discharging. Hydrogen is compressed at pressures up to 700 bar and then it is stored at ambient temperature in gaseous form in cylinders, containers or underground cavities. On the other hand, liquid hydrogen has a higher density, stores more energy and its storage costs is less than compressed gas storage (Tarhan, 2021). However, liquid hydrogen storage tanks are facing problems with heat leaks and therefore hydrogen evaporates after filling the tank. To tackle this problem, insulation systems are necessary to protect the method's efficiency. The losses differ and depend on the quality, capacity and the shape of the tank. The leaks can be minimized due to the use of suitable technologies, but they cannot be totally avoided (Léon, 2009).Another issue is the liquefaction of hydrogen, which should come before the storage and is a complex and energy consuming process. More about the liquefaction of hydrogen is following in section 2.5.

3.5) Hydrogen Liquefaction

According to relative literature, liquefaction is a good practice before hydrogen transportation and storage (Wulf, 2018). The main reasons for hydrogen liquefaction are the following (Liang, 2020):

- Liquified hydrogen storage and distribution is more feasible than gaseous hydrogen considering technical and economic perspectives.
- Liquified hydrogen has a higher density in comparison to gaseous hydrogen and thus it has higher energy content.

Normal hydrogen(mixture of hydrogen at room temperature) is a gas composed of 75% ortho-hydrogen and 25% para-hydrogen, which are two different isometric forms of hydrogen. During the liquefaction process, temperature decreases to 20K and a slow conversion to 100% para-hydrogen takes place via a reversible and exothermic reaction. After its liquefaction, the density of hydrogen is increased to $80 kg/m^3$ at 4 bar, while gaseous hydrogen's density is around $20 kg/m^3$ at 300 bar. Hence, liquified hydrogen requires much lesser storage volume in comparison to compressed gaseous hydrogen, as one liquid hydrogen container is equal 7-8 compressed gaseous hydrogen containers (Léon, 2009). On the other hand, the problem with hydrogen liquefaction is that the whole process takes place at low temperatures (20K) and the fact that hydrogen must be cooled down to those temperatures requires a complex and energy consuming process. The process of hydrogen liquefaction will not be analyzed further, as it is out of the scope of this thesis.

3.6) Hydrogen Distribution

Hydrogen distribution can be achieved either by road transport or by pipelines network. A brief presentation of the main transportation methods is following, with information obtained from Faye et al. publication (Faye, 2022).

Hydrogen can be distributed with trucks, depending on the quantity of hydrogen needed. Trucks are able to carry either gaseous or liquid hydrogen. A short analysis of each transportation method is following, so that their advantages and disadvantages are understood.

- Gaseous hydrogen can be transported by trucks using compressed gas containers with gas cylinders or tubes, where hydrogen is pressurized in a range of 200-500 bar. This method is suitable for medium quantities of hydrogen; for larger quantities pressurized gas cylinders or tubes are usually attached to compressed gas hydrogen tube trailers. As far as the quantity of hydrogen transported is concerned, a tube trailer with steel cylinders can carry up to 420kg of hydrogen (25000L at 200 bar), while the quantity could rise if lighter tank materials were used. Gaseous hydrogen road transport is also considered cost-effective, with a cost of 1$/kg H2. However, trucks are nowadays not an eco-friendly way of transportation, and their emissions should be taken into consideration, while there are also safety issues associated with hydrogen leakages or explosions.
- Liquid hydrogen transportation is an alternative for distributing hydrogen by trucks. Liquified hydrogen can be transported in greater quantities than gaseous hydrogen, however, the problems associated with the liquefaction process (evaporation of hydrogen, leakages and energy losses) form an important drawback. The cost of liquid hydrogen transportation is around 0,4$/kg H2, though, the liquefaction cost should be added in order to compare with the cost of gaseous hydrogen transportation. A future reduction of the liquefaction cost would undoubtedly make the cryogenic liquid tankers even more efficient.

Pipelines, on the other hand, are the most cost-effective option for transporting large quantities of hydrogen. Except for the cost, pipelines are more eco-friendly than trucks, their lifetime lasts for several decades, and they are safer, as they are buried underground. However, the infrastructure of the pipeline network should undoubtedly be improved in the future, and this remains challenging, as it requires investments of billions dollars. Another problem is the need to compress hydrogen to high pressures up to 10-20 bars in order for its delivery speed inside the pipe to increase. This step is necessary so as to contain the losses of hydrogen inside the pipe, which might be greater in comparison with other fuels (for instance with natural gas).

3.7) Hydrogen combustion: The case of fuel cells

3.7.1) Introduction

Hydrogen can be used as a fuel either for internal combustion engines or for fuel cells, where it is converted into electricity. The relative bibliography focuses more on the use of fuel cells for hydrogen and thus, the next paragraphs are dedicated to the analysis of fuel cells.

Fuel cell application has been tested for all transport types. Research and development of fuel cells began back in the early 1800s, while the first operational fuel cell was demonstrated in 1959 and was used the years after by NASA. As far as shipping is concerned, fuel cells had few applications and were mostly used for some submarine types. Fuel cells have nowadays regained a lot of interest, since they are the perfect platform for alternative fuels like hydrogen and they emit zero carbon during their operation. According to market studies, fuel cells are commercially available, and their market is expected to grow up to 42,3 billion dollars by 2030; almost 10 times greater in comparison to 4,5 billion dollars of 2020 (Figure 5).

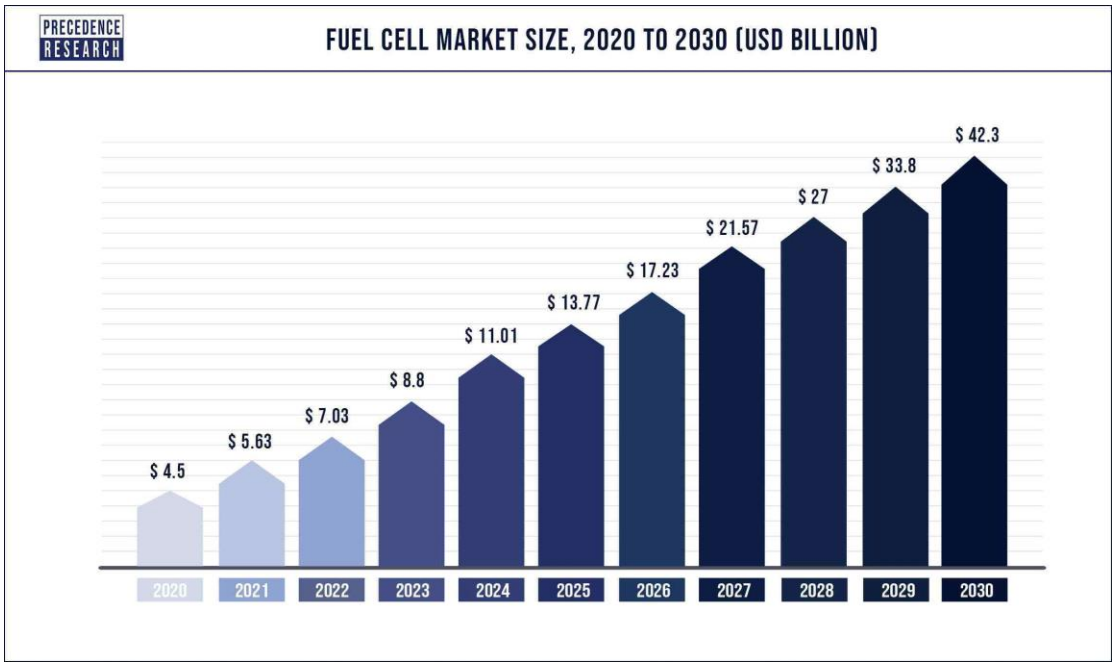

Figure 5: fuel cells annual market growth

3.7.2) Main Principles of Fuel Cells

A fuel cell is an electrochemical device that converts chemical energy stored in a gaseous or liquid fuel directly into electrical energy. The whole process in a fuel cell differs from the classic thermomechanical energy conversion and does

not obey to the Carnot principle (Timoleon, 2019). The hydrogen combustion reactions occurring in a fuel cell are the following:

- $H_2 \leftrightarrow 2H^+ + 2e^-$
- $\frac{1}{2}O_2 + 2H^+ + 2e^- \leftrightarrow H_2O$

The two reactions are spatially separated using an electrolyte, which allows ions to flow, but no electrons. The fuel cells possess two electrodes, one for each reaction that takes place (O'hayre, 2016).

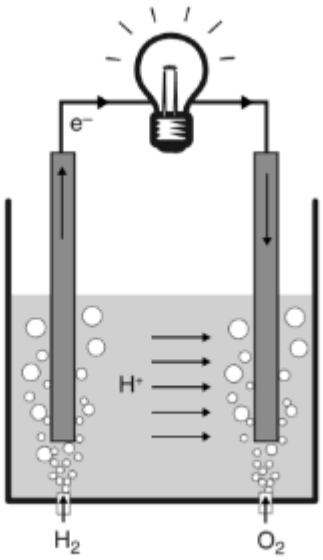

Figure 6: Simple H2-O2 fuel cell(source:Fuel Cells Funfamentals)

Figure 6 shows a simple H2-O2 fuel cell, which consists of two dipped into an electrolyte (sulfuric acid). Hydrogen is split into protons (H^+) and electrons, according to the first reactions written before. Protons flow through the electrolyte, while the electrons flow from left to right through a piece of wire that connects the two electrodes. After electrons reach the right electrode, they recombine with protons and oxygen and form water, according to the second chemical reaction written before. Electricity is finally produced when a load is introduced along the path of the electrons and so the following electrons provide power to the load (O'hayre, 2016).

3.7.3) Fuel Cell Types

There are basically five types of fuel cells (Sürer, 2022):

- Proton exchange membrane fuel cell (PEMFC)
- Alkaline fuel cell (AFC)

- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

PEMFC and SOFC are the most suitable for maritime applications and a brief analysis of each type is following:

In PEMFCs a thin polymer membrane is used as an electrolyte, which is usually made by a material called Nafion. Protons are the ionic charge carrier inside the PEMFC membrane (O'hayre, 2016). The reactions occurring inside the fuel cell are the following:

- $H_2 \leftrightarrow 2H^+ + 2e^-$
- $\frac{1}{2}O_2 + 2H^+ + 2e^- \leftrightarrow H_2O$

PEMFC are ahead of other fuel cells for marine applications, since they have mature technology, cost partly less and can operate at lower temperatures. Moreover, they have high power density and can deliver to load changes (Sürer, 2022).

In SOFCs a thin ceramic membrane is used as an electrolyte, which is usually made by a material called yttria-stabilized zirconia(YSZ). Oxygen ions (O^{2-})are the ionic charge carrier inside the PEMFC membrane (O'hayre, 2016). The reactions occurring inside the fuel cell are the following:

- $H_2 + O^{2-} \leftrightarrow H_2O + 2e^-$
- $\frac{1}{2}O_2 + 2e^- \leftrightarrow O^{2-}$

SOFCs are highly efficient and fuel flexible, however, they operate at high temperatures over 600 °C and thus, a battery is usually used in order the SOFC to be preheated and reach its operational temperature.

3.7.4) General Discussion about Fuel Cells

Hydrogen fuel cells are undoubtedly one of the strongest candidates for the decarbonization of shipping. Their main advantages versus internal combustion engines are the following (Sürer, 2022):

- Zero carbon emissions: Fuel cells emissions during the ship's operations are practically negligible.
- High efficiency: Since fuel cells convert chemical energy directly to electricity, they are characterized by high fuel efficiency.
- Low noise: Since fuel cells do not have moving parts like diesel engines, they only create noise from the auxiliary equipment.

- Low maintenance cost: Fuel cells have no need for lubricant oil.
- Goad part load performance: Fuel cells are more efficient in comparison to diesel engines when they operate at partial loads.

On the other hand, fuel cells have various challenges to overcome before they become fully applicable for ships. The most serious barriers of fuel cells are the following:

- Fuel cells include high capital and operating cost. More specifically, the platinum-based catalysts used in fuel cells correspond to 56% of the total capital and thus, it is necessary that cheaper electrode materials are used, in order the total cost to be reduced.
- Fuel cells have lower durability than diesel engines. A possible replacement of fuel cells after some years of operation would increase the cost even more and make them unaffordable for the ship owner.
- The logistics of hydrogen, which is the main fuel candidate to be combusted in fuel cells, still face difficulties. Hydrogen storage is problematic, as the two basic storage methods (gaseous and liquid hydrogen) face their own difficulties and therefore, further research is needed in order storage technologies to be improved. Moreover, fuel supply is under is under question, since production and distribution of big quantities of hydrogen might prove troublesome.

4) Methodology: Life cycle approaches (LCA and LCCA)

Life cycle approaches are becoming more and more popular in the shipping industry, as they can estimate emissions and costs, even from early design stages. Environmental impacts are examined through the LCA, which is a process standardized under the ISO framework. On the other hand, LCCA is a tool for the economic impact assessment, which evaluates various designs or alternatives and chooses the most cost-effective option. It is worth noting that LCA and LCCA are often conducted together and their results are combined for the determination of the final design. Although life cycle approaches were firstly treated with skepticism in the shipping industry, as they were considered complex, their use is nowadays gaining ground, focusing mostly on ship design, ship building, ship maintenance and retrofitting technologies (Ventikos, 2022).

In this chapter, the basic principles and the framework of both LCA and LCCA are going to be analyzed.

4.1) LCA (Life Cycle Assessment)

The increased awareness of the importance of environmental protection and the further discussion about the impacts of some products manufacturing and consumption has led to the development of methods, which can assist in a more precise understanding and evaluation of those impacts. One of the most used methods is LCA, which is developed by two ISO standards (ISO 14044, 2006), (ISO14040, 2006). LCA addresses the environmental aspects and the possible environmental consequences throughout a product's life cycle, starting from the production's phase and continuing with the use phase, the end-of-life treatment, the recycling phase and the product's final disposal. However, it is worth saying that a LCA can only be used as a part of a more comprehensive decision process and of course it is not suitable for all situations, as it does not address issues such as cost or social aspects. Moreover, it is only possible to compare two different LCA studies when the same assumptions are made, and their context is equivalent.

According to ISO 14040 (ISO14040, 2006), a LCA consists of four main phases (Figure 7):

- Goal and scope definition phase: The scope of a LCA includes the system boundaries and the level of detail and depends on the subject and the intended use of the study. The depth and the breadth of a LCA varies,

depending on its particular goal. In this stage, the basic parameters and the functional units of the system should be determined.

- Inventory analysis phase (LCI): This second phase includes the inventory of all the input/output data of the system being studied. This stage includes the collection of the necessary data, as well as the quantification of all the output data produced during the system's life cycle. For example, such output data could be gas emissions or solid waste.

- Impact assessment phase (LCIA): In this third stage of the LCA, the purpose of LCIA is to provide additional information about a product's or a system's results, so as to understand its environmental impact or its impact on human's health.

- Interpretation phase: In this final phase, the results of LCI and LCIA are being summarized and discussed. This phase includes also conclusions, recommendations for future research and decision making.

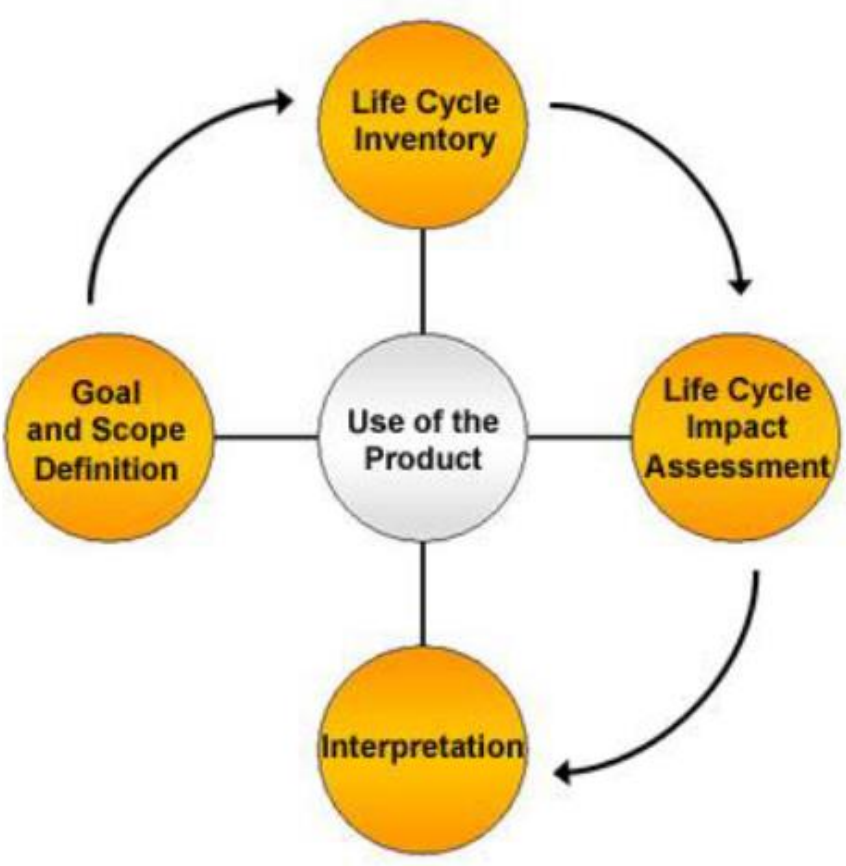

Figure 7: The 4 phases of LCA

4.2) LCCA (Life Cycle Cost Assessment)

The goal of a LCCA is to estimate the economic impacts of GHG emission reduction technologies. The LCCA framework includes the whole system's life, starting from construction to end of life phase (disposal, recycling etc.). The LCCA phases are shown in Figure 8:

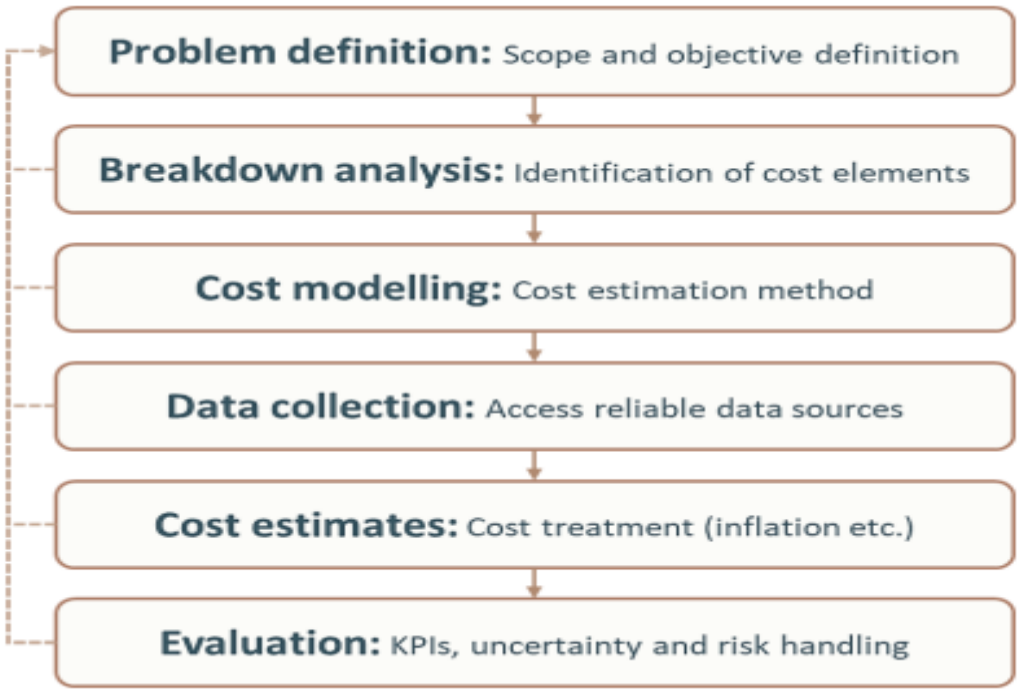

Figure 8: LCCA framework

A brief analysis of each LCCA phase is following, with information adapted from the work of Ventikos et al. (Ventikos, 2022):

- Problem definition: The process of the LCCA framework begins with the scope and the objective definition. The objective is usually cost minimization in a life-cycle perspective, while the scope differs in each case and is set by the nature of the system examined.
- Breakdown analysis: The breakdown analysis phase includes the separation of the entire life-cycle cost into individual cost elements. The life-cycle cost can be divided into four main costs:
    1. Construction costs
    2. Operation costs
    3. Maintenance costs
    4. End of life-disposal costs

  Adoption of this approach ensures a more accurate estimation of each individual cost. The phases of construction, maintenance and disposal share a common basis of breakdown analysis, since they are driven by cost elements defined by the system's structure. On the other hand, the

operation phase has a different analysis basis, as the main cost elements include fuel and lubricant oil consumption.

- Cost modelling: The costs analyzed in the breakdown analysis phase are then estimated in the cost modelling phase. This estimation can be achieved using three model categories:
  - Analogy models
  - Parametric models
  - Engineering models

  The most suitable method to be used is defined by the nature of the cost element and the available data.

- Data collection: Generally, data can be collected from literature references, manufacturers, industry employees or other detailed sources.
- Cost estimates: Since the LCCA framework examines the entire life cycle of a system, the change of money value through the years should be counted. Hence, cost treatment is vital and so the costs should be considered in their present value. In some cases, inflation should also be counted.
- Evaluation: The evaluation phase includes the calculation of the KPIs, which evaluate the system's economic efficiency. Such KPIs might be NPV (Net Present Value), NPC (Net Present Cost) or IRR (Internal Rate of Return).

5) LCA and LCCA model

After the theoretical analysis, which took place in the previous chapter, this chapter is dedicated to analyzing the model used, in order a LCA and a LCCA simulation for a hydrogen-fueled ship to be conducted. Each life cycle approach will be examined in the next sections.

5.1) LCA model

This section includes the LCA process used to evaluate the environmental impacts of a hydrogen- fueled ship for its whole lifetime. Moreover, a comparison with a LS-MGO-fueled ship will follow, so as to determine whether the adoption of hydrogen as a marine fuel is worth for the decarbonization of the shipping industry. LS-MGO was selected for the comparison with hydrogen, since it is a fuel suitable for Emission Control Areas (ECA).

Goal and scope

The goal of this LCA model is to evaluate the GHG emissions produced during the ship's life cycle and compare them with the corresponding emissions of a LS-MGO-powered ship. The lifespan for both ships is considered to be 25 years and includes the construction, operation, maintenance and disposal phase. The functional unit used in the calculation of GHG emissions is CO_2 equivalent (CO_{2eq}), which is a metric measure used to compare the emissions of GHG on the basis of global warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming.

LCI phase

In the LCI phase, the amount of GHG emissions produced from each ship is going to be accurately calculated. Since the scope of the study focuses on the comparison of the two ships, the emphasis will be put on the systems differing between the two ships. For example, the hull construction remains the same for both ships and hence will not be part of the LCI, whereas the two ship's engine rooms are different, and this should be appreciated in the LCI. The LCI includes the four main life-cycle phases: construction, operation, maintenance and disposal.

Construction phase's emissions are considered to be produced from the manufacturing of two main subsystems: hull and machinery (Chatzinikolaou, 2015). Since the hull subsystem is expected to be the same for both the diesel and the hydrogen-fueled ship, the focus will be put on the machinery subsystem.

The hydrogen-fueled ship is assumed to be equipped with a PEMFC, along with auxiliary engines. As the maker gives no further data for the construction's emissions, an analogy model will be used to estimate the total emissions produced. Table 1 includes the quantity of materials used for the construction of 1kW PEMFC, along with the emissions to produce those materials (Table 1), (Stropnik, 2019).

Table 1: Inventory list to produce 1 kW PEMFC)

	Inventory list(1 kW PEMFC)				
	Material	**Value**	**Unit**	**kg CO2eq/1 gram material**	**kg CO2eq emissions**
Stack	Graphite	4,5	kg	0,0000755	0,33975
	PVdC	1,1	kg	0,00453	4,983
	Aluminium	0,3	kg	0,00826	2,478
	Chromium Steel	0,1	kg	0,00268	0,268
	Glass fibers	0,1	kg	0,00173	0,173
	PFCA(Nafion)	0,07	kg	0,831	58,17
	Carbon black	0,0008	kg	0,00254	0,002032
	Platinum	0,00075	kg	28,5	21,375
BoP	Steel product	3,7	kg	0,00219	8,103
	HDPE	1,5	kg	0,00148	2,22
	Chromium Steel	1,1	kg	0,00268	2,948
	Cast iron	0,8	kg	n.a	0
	Aluminium	0,75	kg	0,00826	6,195
	PP	0,25	kg	0,002	0,5
	sum	14,27155	kg		
	Material	**Value**	**Unit**	**kg CO2eq/kWh**	**kg CO2eq emissions**
System	Electricity	16,9	kWh	0,285	4,8165
				sum	112,571282

The LS-MGO-fueled ship is assumed to be equipped either with a two-stroke or with a four-stroke diesel engine, along with diesel generators. The representative air emissions from the machinery subsystem inventory are obtained from Ventikos and Chatzinikolaou study (Chatzinikolaou, 2015) and are presented below (Table 2).

Table 2: Representative emissions from machinery building inventory

	Substance	**Unit**	**per kW installed**
1	CO2	kg	84,827
2	CO	kg	0,183
3	CH4	kg	0,104
4	NO2	kg	0,034
5	NOx	kg	0,236
6	PM (all)	kg	0,557
7	SO2	kg	0,279
8	SOx	kg	0,011
9	VOC	kg	0
10	NMVOC	kg	0,018

The operation phase's emissions differ significantly between the two ships. The conventional ship produces GHG emissions through the combustion of LS-

MGO, whereas hydrogen ship produces zero emissions during its operation. However, hydrogen production and its further treatment is responsible for multiple air emissions, depending on the production method used for the hydrogen.

The operation phase for both ships can be divided into three separate phases:

- Voyage time: The total voyage time, t_v, is obtained from databases. For the scope of this thesis, voyage time is not separated into ballast and laden legs, due to lack of detailed operational data.
- Maneuvering time: The maneuvering time, t_m, for berthing and departure can be estimated using empirical equations from relative literature. A good estimation is given through the next formula, which correlates maneuvering time with the ship's length and calculates it in minutes (Özkulluk, 2023):
  $t_m = \begin{cases} 0{,}3138 * L_{OA}, berthing \\ 0{,}1179 * L_{OA} + 5{,}6228, departure \end{cases}$ (1)
- Port/anchorage/idle time: The port/anchorage/idle, t_p, time can be obtained from databases. During this time, it is assumed that the main engine does not operate, however, auxiliary engines remain in operation.

Ships are usually designed to navigate at operating speeds, $V_{des}\ (kn)$, which are equal to 100% of the main engine load. By using the propeller's law, the main engine power during voyage time, $P_{ME,ave}\ (kW)$,can be calculated through the following equation:

$P_{ME,ave} = P_{ME} * (\frac{V_{ave}}{V_{des}})^n$ (2), in which:

- P_{ME}: main engine design load
- V_{ave}: average ship speed
- The approximate n value is given by brochures of engine makers (MAN Energy Solutions), using the next table (Table 3)

Table 3: Example ships with exponents to the power curve(source: MAN Energy Solutions)

Category	Propeller	Length overall	Breadth	Draught	CB	V,kn(=n)	V,kn(=n)	V,kn(=n)	V,kn(=n)
Tanker,product	1 FP	174	32,2	11	0,78	13 (3,2)	14 (3,4)	15 (3,6)	16(3,8)
Bulk carrier	1 FP	273	46	16,5	0,83	13 (3)	14(3,1)	15 (3,3)	16 (3,6)
Container ship	1 FP	375	59	16	0,68	21 (3,2)	22 (3,3)	23 (3,3)	24 (3,4)
Container ship	2 FP, twin skeg	375	59	16	0,68	21 (3,1)	22 (3,2)	23 (3,2)	24 (3,3)
Ro-pax	2 CP, twin skeg	200	31,8	7	0,61	21 (3,4)	22 (3,7)	23 (4,1)	24 (4,8)

The average load of the auxiliary engines is assumed to be 50% of the design load $P_{AE}\ (kW)$. Hence:

$P_{AE,ave} = 0{,}5 * P_{AE}$ (3)

The total average ship power, $P_{ave}\ (kW)$, is calculated by summing $P_{ME,ave}$, $P_{AE,ave}$:

$$P_{ave} = P_{ME,ave} + P_{AE,ave} \quad (4)$$

Equations (1)-(4) are valid for both types of ships.

Hydrogen-fueled ship

For the hydrogen-fueled ship specifically, the required power of a PEMFC should be increased by 10% when hydrogen is used as a fuel (Perčić, 2022). Hence:

$$P_{PEMFC} = 1{,}1 * P_{ave} \quad (5)$$

In order the operating temperature of a PEMFC to be reached, a few minutes or even seconds are required, according to the relative bibliography. In this thesis it is assumed that the operating temperature is reached within three minutes. The power needed for the heating of the fuel cell system can be provided by shore electricity in a port or by onboard batteries (Figure 9). Batteries are mostly used for SOFC systems, which require a 6,7 times greater heating time in order their operating temperature to be reached. For the PEMFC system being simulated, shore electricity is assumed.

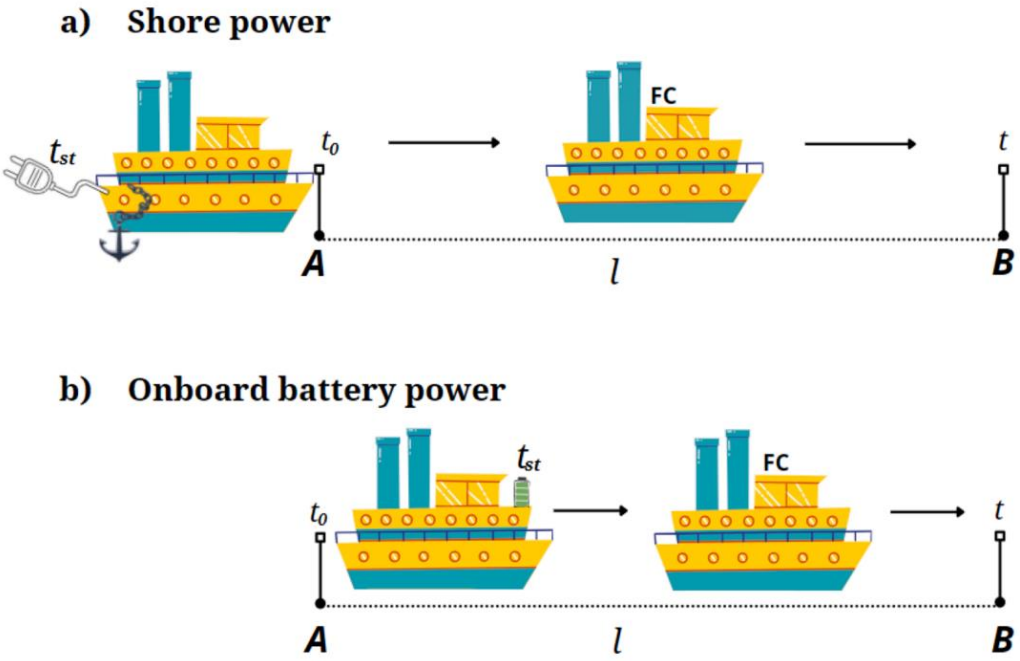

Figure 9: considered options for reaching the operating temperature of a fuel cell

The energy demand for the heating of the PEMFC system is assumed to be 0,015 kWh/kW (Perčić, 2022). Hence, the required energy for the system heating, EH (kWh), is calculated through the following equation:

$$EH = 0{,}015 * P_{PEMFC} \quad (6)$$

The fuel consumption for the voyage time of the year, FC (kg/year), is calculated as:

$FC_v = \frac{P_{ave} * t_v}{\eta_{PEMFC} * NCV}$ (8), in which:

- η_{PEMFC}: fuel cell's efficiency
- NCV: Net calorific value of hydrogen fuel. The NCV for hydrogen is equal to 33,33 kWh/kg.

The total fuel consumption, FC_{year} (kg/year), is calculated by adding the fuel consumption during maneuvering time and during port/anchorage/idle time. The fuel consumption should also be increased by 10%, in order the effect of bad weather to be taken into consideration.

As already mentioned before, hydrogen fuel produces zero GHG emissions during ship's operation. However, hydrogen is responsible for GHG emissions during:

- Production procedure
- Liquefaction procedure (in case LH_2 is used)
- Storage procedure
- Transportation procedure
- Regasification procedure(in case LH_2 is used)

For the production procedure, GHG emissions are obtained from relative bibliography. The amount of emissions differs significantly dependent on the production method used. For the scope of this thesis, the cases of grey hydrogen, blue hydrogen and green hydrogen will be examined. The GWP values for each hydrogen case are obtained directly from relative bibliography (Cetinkaya, 2012), (Hermesmann, 2022).

The liquefaction procedure's emissions, L_{em} (kg $CO2_{eq}$/kg H_2 liquified), are calculated through:

$L_{em} = H2_{liq} * CO2_{perkWhel}/1000$ (10), in which $H2_{liq}$ (kWh/ kg CO_2) is modeled as the energy demand for the liquefaction of one kilogram of hydrogen. The value of $H2_{liq}$ can be obtained from three different studies (Wulf, 2018), (Zhang, 2023), (Isotta, 2012). In this thesis, $H2_{liq}$ is considered as the mean value of the three studies mentioned and is equal to 12,94 kWh/ kg CO_2.

The storage procedure's emissions, ST_{em} (kg $CO2_{eq}$/kg H_2 stored), can be modeled as:

$ST_{em} = H2_{stor} * CO2_{perkWhel}/1000$ (11), in which $H2_{stor}$ (kWh/ kg H2) is the specific energy required for the storage of the liquified hydrogen. $H2_{stor}$ is considered to be equal to 1,97 kWh/ kg H2 for liquified hydrogen (Park, 2022). In the case of compressed hydrogen, storage emissions are mainly associated with hydrogen compression (assumption for compression from 30 to 120 bar) and

drying, after it is extracted from the storage tank. The GWP values for gaseous hydrogen compression and drying are obtained from a publication of Joint Research Center(JRC) of the European Union (European Commission, Joint Research Centre, Arrigoni, A., Agostini, T., Eynard,, 2024).

The hydrogen's distribution process can be accomplished either via pipelines or by truck. Since the hydrogen pipeline infrastructure in Greece is still in a pure level, hydrogen is assumed to be transported by truck. Hence, the hydrogen transportation emissions, T_{em} (kg $CO2_{eq}$/kg H_2 delivered), are calculated through:

$T_{em} = H2_{trans} * CO2_{perkWhel} * \frac{trans_{dist}}{100}/1000$ (12), in which:

- $H2_{trans}$: the energy required for transporting 1 kg of hydrogen for 100 km. It is used that $H2_{trans}$=0,39 kWh/ kg H2 (Park, 2022)
- $trans_{dist}$: distance the truck covers till the delivery of hydrogen. In this study, the transportation distance is assumed to be 150km.

According to everything mentioned above, GHG emissions associated with hydrogen can be expressed through the next formula:

$H2_{emissions} = P_{em} + L_{em} + ST_{em} + T_{em}$ (13), in which P_{em} is the amount of emissions coming from hydrogen production.

The annual amount of emissions(kg $CO2_{eq}$/year) can be modeled as:

$EM_{year} = FC_{year} * H2_{emissions} + EH * CO2_{per_{kWhel}} * PC$ (14), in which PC refers to the annual number of port calls.

The total emissions in the ship's operational life are estimated by multiplying annual emissions with the system's lifespan, which is already assumed to be 25 years.

LS-MGO-fueled ship

To continue with the LS_MGO-fueled ship, its operation phase's emissions are estimated using almost the same principles as the hydrogen-fueled ship. The total average ship power, $P_{ave}(kW)$, can be calculated using equations (2)-(4). The fuel consumption for the voyage time of the LS-MGO-fueled ship can be modeled as:

$FC_{v,MGO} = t_v(EC_{D,ME} * SFC_{ME} + EC_{D,AE} * SFC_{AE})$ (15), in which SFC is the specific fuel oil consumption of the diesel engine. The overall fuel consumption per year,$FC_{year,diesel}$ is calculated by adding the fuel consumption during maneuvering time and during port/anchorage/idle time. The fuel consumption should also be increased by 10%, in order the effect of bad weather to be taken into consideration. The same practice is also applied to the hydrogen-fueled ship.

The GHG emissions per year can be calculated by multiplying $FC_{year,diesel}$ with the emission factor, EF (kg CO_{2eq}/kg fuel):

$EM_{year,MGO} = FC_{year,MGO} * EF$ (16)

Emission factors for each fuel are obtained from IMO (MEPC.376(80), 2023).

The total emissions in the ship's operational life are estimated by multiplying annual emissions with the system's lifespan.

Maintenance and disposal phase

The maintenance phase's emissions can be ignored for both the hydrogen and the diesel-fueled ship due to lack of data in the relative bibliography. This practice is also adopted in most relative LCA studies and does not influence significantly the results, since maintenance phase's emissions are associated with only a small share of the total GHG emissions. This assumption is also supported by Ventikos and Chatzinikolaou study, who performed a LCA for a diesel-fueled ship and concluded that maintenance phase's emissions where only responsible for 0,87% of the total emission's share (Chatzinikolaou, 2015).

The disposal phase's emissions are also going to be ignored, due to lack of credible data. The amount of disposal phase's emissions is also negligible and hence, ignoring them is not going to influence significantly the final results.

LCIA phase

The last step of the LCA simulation is related to the estimation of environmental impacts of both the hydrogen and the LS-MGO-fueled ship. In this LCA simulation, environmental impacts are going to be estimated using Global Warming Potential for 100 years (GWP_{100}) as a KPI. The unit used for the GWP calculation is CO_{2eq}, which is already mentioned before. Emissions not given in CO_{2eq} unit can be transformed to CO_{2eq} using the following equation (MEPC.376(80), 2023):

$gCO_{2eq} = gCO_2 + 28 * gCH_4 + 265 * gN_2O$ (17)

5.2) LCCA model

This section includes the LCCA process used to evaluate the economic impacts of hydrogen usage as a marine fuel for a ship's lifespan. Moreover, a comparison with a LS-MGO-fueled ship will follow, so as to determine whether the adoption of hydrogen is economically beneficial or not.

Problem definition

Goal of this LCCA simulation is to accurately estimate the economic performance of a hydrogen-fueled ship for its lifespan. The results will be compared with the case of a LS-MGO-fueled ship, in order to be determined whether or how much the adoption of hydrogen increase the life cycle costs.

Breakdown analysis, cost modeling and data collection

In this step, the entire life cycle cost should be divided into individual cost elements. A first approach can divide the cost into four separate life cycle cost phases: construction, operation, maintenance, disposal(Figure 10), (Ventikos, 2022).

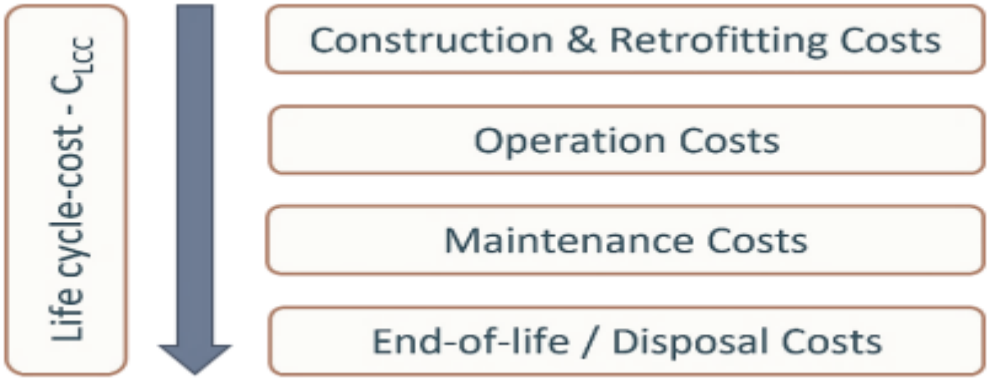

Figure 10: The 4 phases of breakdown analysis step

In this LCCA model, maintenance and disposal costs are ignored, since it was not possible to find accurate data from manufacturers or shipping companies for PEMFC maintenance and disposal. Hence, it was preferred to ignore maintenance and disposal costs for both systems, so as to keep the same boundaries and compare them correctly. The construction costs are obtained from relative literature, while for the operation costs engineering models are used.

Construction costs refer mainly to the construction of two main subsystems: hull and machinery. Since the hull is expected to be the same for both types of ships, the focus will be put on the machinery costs, which are different for the hydrogen and the diesel-fueled ship. Moreover, the fuel's storage tank cost will also be taken into account, since the cost of the hydrogen storage tank is expected to be almost 10 times greater in comparison to diesel oil storage tank. The values for each storage tank's prices are obtained from relative study (Horvath, 2018).

For the hydrogen-fueled ship case, the PEMFC construction cost can be found using Figure 11, which is obtained from a work of Department Of Energy (DOE) from USA (Papageorgopoulos, 2023).

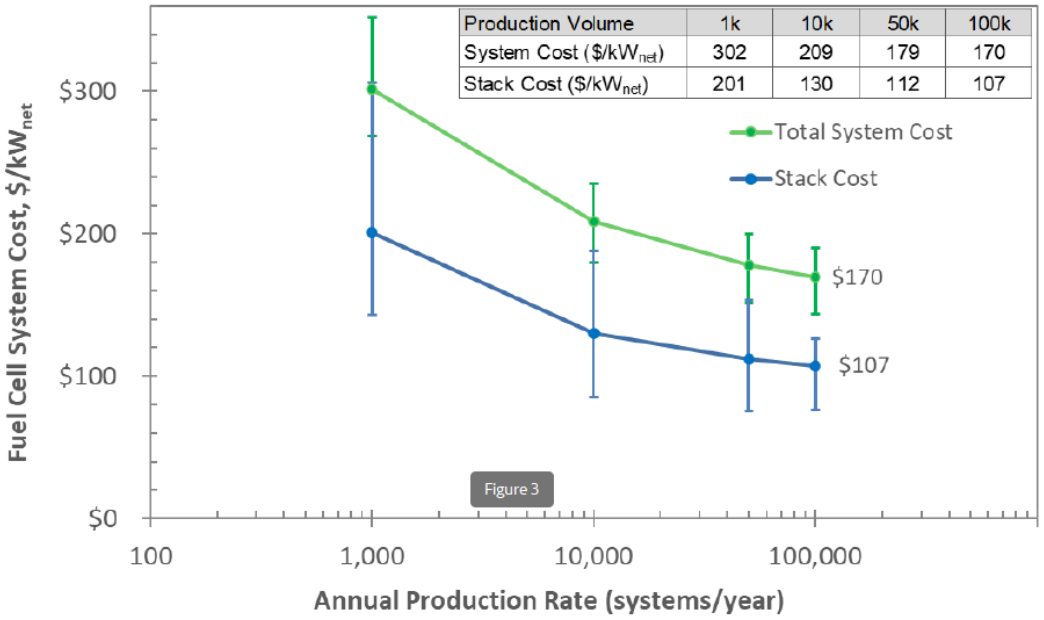

Figure 11: fuel cell system cost(source: DOE)

For the case of this LCCA simulation, an annual production rate of 10000 PEMFC systems per year can be assumed and hence, the PEMFC system cost can be taken equal to 209$/kW. The whole PEMFC system cost, $PEMFC_{totalcost}$ (mil USD), can be calculated through:

$$PEMFC_{totalcost} = PEMFC_{cost} * (P_{ME} + P_{AE}) * 10^{-6} \quad (18)$$

The Capital Expenses (CapEx) include the investment for the PEMFC system along with the appropriate fuel storage tank. Hence, CapEx (mil USD) for the hydrogen-fueled ship is estimated through the following equation:

$$CapEx_{H2} = PEMFC_{totalcost} + StorageTank_{cost} \quad (19)$$

It should also be noted that PEMFC systems have a smaller lifetime in comparison with diesel engines and this must be taken into consideration in the analysis, because the PEMFC system might need to be changed after some years of operation. According to data obtained from PEMFC makers, the PEMFC lifetime is expected to be 35000 hours.

On the other hand, the diesel engine price can be estimated 360$kW for globally known brands (Lyu, 2022). Hence, the CapEx (mil USD) for the diesel case can be calculated as:

$$CapEx_{diesel} = engine_{price} * \frac{P_{ave}}{1000000} + StorageTank_{cost} \quad (20)$$

The operational costs of each case are mainly driven by the fuel consumption cost. Since the two fuels require a completely different treatment, a separate analysis for each case is following in the next paragraphs.

The operational expenses (OpEx) of the hydrogen-fueled ship can be separated into fuel cost and shore electricity cost.

The hydrogen fuel's cost can be modeled as following:

- Hydrogen production cost (P_{cost})
- Hydrogen liquefaction cost (L_{cost}), in case liquified hydrogen is used
- Hydrogen compression cost(C_{cost}), in case gaseous hydrogen is used
- Hydrogen storage cost (St_{cost})
- Hydrogen transportation cost (T_{cost})

The hydrogen production cost varies in the literature, as it depends on many factors and especially on the production method used. A good estimation for each hydrogen type's cost is given by a report of EU Hydrogen Policy (EU hydrogen policy, 2021). Liquefaction and compression costs are obtained directly by a technical report from Hydrogen Council (Hydrogen Council, 2020). The exact values are L_{cost}=1,6$/kg H_2 and C_{cost}=0,8$/kg H_2.The gaseous hydrogen's storage cost is taken equal to 0,14$/kg H_2, assuming that hydrogen is stored in salt caverns $(\text{Abdin}, 2022)$. In case of liquid hydrogen, the storage cost is taken equal to 0,09$/kg H_2 for an above ground liquid storage tank (Burke, 2024).Transportation costs are also estimated by Hydrogen Council (Hydrogen Council, 2020), with their values being 0,4$/kg H_2 for liquid trucking and 1$/kg H_2 for gaseous trucking.

Hence, fuel cost is calculated through the next formula:

$$H2_{cost} = \begin{cases} P_{cost} + L_{cost} + St_{cost} + T_{cost}, liquified\ hydrogen \\ P_{cost} + C_{cost} + St_{cost} + T_{cost}, gaseous\ hydrogen \end{cases} \quad (21)$$

The shore electricity cost ($) in an annual basis can be modeled as:

$EH_{cost,year} = EH * elect_{cost} * portcalls$(22), in which $elect\_cost$ is the price for electric current. For the Greek case it is taken equal to 0,15$/kWh.

Finally, the OpEx ($/year)for the hydrogen fueled ship is calculated through:

$OpEx_{H2} = H2_{cost} * FC_{year} + EH_{cost,year}$ (23)

The OpEx of the LS-MGO-fueled ship can be separated into fuel cost and lubricant oil cost. Furthermore, the EU ETS carbon tax cannot be ignored, as it influences significantly the OpEx analysis.

The LS-MGO fuel cost ($) and lubricant oil cost ($) for a whole year are calculated using the following equations:

$LS\_MGO_{cost} = FC_{year,MGO} * LS\_MGO_{price}$ (24)

$Lub_{cost} = SLOC * P_{ave} * t_v * lub_{price}$(25), in which $SLOC$ refers to the specific lubricant oil consumption of the diesel engine. The prices for diesel oil and lubricant oil are obtained using real data for the port of Piraeus.

The EU carbon permit price is nowadays equal to 65$/t CO_2, using real data for September 2024. Hence, the total carbon tax ($) for a year is equal to:

$$Carbon_{cost} = CO2_{cost} * \frac{FC_{year,MGO}}{1000} * EF \quad (26)$$

Finally, the OpEx ($/year)for the diesel-fueled ship is calculated with combination of equations (24)-(26):

$$OpEx_{diesel} = LS\_MGO_{cost} + Lub_{cost} + Carbon_{cost} \quad (27)$$

Maintenance and end of life costs are totally ignored for both ships in the present diploma thesis, since it was impossible to find accurate data from engine makers or shipowner companies. This practice is also adopted by some other LCCA studies, while a few studies use empirical equations to estimate maintenance or end of life costs. However, empirical equations do not always give credible results for all types of ships and hence it was preferred not to use them.

Cost estimates and evaluation

In the cost estimates phase, cost elements are brought together in order to form the final cost estimate. The proper treatment of future cost values requires the use of the nominal discount rate (r_{nom}) and inflation rate (r_{infl}). The relationship between nominal discount rate and inflation rate is given through the next equation (Ventikos, 2023):

$$r_{real} = \frac{1+r_{nom}}{1+r_{infl}} - 1 \quad (28)$$

For the scope of this thesis, nominal and inflation rates are assumed to be constant during the ship's lifetime. The values taken are $r_{nom} = 4\%$ and $r_{infl} = 2\%$. The KPI chosen for the evaluation of the LCCA is Net Present Cost (NPC), which sums the present value of all cost elements during the ship's lifetime. NPC is estimated through the next formula:

$$NPC = CaPex + OpEx * \frac{(1+r_{real})^{25}-1}{r_{real}*(1+r_{real})^{25}} \quad (29)$$

6) Case studies: Analysis and results

6.1) Ship characteristics and operational data

The LCA and LCCA models described in Chapter 5 will be applied in five different ships. Their main particulars and operational data are summarized below (Table 4),(Table 5). Operational data are obtained using real data from databases. The main engine load (%) during maneuvering time is obtained from relative technical report (Winebrake, 2007). The maneuvering time is generally obtained from equation (1), apart from the Ro-pax and the cruise ship, which maneuvering time is assumed to be 10 and 15 minutes respectively in both berthing and departure. This differentiation is made because the Ro-pax and the cruise ship operate in smaller ports, in which the maneuvering time is expected to be less. Another differentiation for the Ro-pax ship is that port time is estimated as the time for loading/unloading, which is taken equal to 30 minutes per port call. The rest of the time the ship remains inactive in the port and all engines are assumed to be switched off.

Table 4: Main ship particulars

Main ship particulars					
	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5
Ship Type	Ro-pax	Bulk carrier	Tanker	Containership	Cruise/passenger
Length overall(m)	96,5	99,05	104,99	99	99,9
Breadth(m)	16,6	16	19,05	22	16,8
Depth(m)	4,05	7,7	9,9	5	4,75
Main Engine Power(kW)	1342	2060	3309	1617	1920
Main Engines Number	4	1	1	2	2
Main engine SFOC(gr/kWh)	205	198	200	200	219
Auxiliary Engine power(kW)	447	200	400	225	533
Auxiliary Engines Number	2	3	3	3	3
Auxiliary engine SFOC(gr/kWh)	215	215	215	215	215
Design Speed(kn)	17	11,6	12,3	12,2	17
Average speed(kn)	13,3	7,8	9	9,9	10,2

Table 5: Operational data

Operational data					
	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5
Port calls(per year)	904	67	84	105	120
Voyage time(hours per year)	1280,7	3691,4	3552,7	5269,0	2220,0
Maneuvering time(min. per port call)	301,3	52,6	71,3	83,0	60,0
Main engine load maneuvering(%)	25,00%	8,00%	8,00%	8,00%	25,00%
Port/Anchorage/Idle time(hours per year)	1168	5016	5136	3408	6480

6.2) Results

This section includes the results of both LCA and LCCA simulations. Firstly, the results are presented for each ship separately. This section includes the result for the Ro-pax ship, while the results for the rest of the ships are similarly presented in Appendix A.

The results for the Ro-pax ship are presented in Figure 12 and Figure 13. The comparative results with LS-MGO are summarized in Table 6.

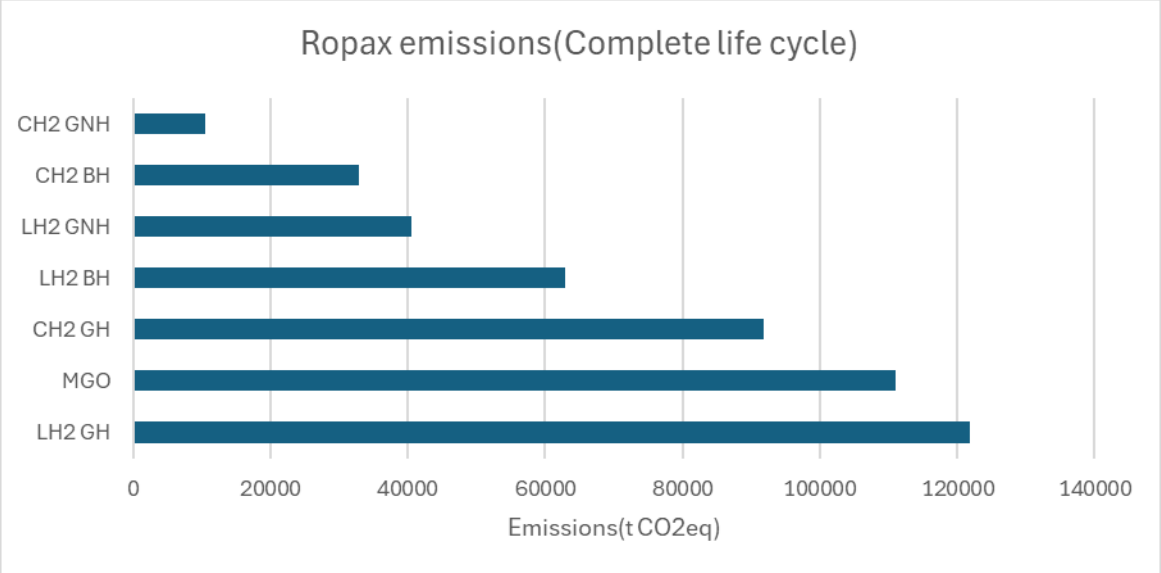

Figure 12: Ro-pax ship LCA results

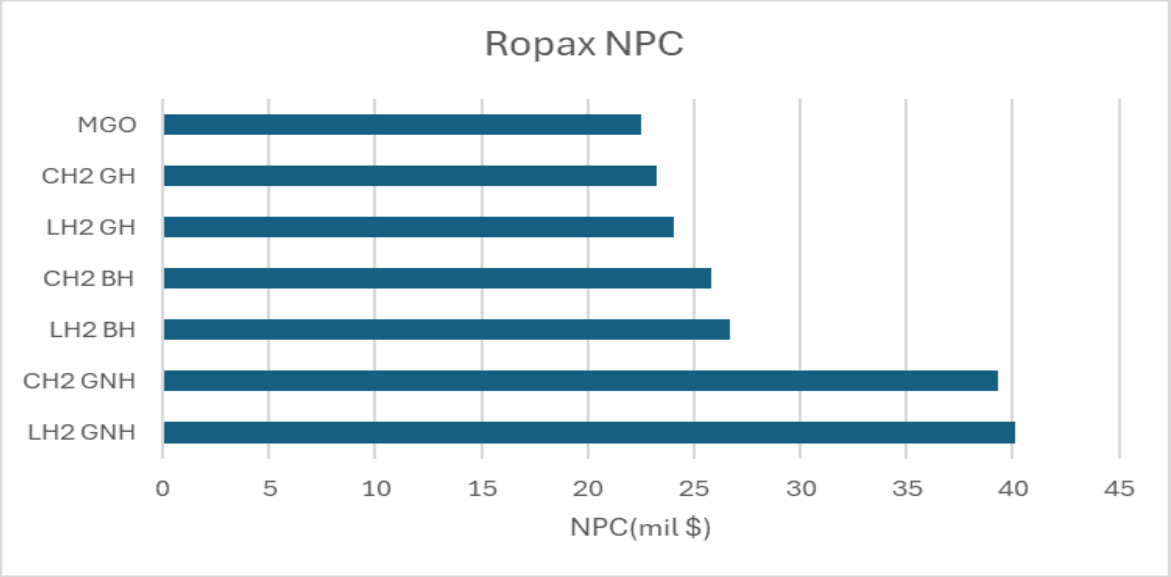

Figure 13: Ro-pax ship LCCA results

Table 6: Summarized comparative life cycle results for the Ro-pax ship

Ro-pax comparative LCA,LCCA results						
Fuel	GH-LH2	GH-CH2	BH-LH2	BH-CH2	GNH-LH2	GNH-CH2
Emissions % differentiation	9,75%	-17,33%	-43,37%	-70,43%	-63,48%	-90,54%
NPC % differentiation	7,05%	3,15%	18,74%	14,84%	78,47%	74,58%

The main conclusions are the following:

- Liquified grey hydrogen (LH2 GH) results to be more harmful than LS-MGO, increasing the total emissions by 9,75%. All other types of hydrogen are environmentally beneficial compared to LS-MGO. The maximum reduction of emissions is observed in the case of compressed green hydrogen (CH2 GNH), in which the total emissions are reduced by 90,54%. It is also remarkable that blue hydrogen contributes significantly to emission's reduction, as compressed blue hydrogen is observed to reduce the total emissions up to 70,43% compared to LS-MGO. Liquified blue and green hydrogen give also promising results with reductions up to 43,37% and 63,48% respectively. Compressed grey hydrogen (CH2 GH) would also be slightly beneficial compared to LS-MGO, offering a reduction of 17,33% in the ship life cycle's emissions.
- LS-MGO results to be the cheaper option for the ship's life cycle. Grey hydrogen, either compressed or liquified, is expected to slightly increase NPC (by 3,15% and 7,05% respectively). The adoption of blue hydrogen raises NPC by 14,84% for the case of compressed hydrogen and 18,74% for the case of liquified hydrogen. However, in green hydrogen case the NPC is significantly higher with an increase up to 74,58% for compressed hydrogen and 78,47% for liquified hydrogen.

- Compressed hydrogen is associated with significantly lower amounts of emissions compared to liquified hydrogen. For the grey hydrogen case, emissions rise by 32,75% when liquified hydrogen is used instead of compressed hydrogen. The differentiation is even more significant in the case of blue hydrogen, for which emissions increase by 91,5% when the hydrogen is liquified. If green hydrogen is used, liquified hydrogen's emissions are 3,86 times higher than compressed hydrogen's emissions.
- Liquified and compressed hydrogen's NPCs do not differ significantly.

After the analysis of results for each ship type separately, it is also considered useful to compare the results of the five ship types altogether. The LCA results of the five ships for the green hydrogen case are presented in Figure 14. The results for grey and blue hydrogen respectively are presented in Appendix A in a similar way.

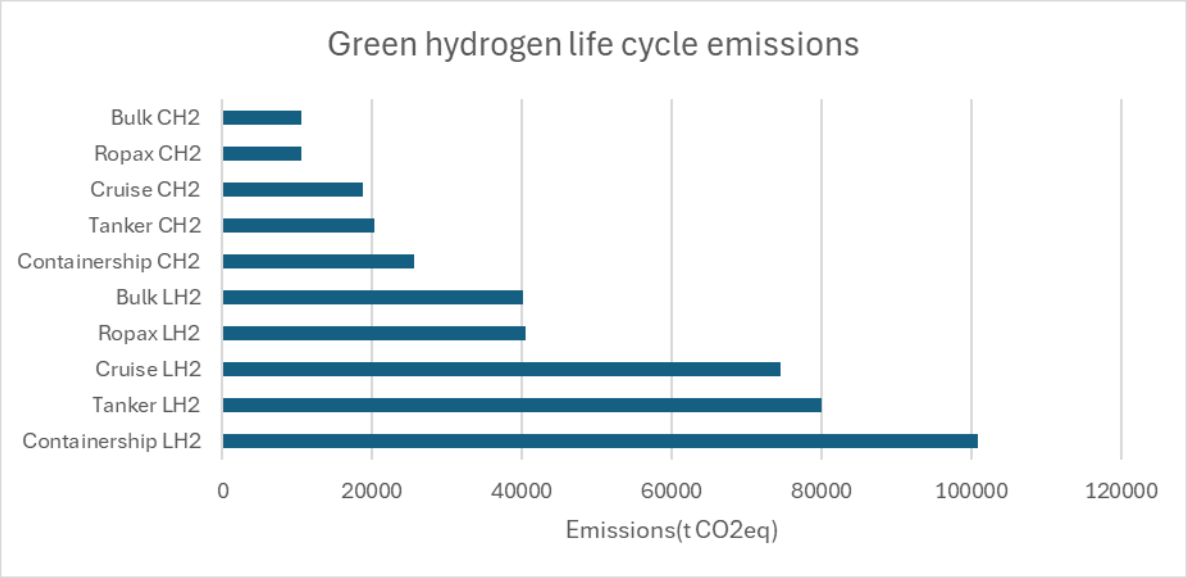

Figure 14: Green hydrogen LCA results

According to Figure 14, it is clearly observed that the life cycle emissions differ significantly between the five ship types. For example, the containership's emissions are 2,52 times higher compared to the Bulk carrier ship emissions, assuming that both ships use liquified hydrogen. Similar differences can also be found when other ship types are compared. These differences, however, seem to be reasonable, since the five ships have completely different operational profiles and designs. The hydrogen-fueled ship's emissions are also compared to the LS-MGO case. The comparative results are presented in Figure 15:

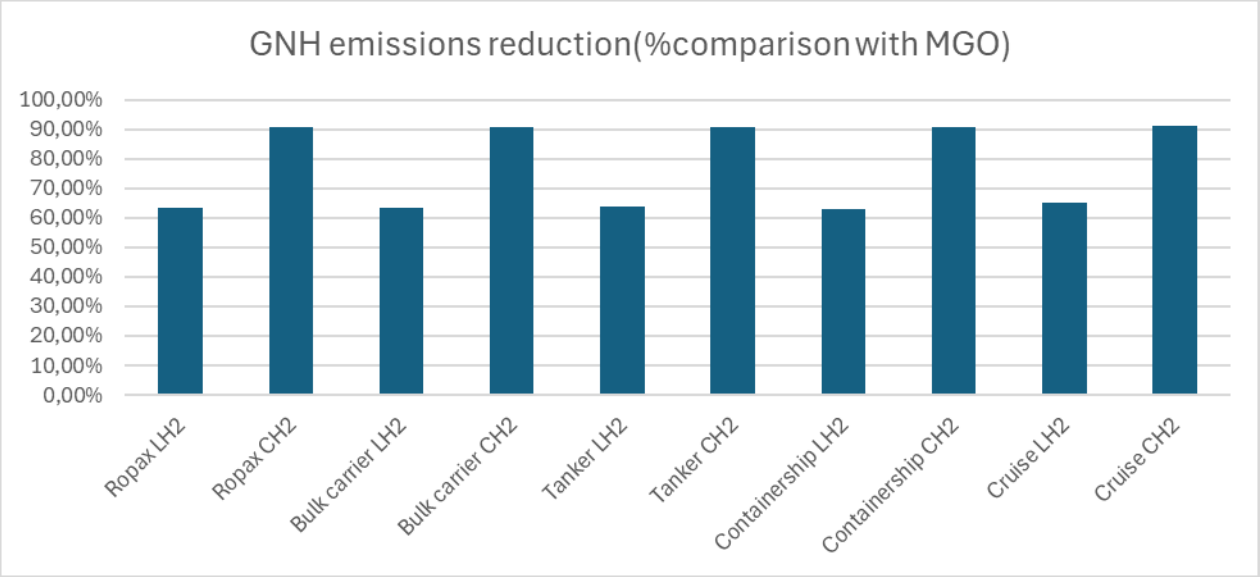

Figure 15: Green hydrogen LCA results compared with LS-MGO

According to Figure 15, it is observed that the emission's reduction is similar for all ship types (almost 90% for compressed hydrogen and 60% for liquified hydrogen). The only differentiation is between liquified and compressed hydrogen, as liquified hydrogen is associated with significantly higher emissions.

The LCCA results of the five ships for the green hydrogen case are presented in Figure 16. The results for grey and blue hydrogen respectively are presented in Appendix A in a similar way.

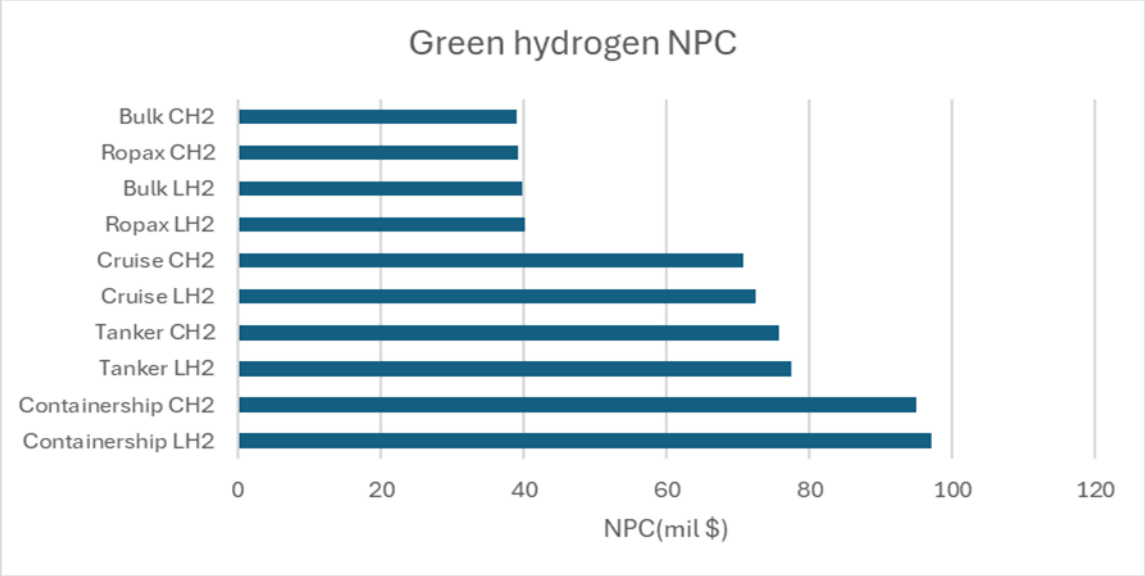

Figure 16: Green hydrogen LCCA results

As expected, there are significant differentiations between the results of each ship type. For example, if the containership with the bulk carrier is compared, the containership's NPC is 143% higher when compressed hydrogen is assumed.

Similar differences can also be found when other ship types are compared. These differences, however, seem to be reasonable, since the five ships have completely different operational profiles and designs. The hydrogen-fueled ship's NPCs are also compared to the LS-MGO case. The comparative results are presented in Figure 17:

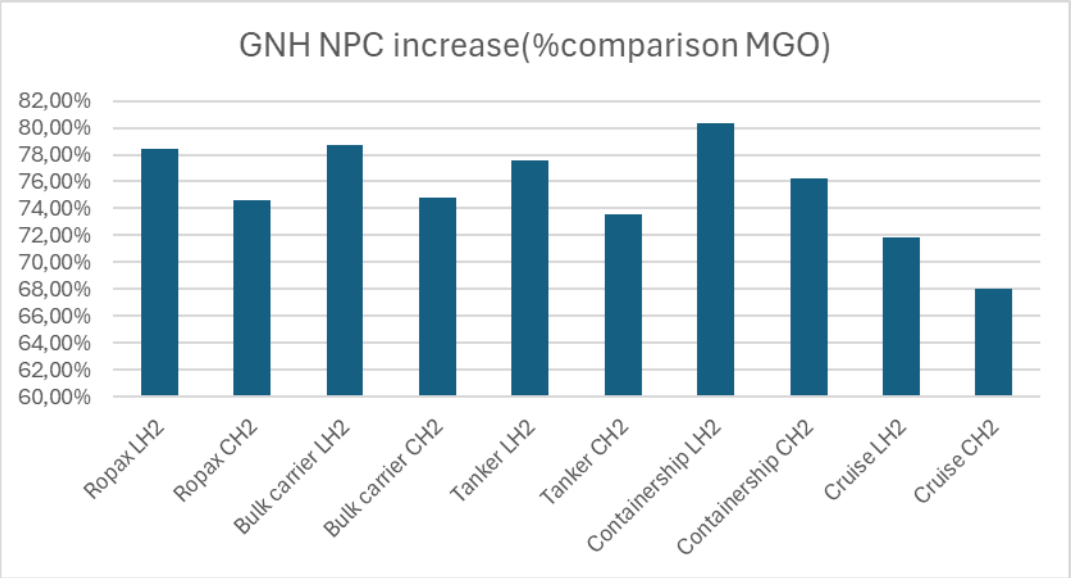

Figure 17: Green hydrogen LCCA results compared with LS-MGO

According to Figure 17, it is observed that the NPC increase is similar for all ship types (between 68%-76% for compressed hydrogen and 72%-80% for liquified hydrogen). The differentiations between liquified and compressed hydrogen are slight.

6.3) Results discussion and comparison with similar studies

This section includes the discussion of the main results and conclusions reached in Section 6.2. A direct comparison with similar studies is also considered necessary, so as to validate the accuracy of the results presented above.

Figure 18 depicts the emission factors of each hydrogen type, including production stage and the rest of procedures needed before hydrogen is combusted in the fuel cell. Emission factors presented in Figure 18 are in accordance with the results presented in Figure 12 for the Ro-pax ship.

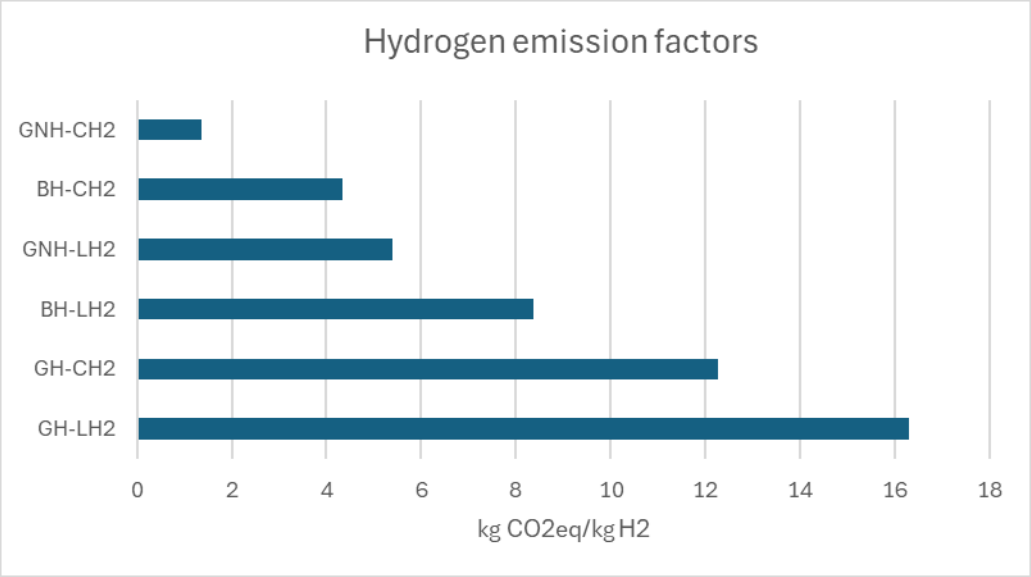

Figure 18: Hydrogen emission factors

A more detailed analysis of hydrogen's emission factors is following in Table 7 for liquified hydrogen and Table 8 for compressed hydrogen.

Table 7: Liquified hydrogen EF analysis

	GH-LH2	%	BH-LH2	%	GNH-LH2	%
Production(kg CO2eq/kg H2)	11,89	72,92%	3,97	47,34%	0,97	18,01%
Liquefaction(kg CO2eq/kg H2)	3,69	22,61%	3,69	43,98%	3,69	68,47%
Storage(kg CO2eq/kg H2)	0,56	3,44%	0,56	6,70%	0,56	10,42%
Transportation(kg CO2eq/kg H2)	0,17	1,02%	0,17	1,99%	0,17	3,10%
Emissions sum(kg CO2eq/kg H2)	16,31		8,39		5,39	

Table 8: Compressed hydrogen EF analysis

	GH-CH2	%	BH-CH2	%	GNH-CH2	%
Production(kg CO2eq/kg H2)	11,89	96,90%	3,97	91,25%	0,97	71,83%
Compression(kg CO2eq/kg H2)	0,19	1,51%	0,19	4,26%	0,19	13,72%
Drying(kg CO2eq/kg H2)	0,03	0,23%	0,03	0,66%	0,03	2,11%
Transportation(kg CO2eq/kg H2)	0,17	1,36%	0,17	3,83%	0,17	12,35%
Emissions sum(kg CO2eq/kg H2)	12,27		4,35		1,35	

Table 7 and Table 8 explain the differentiation of life cycle emissions between compressed and liquified hydrogen, since liquefaction procedure is energy-intensive and associated with emissions equal to 3,69 kg $CO2_{eq}$/kg H_2. In the case of green hydrogen especially, liquefaction is responsible for 68,47% of the overall emissions. Hence, it is reasonable that the emission factor for liquified hydrogen is 3,86 times higher; a conclusion also reached in Section 6.2 for the Ro-pax ship.

Alghool et al. also found increased emissions for liquified hydrogen compared to compressed hydrogen (Alghool, 2024). However, they only observed a rise equal to 47% for the case of green hydrogen, whereas in the present thesis

the increase is found equal to 286%. The reasons for this differentiation are the following:

- In the referred study the authors assumed green hydrogen production using renewable energy from CPV-T Collectors. Emissions in the hydrogen production stage are taken equal to 2,5 kg $CO2_{eq}$/kg H_2. On the other hand, the present thesis assumes green hydrogen production using wind electrolysis and the emissions for the production stage are taken equal to 0,97 kg $CO2_{eq}$/kg H_2.
- The two studies adopt different values for the energy demands of the procedures during hydrogen production. For example, liquefaction procedure's emissions are taken equal to 12,94 kWh/ kg H_2 in the present thesis, whereas Alghool, Haouri and Trucco assume 10 kWh/ kg H_2 for the liquefaction stage.
- Alghool, Haouri and Trucco assume that all necessary procedures(liquefaction, storage, regasification, compression etc.) are completed using electricity from renewable sources. On the other hand, the present thesis scenario refers to electricity coming from the current Greek electricity mix.

As far as the economical analysis is concerned, the cost of each hydrogen type is depicted in Figure 19. Table 9 and Table 10 present a more detailed analysis of the total fuel cost.

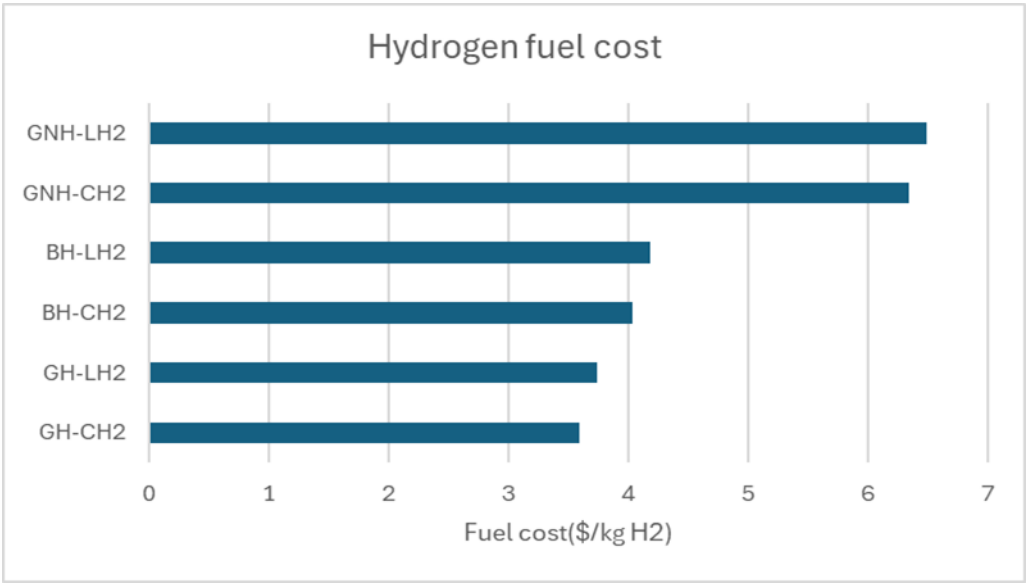

Figure 19: Hydrogen fuel costs

Table 9: Liquified hydrogen cost analysis

	GH-LH2	%	BH-LH2	%	GNH-LH2	%
Production($/kg H2)	1,65	44,12%	2,1	50,12%	4,4	67,80%
Liquefaction($/kg H2)	1,6	42,78%	1,6	38,19%	1,6	24,65%
Storage($/kg H2)	0,09	2,41%	0,09	2,15%	0,09	1,39%
Transportation($/kg H2)	0,4	10,70%	0,4	9,55%	0,4	6,16%
Sum cost($/kg H2)	3,74		4,19		6,49	

Table 10: Compressed hydrogen cost analysis

	GH-CH2	%	BH-CH2	%	GNH-CH2	%
Production($/kg H2)	1,65	45,96%	2,1	51,98%	4,4	69,40%
Compression($/kg H2)	0,8	22,28%	0,8	19,80%	0,8	12,62%
Storage($/kg H2)	0,14	3,90%	0,14	3,47%	0,14	2,21%
Transportation($/kg H2)	1	27,86%	1	24,75%	1	15,77%
Sum cost($/kg H2)	3,59		4,04		6,34	

The differentiation between NPC values presented in Figure 13 for the Ro-pax ship seems reasonable, given the fuel costs presented in Figure 19. Another conclusion drawn in Section 6.2 is that NPCs values for liquified and compressed hydrogen do not differ significantly and this, indeed, is confirmed by Table 9 and Table 10. Liquefaction procedure is more expensive than compression procedure, however, liquified hydrogen is associated with lower transportation and storage costs. Hence, liquified and compressed hydrogen costs end up very close and the NPCs of each case are correctly found to be close.

The comparative LCA results (comparison of hydrogen-fueled ship with LS_MGO-fueled ship) can directly be compared with other similar studies.

Wang et al. studied the case of a mainland ferry using MDO and concluded that CO_{2eq} emissions would reduce up to 80,3% if green hydrogen was used as a fuel (Wang, 2023). The authors do not make it clear if green hydrogen is compressed or liquified, however it is more possible that they assumed compressed hydrogen, as liquefaction is not mentioned in the study. Those results are close with those observed in the present thesis.

Ana Fernandez-Rios et al. reached the conclusion that GWP increases by 7% when compressed SMR hydrogen(grey hydrogen) is assumed, whereas they stated that GWP decreases by almost 81% when blue hydrogen is assumed (Fernández-Ríos, 2022). Their results are very close to those observed in this thesis for the case of grey and blue hydrogen.

The comparative LCCA results(comparison of hydrogen-fueled ship with LS_MGO-fueled ship) can directly be compared with the study of Percic et al. (Perčić, 2022). The authors concluded that NPC is increased by 95% for liquified grey hydrogen, 125% for liquified blue hydrogen and 227% for liquified green hydrogen compared to MDO. At a first glance, these results are not even close with

those observed in the present thesis. The different results are due to the fact that the authors of the study did not take carbon cost into account, while they also assumed a three times higher cost for the PEMFC system. Moreover, they assumed higher storage and transportation costs for the hydrogen case. Without these differentiations the two studies would produce similar results.

7) LCCA under uncertainty

7.1) Introduction

Section 5.2 was devoted in describing the LCCA framework used to estimate the NPC of the hydrogen and conventional-fueled ships respectively. In this analysis the hydrogen fuel cost was estimated step by step using data from relative literature and no real market prices were used. Except for that, all fuel prices and the carbon price were assumed to be constant during the ship's lifetime and hence, the fluctuation of the prices was not taken into account. In this chapter an uncertainty analysis will be carried out, using real fuel and carbon prices for the interval between September 2021-September 2024. The historical prices for the fuels and the carbon tax were obtained from available sources (BusinessAnalytiq, 2024), (Ship&Bunker, 2024) and their time series are shown below (Figure 20), (Figure 21), (Figure 22), (Figure 23), (Figure 24). It should be noted that the source used for the hydrogen prices does not make it clear if prices refer to compressed or liquified hydrogen. The goal of the analysis is to produce the histogram of NPC and estimate the possibility of a hydrogen-fueled ship investment to be beneficial compared to a conventional diesel-fueled ship. The methodology used to determine which distribution fits best the fuel prices and NPC values is Anderson-Darling Test, which is going to be briefly analyzed in Section 6.2. with information found in relative literature (Engmann, 2011).

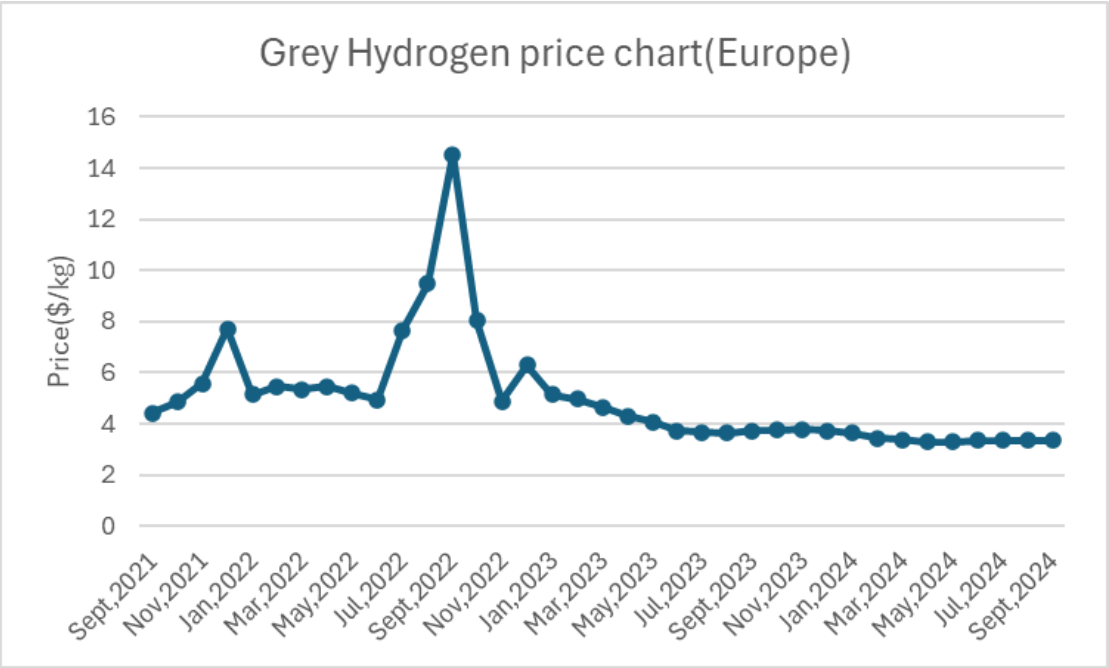

Figure 20: Grey hydrogen historical prices(source:BusinessAnalytiq)

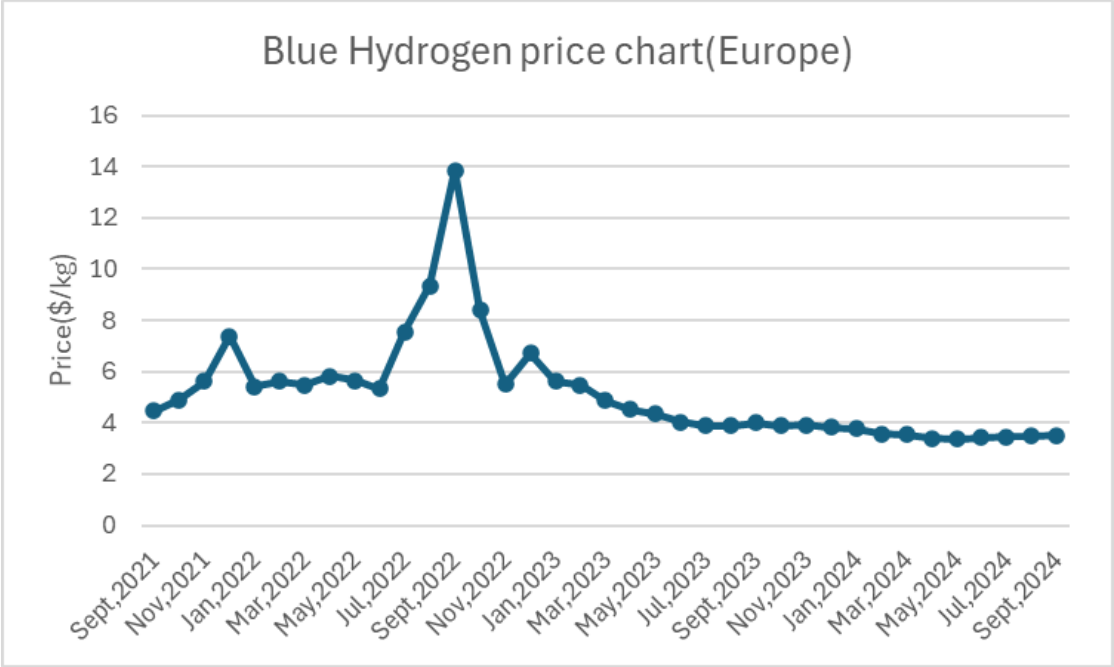

Figure 21: Blue hydrogen historical prices(source: BusinessAnalytiq)

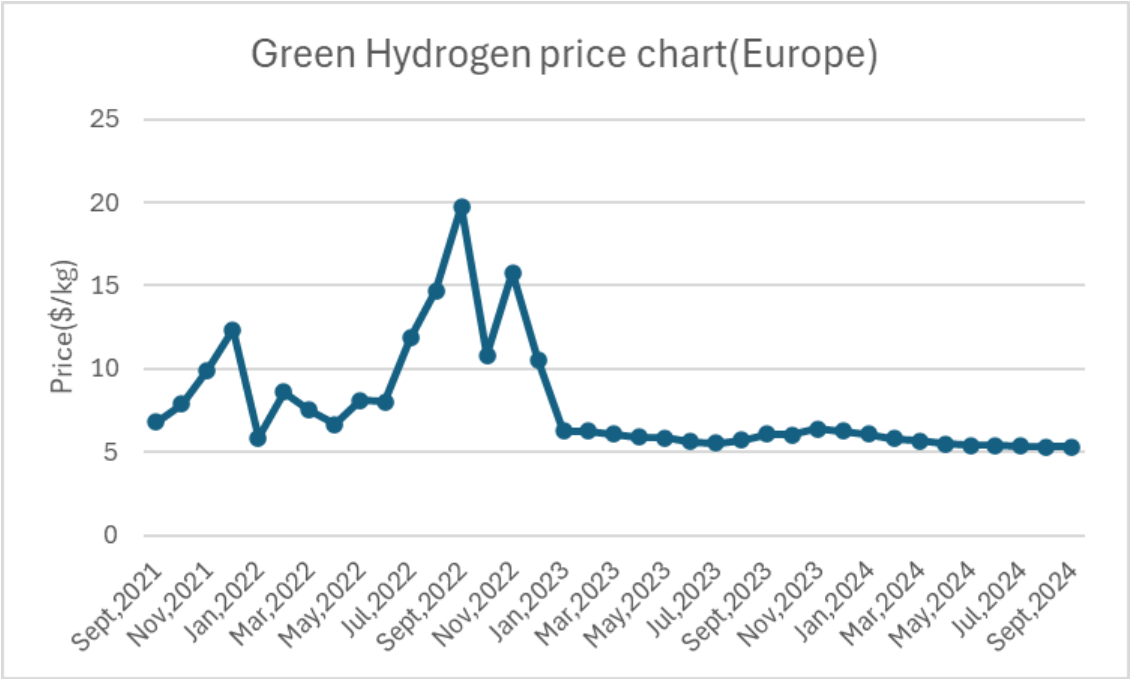

Figure 22: Green hydrogen historical prices(source:BusinessAnalytiq)

According to Figure 20**,** Figure 21 and Figure 22**,** hydrogen price peaked in September 2022, but afterwards prices started decreasing, reaching even lower levels compared to September 2021. The fluctuation of the prices in the interval September 2021- September 2024 is significant, with differentiations up to 300%.

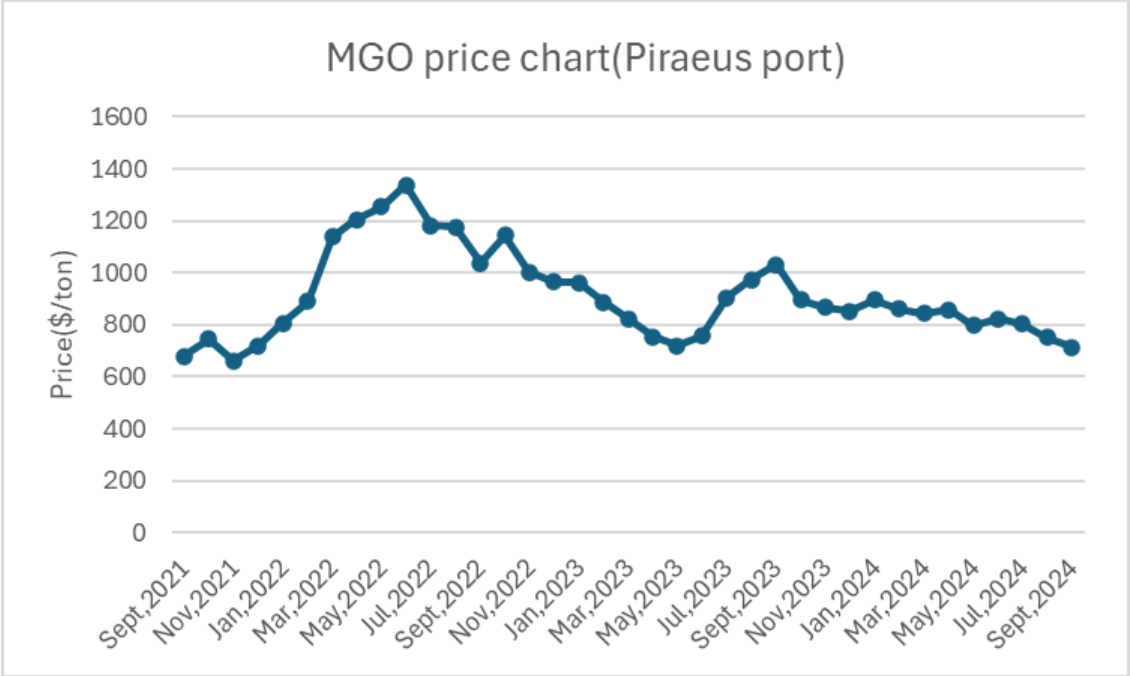

Figure 23: MGO historical prices(source: Ship&Bunker)

The LS-MGO price peak is observed in May 2022. The maximum fluctuation observed is significantly lower compared to the hydrogen case.

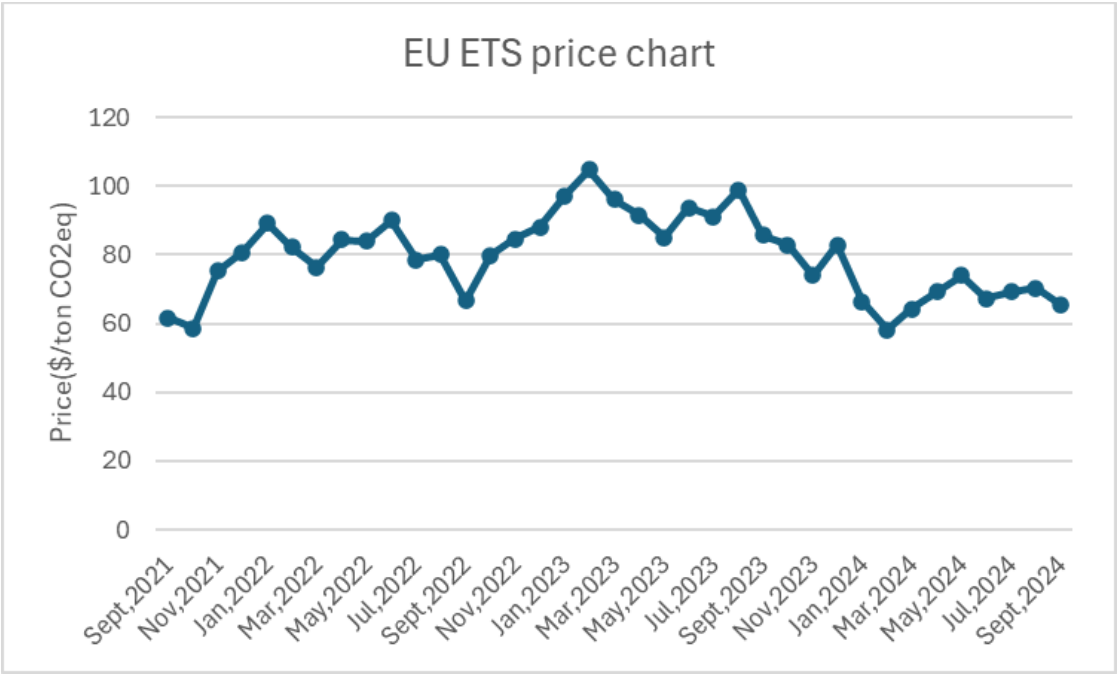

Figure 24: EU ETS historical prices(source:Ship&Bunker)

The EU ETS price peaked in February 2023, reaching 104,8$. Since then, the price has decreased by almost 38%, reaching 65,56$ in September 2024.

7.2) Methodology: The Anderson-Darling Test

The Anderson-Darling test (AD-test)was first developed in 1952 by T.W. Anderson and D.A. Darling, as an alternative statistical test able to determine whether a sample of data follows the normal distribution (Anderson, 1952). However, it can also be applied to other distributions such as exponential, Weibull, and logistic etc. Just like other statistical tests, the AD-test is mainly used for engineering purposes. The AD-test statistic is calculated from the formula:

$AD = -n - \frac{1}{n} * \sum_{i=1}^{n}(2 * i - 1) * (\ln F(x_i) + \ln(1 - F(x_{n+1-i})))$ (33), in which:

- x_i: the ordered sample size of n, from smallest to largest element.
- $F(x_i)$: The CDF of the theoretical distribution to which the sample data is being compared.

The null hypothesis that the sample data fits to a certain distribution is rejected when the AD-test statistic value is greater than the critical value, otherwise the null hypothesis is valid, and the data follows the specified distribution. The critical value is calculated by tables based on a specified significance level. For the scope of this study, the significance level is selected to be 5%.

The AD-test is carried out using the MATLAB software. The software returns the following values:

- AD-test statistic
- Critical value
- h: test decision for the null hypothesis. The software returns h=1 when the null hypothesis is rejected and h=0 when the null hypothesis is valid.
- p: The p-value is calculated based on the value of AD-test statistic, but the exact formula for this conversion depends on the distribution being tested. In Matlab software, this conversion is automatically done and the p-value is directly presented as a scalar value in the range[0,1]. The p- value represents the chance of the observed data to occur under the null hypothesis and hence, the distribution with the higher p-value is finally selected. It should also be noted that p-value should be greater than confidence level; otherwise, the null hypothesis is rejected. For the scope of this thesis, a 95% confidence level is selected.

7.3) Simulation and results

Firstly, the MATLAB code developed is asked to fit the fuel prices to the best fitting distributions by testing all available distributions of the MATLAB library. The

program is asked to return the parameters of the selected distribution and plot the fuel price histogram in the same graph with the probability density function (pdf), (Figure 25). The best-fitting distributions and their parameters for each fuel are summarized below (Table 11). The green hydrogen price histogram along with the pdf is depicted below (Figure 26). Similar figures for the rest of the fuels and the EU ETS are included in Appendix A.

fueltest.m

/MATLAB Drive/fueltest.m

```
dist_names = {'normal','Weibull', 'gamma' 'Poisson', 'ev', 'gev', 'gp', 'hn', 'tLocationScale', 'Logistic', 'Loglogistic', 'Lognormal',

num_dists = length(dist_names);
for ii=1:num_dists
dist=fitdist(MGO_price,dist_names{ii})
[h,p(ii)]=adtest(MGO_price,'Distribution', dist);
end
p
% Find the distribution with the smallest AD statistic
[max_p, idx] = max(p);
best_dist_name = dist_names{idx};
fprintf('Best fitting distribution: %s (p_value = %.4f)\n', best_dist_name, max_p);


figure(1)
x_MGO=600:1:1400;
histogram(MGO_price,x_MGO,'Normalization','probability') %istogramma NPC
hold on
pd4=fitdist(MGO_price,'gev')
MGO_pdf=pdf(pd4,x_MGO);
plot(x_MGO,MGO_pdf)
xlabel('LS-MGO price($/ton)')
ylabel('probability')
title('LS-MGO price histogram along with best fitting pdf')
```

Figure 25: MATLAB code for distribution fitting

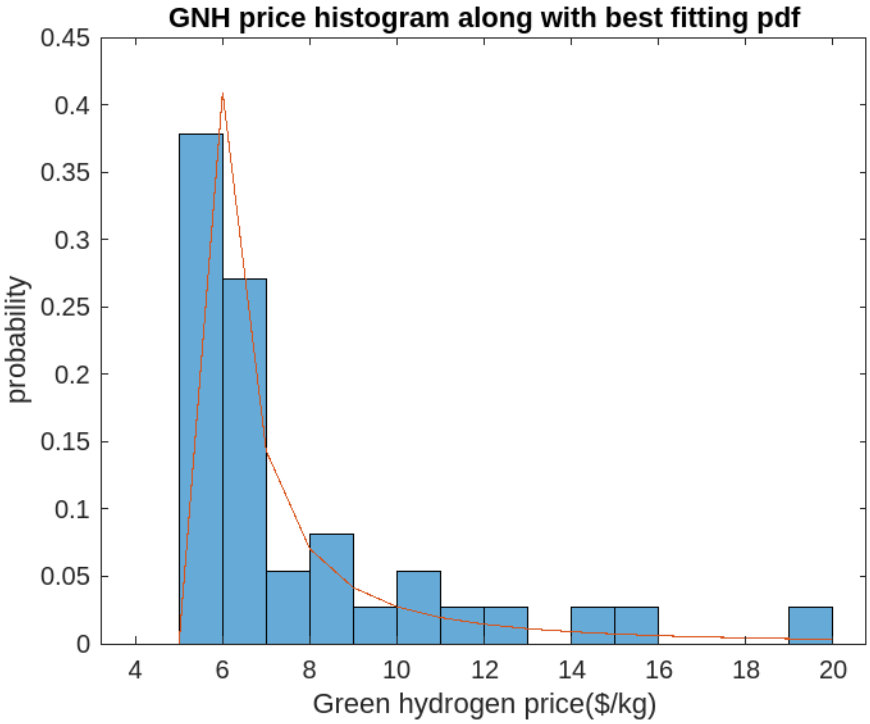

Figure 26: Green hydrogen price histogram along with best-fitting pdf

Table 11: Best-fitting distributions for fuel and EU ETS prices

Fuel	Distribution	k	sigma	mu
Grey hydrogen	Generalized Extreme Value	0,899407	0,643153	3,77923
Blue hydrogen	Generalized Extreme Value	0,679937	0,771867	4,01634
Green hydrogen	Generalized Extreme Value	1,00671	0,769709	5,88102
LS-MGO	Generalized Extreme Value	0,0739998	126,204	839,158

The program is then asked to produce a m x n matrix including random fuel prices, which follow the abovementioned distribution. For the scope of this simulation, it is selected m=1 and n=100000 (Figure 27). NPC values for the random fuel prices are calculated using the equations described in Section 5.2. An AD-test is then performed for the NPC values and the best-fitting distribution along with the corresponding parameters is decided. The analysis output for the Containership's NPCs is presented below for each fuel separately (Figure 28), (Figure 29), (

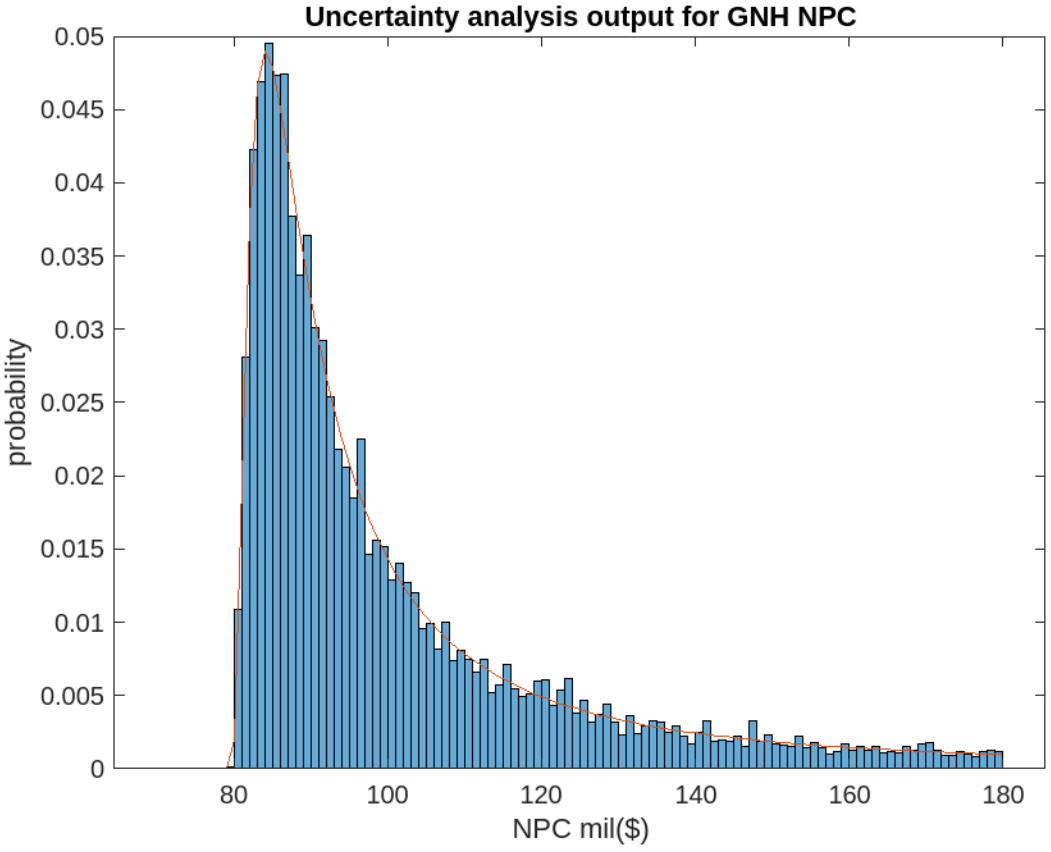

Figure 30), (Figure 31).

```
28    %uncertainty analysis
29
30    m=1;
31    n=10^5;
32
33    GH_price=gevrnd(0.899407,0.643153,3.77923,m,n);
34    BH_price=gevrnd(0.679937,0.771867,4.01634,m,n);
35    GNH_price=gevrnd(1.00671,0.769709,5.88102,m,n);
36    MGO_price=gevrnd(0.0739998,126.204,839.158,m,n);
37    carbon_price=gevrnd(-0.354795,12.0014,75.2559,m,n);
38
```

Figure 27: Random fuel prices production using the distributions of Table 11

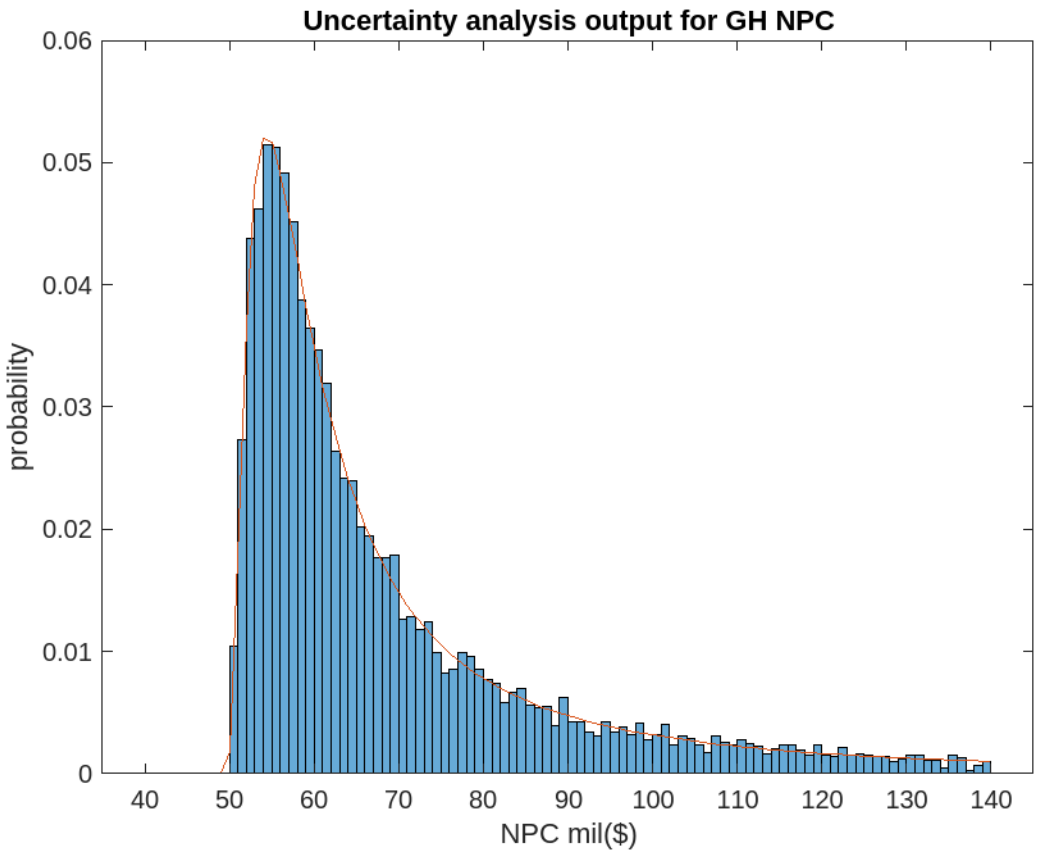

Figure 28: Uncertainty analysis output for Containership's NPC (grey hydrogen case)

According to Figure 28, the mean value calculated for the NPC, assuming a grey hydrogen investment, is equal to 59,1 million $. Compared to the results found in Section 6.3, this value is 4% higher than the NPC value estimated for liquified hydrogen and 8% higher than the NPC value estimated for compressed hydrogen.

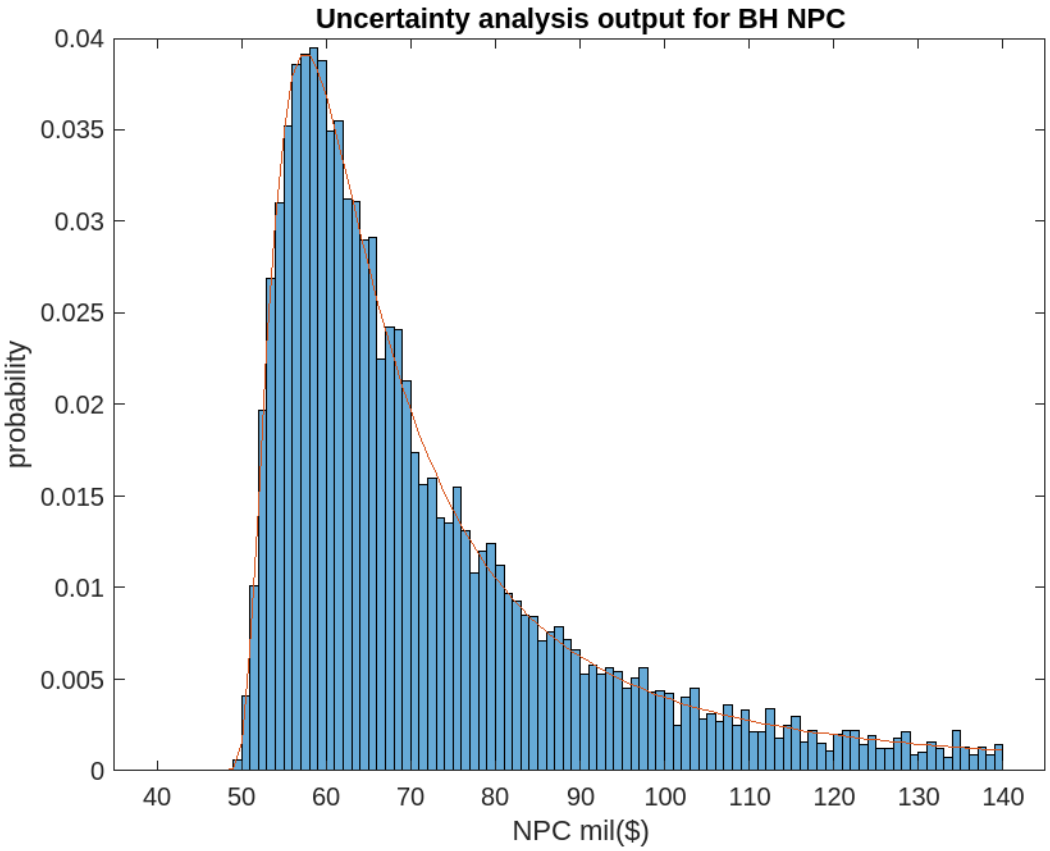

Figure 29: Uncertainty analysis output for Containership's NPC(blue hydrogen case)

According to Figure 29, the mean value calculated for the NPC, assuming a blue hydrogen investment, is equal to 62,4 million $. Compared to the results found in Section 6.3, this value is 1,6% lower than the NPC value estimated for liquified hydrogen and 2% higher than the NPC value estimated for compressed hydrogen.

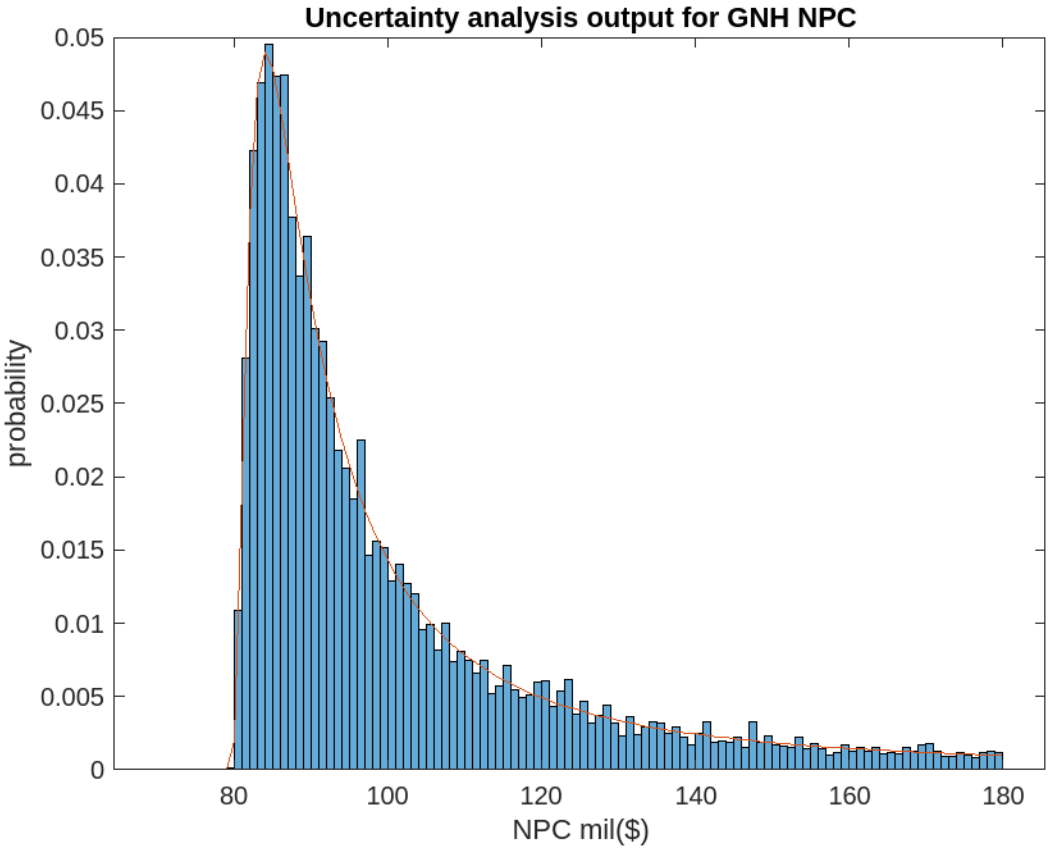

Figure 30: Uncertainty analysis output for containership's NPC(green hydrogen case)

According to

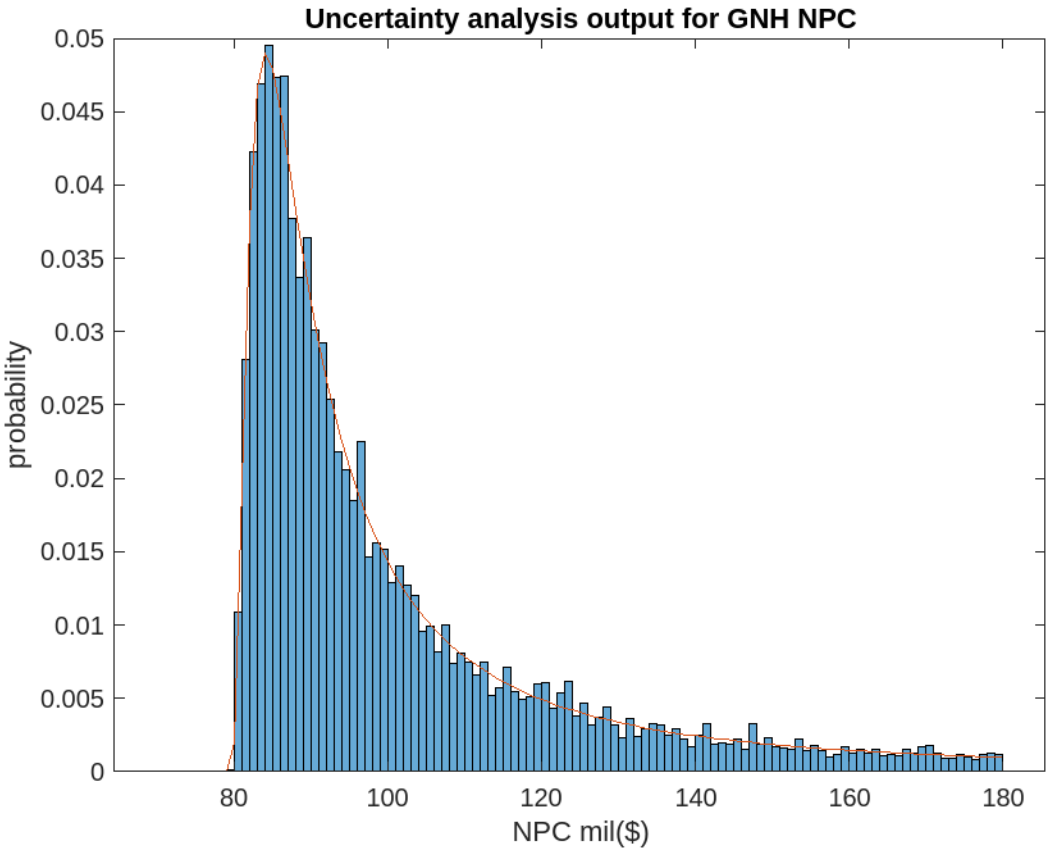

Figure 30, the mean value calculated for the NPC, assuming a green hydrogen

investment, is equal to 89,7 million $. Compared to the results found in Section 6.3, this value is 8% lower than the NPC value estimated for liquified hydrogen and 5,5% lower than the NPC value estimated for compressed hydrogen.

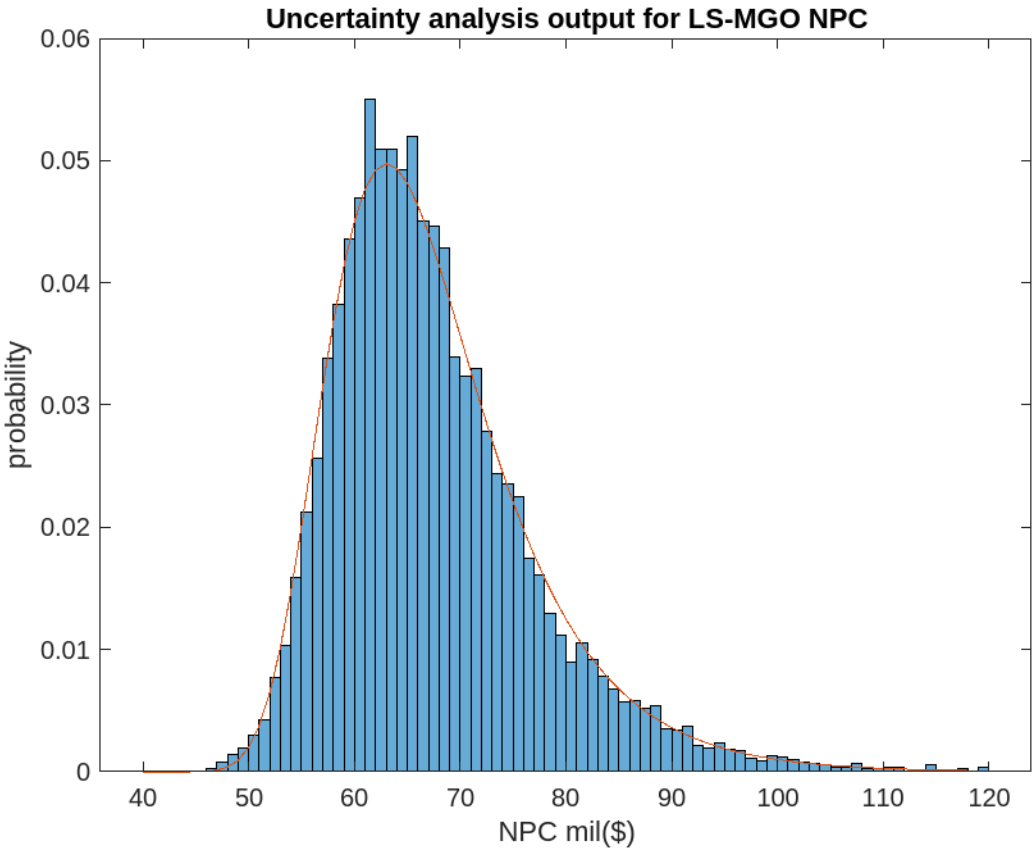

Figure 31: Uncertainty analysis output for containership's NPC (LS-MGO case)

According to Figure 31, the mean value calculated for the NPC, assuming a LS-MGO investment, is equal to 63,1 million $. Compared to the results found in Section 6.3, this value is 17% higher than the NPC value estimated for LS-MGO.

The evaluation of the investment in a hydrogen-fueled ship is accomplished by calculating additional cost (AC), which illustrates the absolute NPC increase compared to the LS-MGO case. Hence:

$$AC = NPC_{H2} - NPC_{LS-MGO} \quad (33)$$

The program's output includes the AC histograms plotted together with the cumulative distribution functions (Figure 32), (Figure 33), (Figure 34). This chapter contains the figures of the containership. Similar figures for the rest of the ships are included in Appendix A. It is obvious that positive values of AC mean a NPC

increase due to the adoption of hydrogen, whereas negative values mean that an investment in hydrogen would be beneficial.

Results for grey hydrogen show a 62,56% chance for the hydrogen investment to be beneficial, while the percentages for blue and green hydrogen are 52,725% and 3,35% respectively. Hence, grey and blue hydrogen investments are more likely to be beneficial, while the chances for green hydrogen are pure.

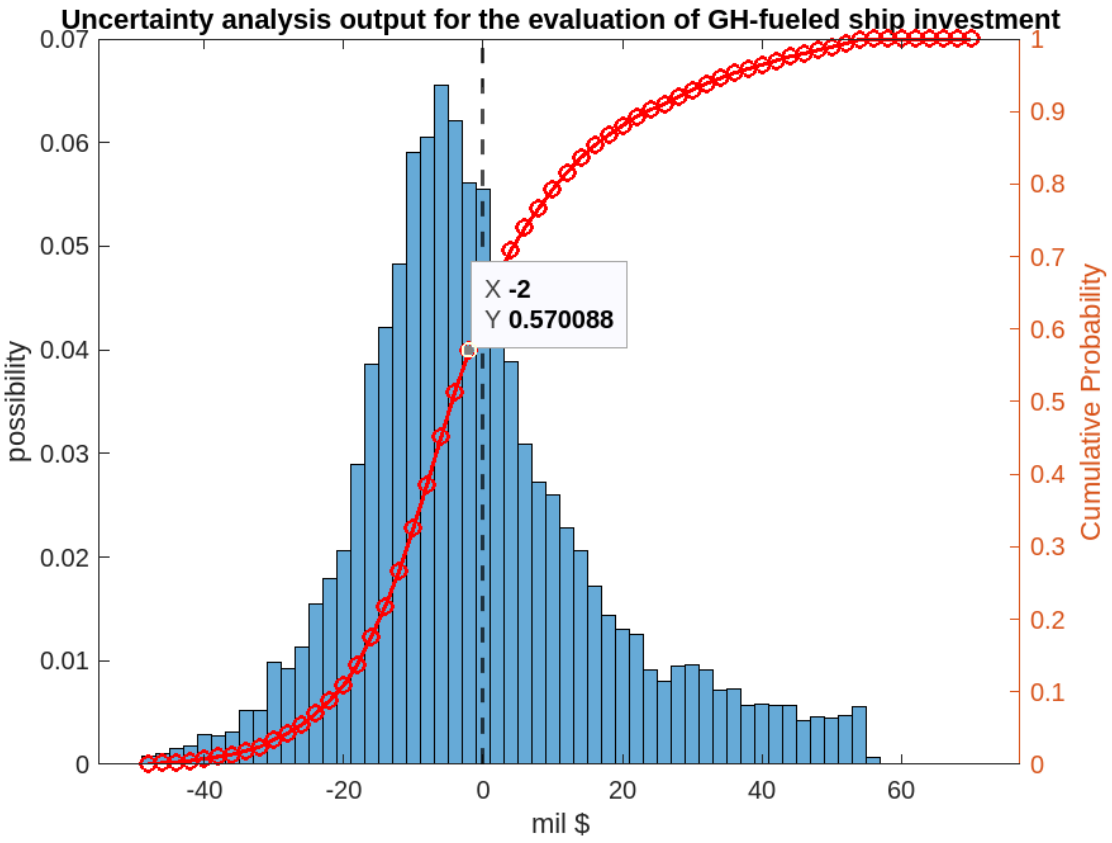

Figure 32: Uncertainty analysis output for hydrogen-fueled Containership's AC (grey hydrogen case)

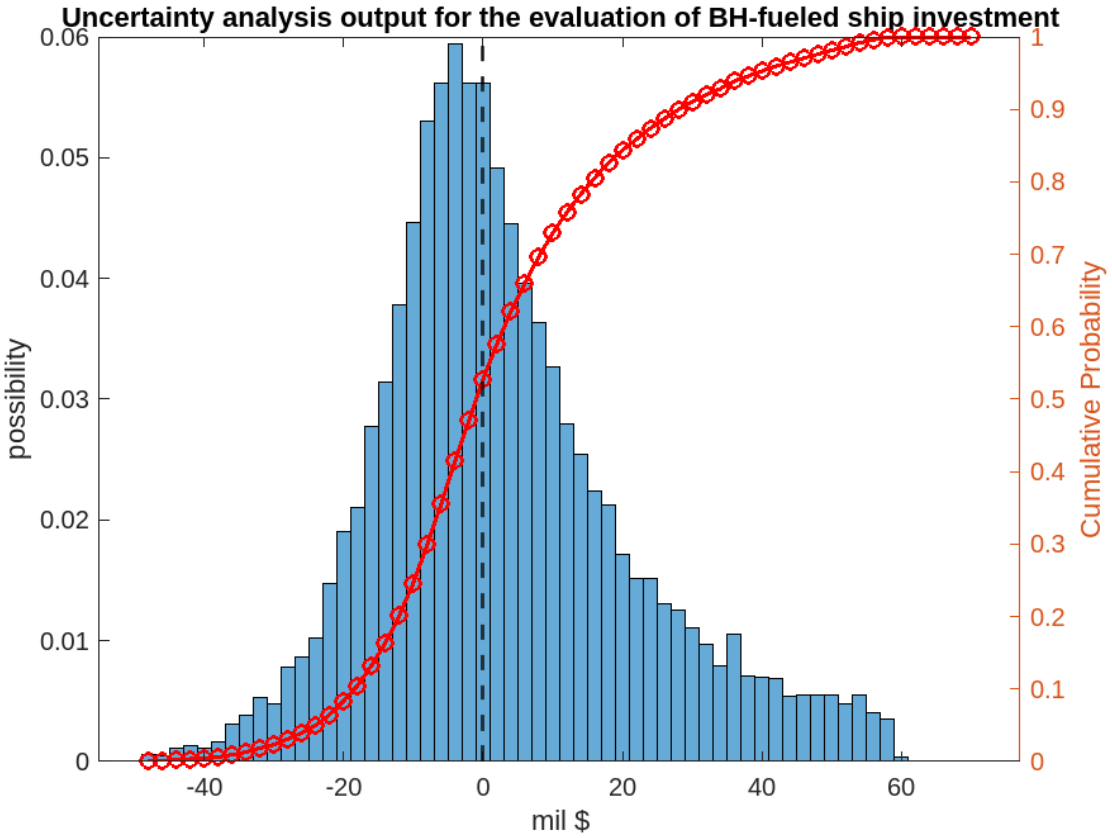

Figure 33: Uncertainty analysis output for hydrogen-fueled Containership AC (blue hydrogen case)

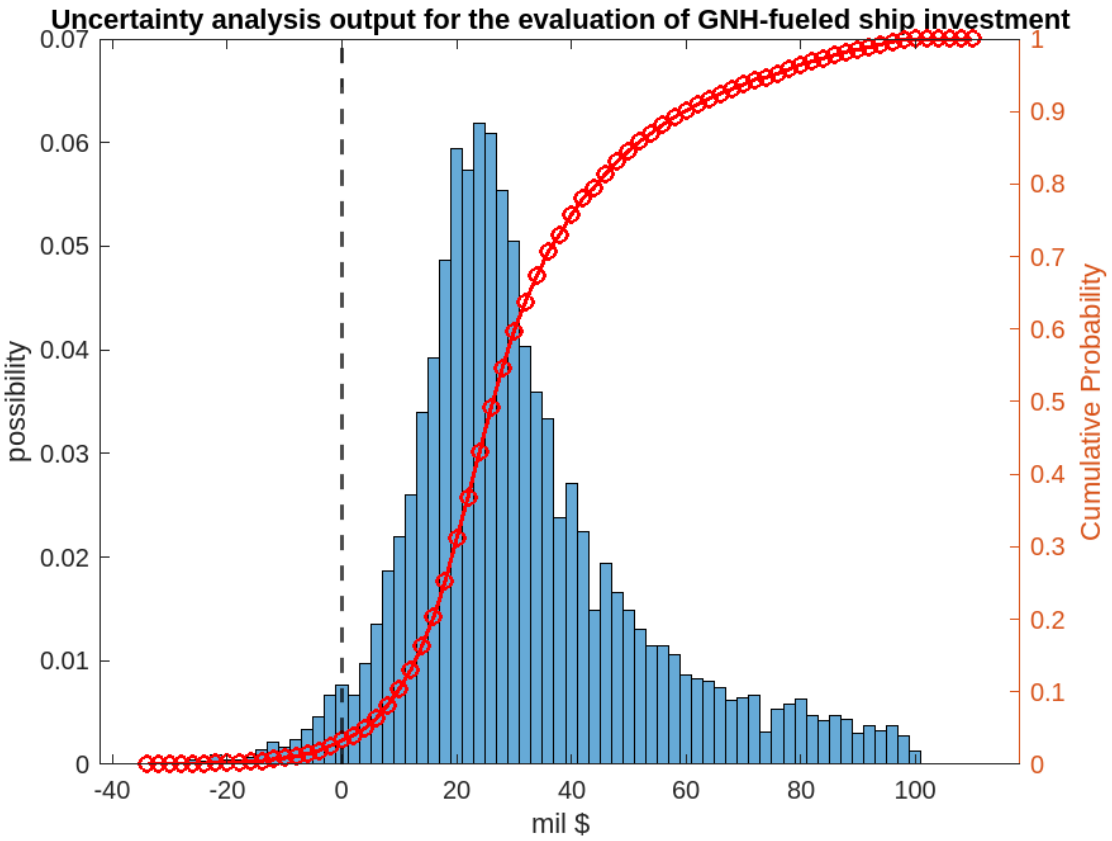

Figure 34: Uncertainty analysis output for hydrogen-fueled Containership AC (green hydrogen case)

8) Conclusions and recommendations for further research

The purpose of the present thesis is to analyze the complete life cycle of hydrogen-fueled ship and compare it with a conventional-fueled ship. More specifically, LCA and LCCA models for both ships were developed, while also an uncertainty analysis was carried out. The model was tested to five different ship types, assuming PEMFCs for the propulsion of the hydrogen-fueled ships.

The main conclusions of the study are summarized as follows:

- Grey hydrogen was found to be more harmful than LS-MGO, if hydrogen is liquified. In the case of compressed hydrogen, grey hydrogen was found to reduce only a few the GWP values. By taking into account other studies mentioned before, which also concluded that grey hydrogen is more harmful than diesel fuels, it is clear that grey hydrogen cannot be a solution for the decarbonization of the shipping industry.
- Blue hydrogen was found to reduce GWP by almost 43%, when liquified, and by 71% when compressed. Reminding that IMO has set the target of 40% GWP reduction by 2030 and 70% GWP reduction by 2040, blue hydrogen could be a good solution for the mid-term interval. A plus of blue hydrogen is that cost increase is not deterrent, while the are good chances for a blue hydrogen-fueled ship investment to be beneficial.
- Green hydrogen is without any doubt the best option for GWP reduction, as it is found to reduce the GWP over 90% for the compressed hydrogen case. The NPC, however, is expected to increase over 70%-75% and probably this increase cannot be absorbed by the shipowners. A decrease of the production cost is necessary, so that green hydrogen gets a bigger share of the market in the future.
- Liquified hydrogen is much more harmful for the environment compared to compressed hydrogen; something that is mainly associated with the energy-demanding process of liquefaction. The reduction of the procedure's energy demands is of great importance, since liquefaction is necessary if hydrogen is to be transported over long distances.
- The model is applied to five different ship types, however the comparative results(comparison with LS-MGO case) showed no big difference between the ship types.

According to the author's opinion, it is recommended that future studies put emphasis on the following objects:

- LCA and LCCA studies for hydrogen-fueled ships found in literature are mostly focused on small ships, especially ro-ro or Ro-pax ships. Similar studies should also be conducted for other ship types like Bulk carriers, Tanker or containerships, which have a completely different operational profile.
- Most studies assume PEMFCs or SOFCs for hydrogen's combustion, without making clear the type of electrolyser used in the fuel cell. The electrolyser selection should be further investigated, since it influences the LCA and LCCA of the fuel cell. Moreover, the case of ICEs for the combustion of hydrogen is rarely found in literature and should be further researched, as it may be possibly beneficial.
- Most studies found in literature ignore the maintenance and disposal/recycling phases, probably due to lack of credible data. The aforementioned phases should be taken into account in future studies, since they may influence the LCCA results.
- Uncertainty is rarely taken into account in hydrogen-fueled ship studies, probably due to lack of credible data. Further research on this field would be advantageous.

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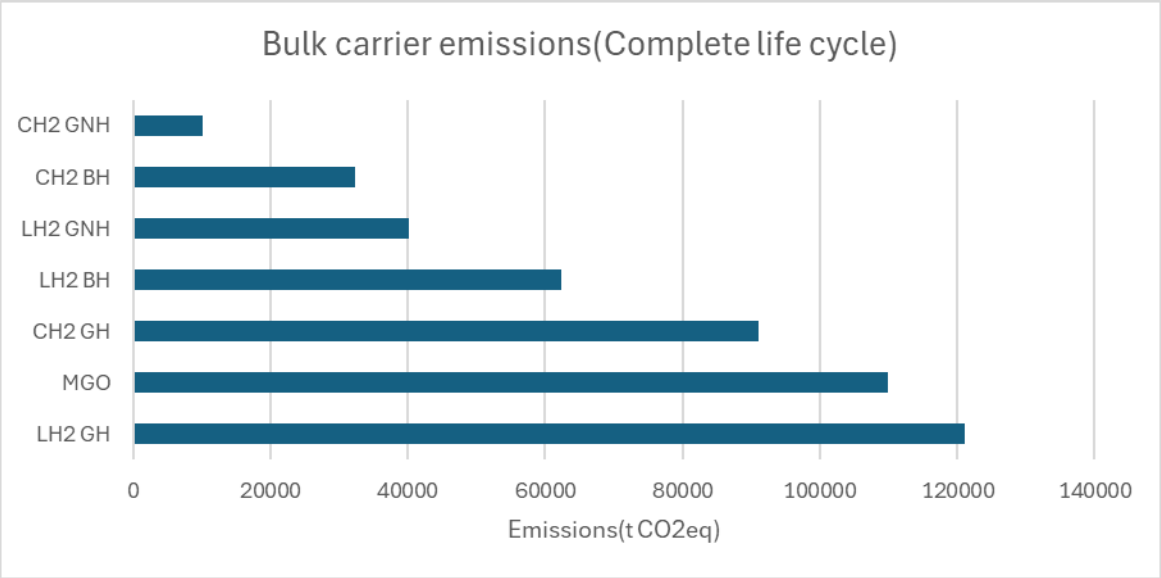
Appendix A

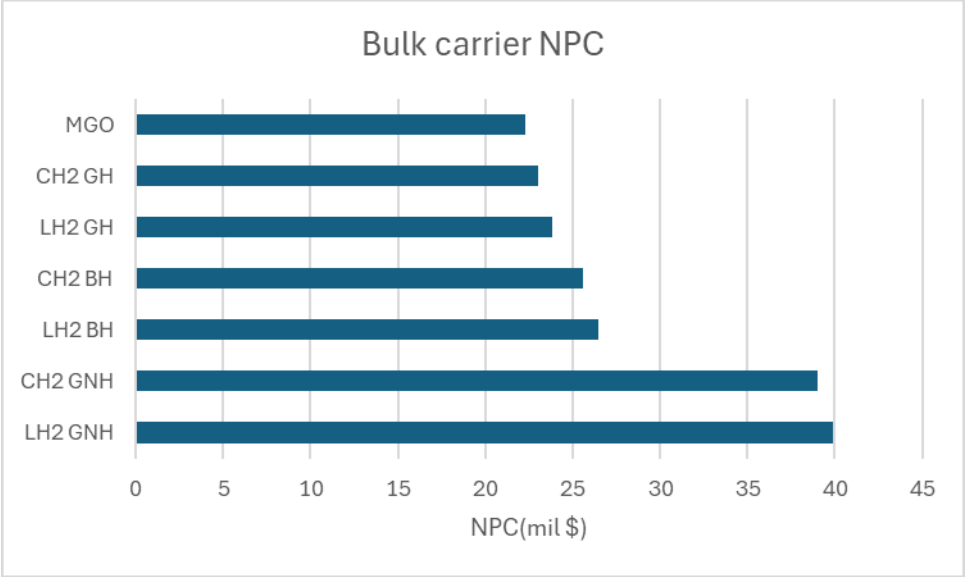
Appendix A contains the figures and tables not presented in the main part of the present thesis.

1)Rest of ship types results

Section 6.2 only included the life cycle results(figures and tables) of the Ro-pax ship. For the rest of the ships, the analytic results are presented below:

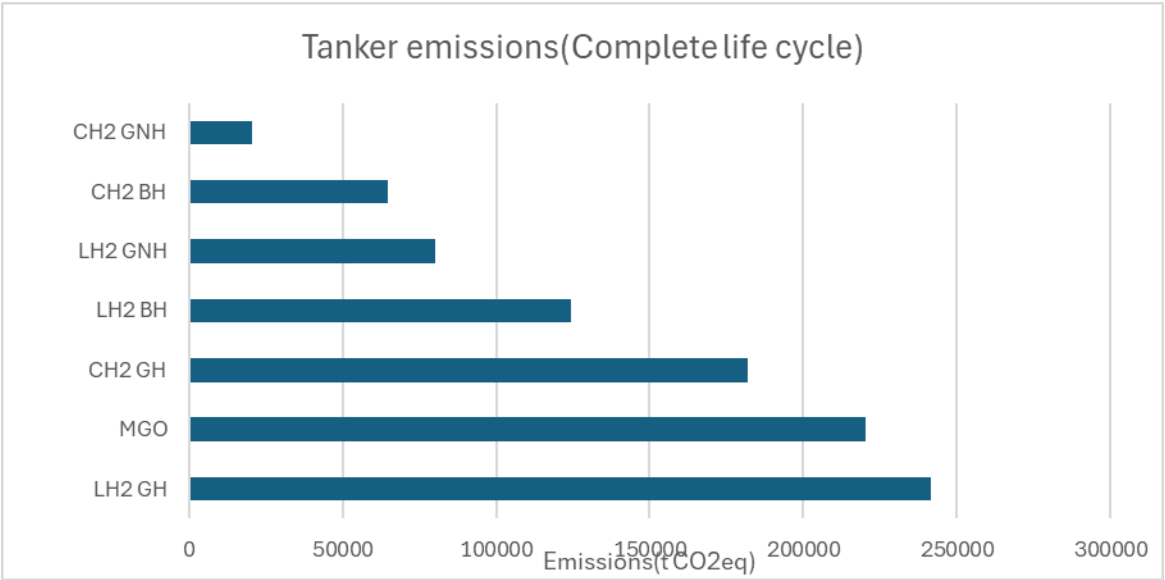
Bulk carrier ship

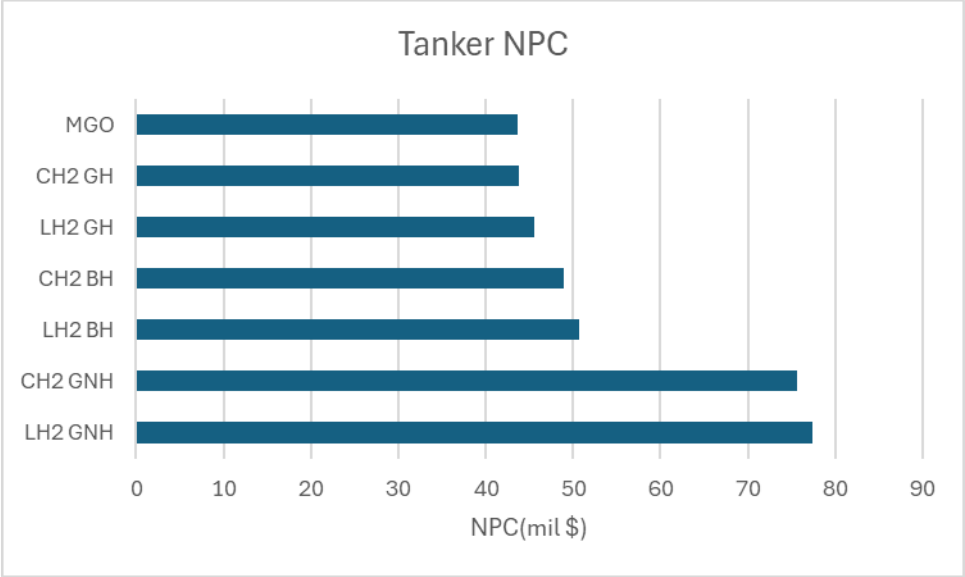




Bulk carrier						
Fuel	GH-LH2	GH-CH2	BH-LH2	BH-CH2	GNH-LH2	GNH-CH2
Emissions % differentiation	10,14%	-17,10%	-43,30%	-70,52%	-63,53%	-90,76%
NPC % differentiation	6,98%	3,06%	18,71%	14,80%	74,79%	77,58%

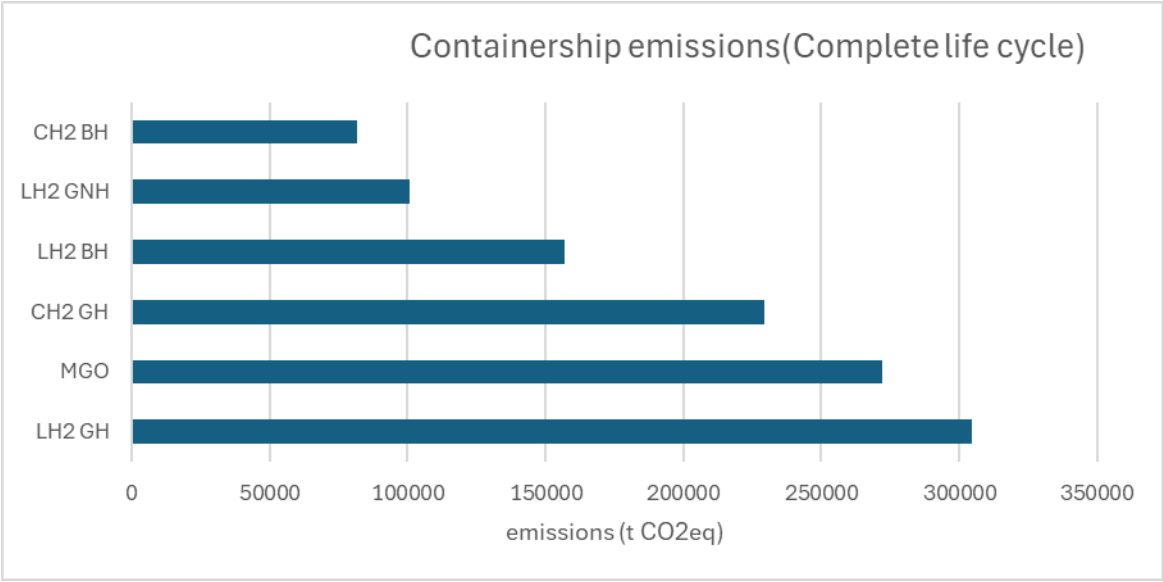
Tanker ship

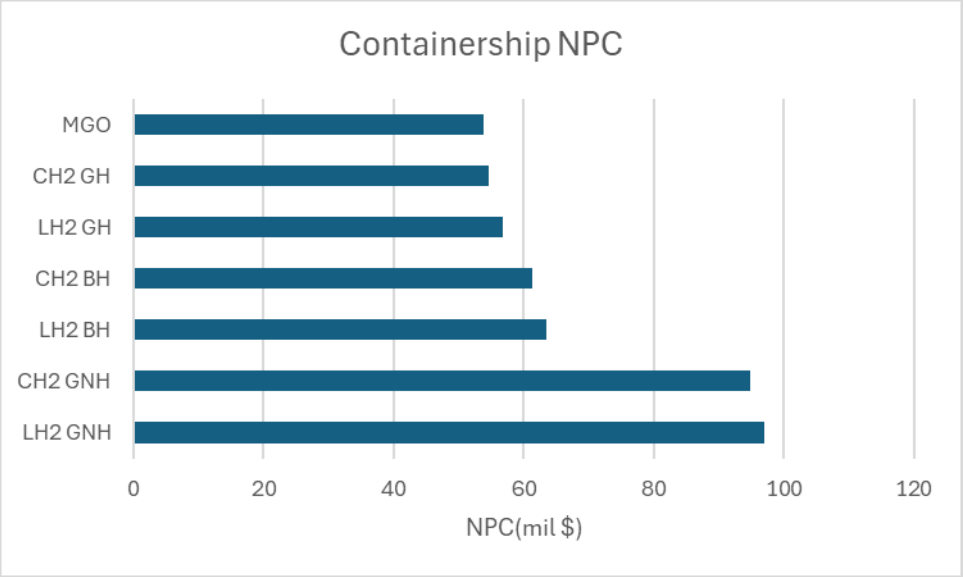




Tanker						
Fuel	GH-LH2	GH-CH2	BH-LH2	BH-CH2	GNH-LH2	GNH-CH2
Emissions % differentiation	9,66%	-17,47%	-43,55%	-70,66%	-63,70%	-90,81%
NPC % differentiation	4,38%	0,39%	16,36%	12,37%	77,58%	73,59%

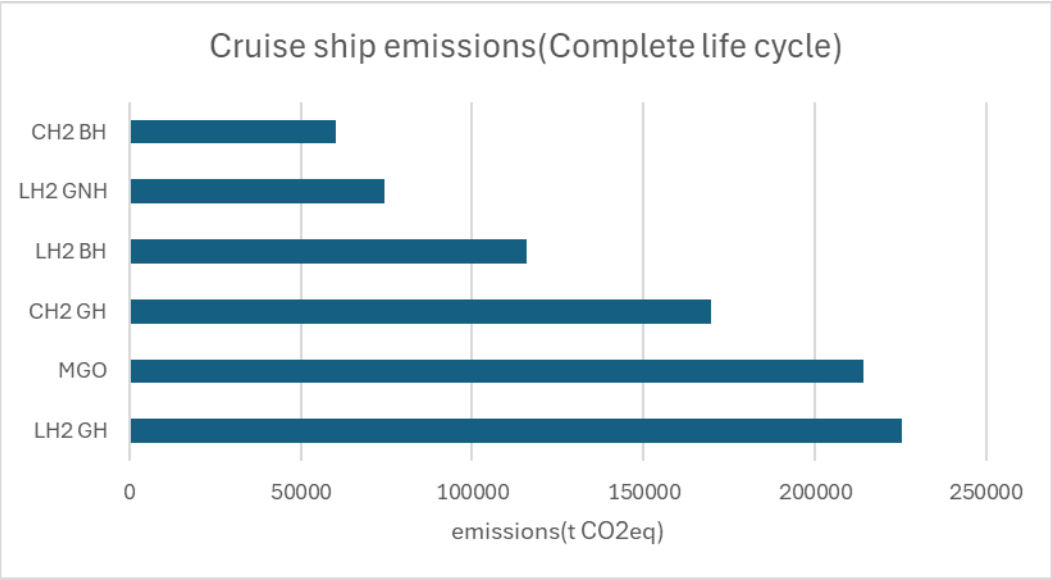
Containership

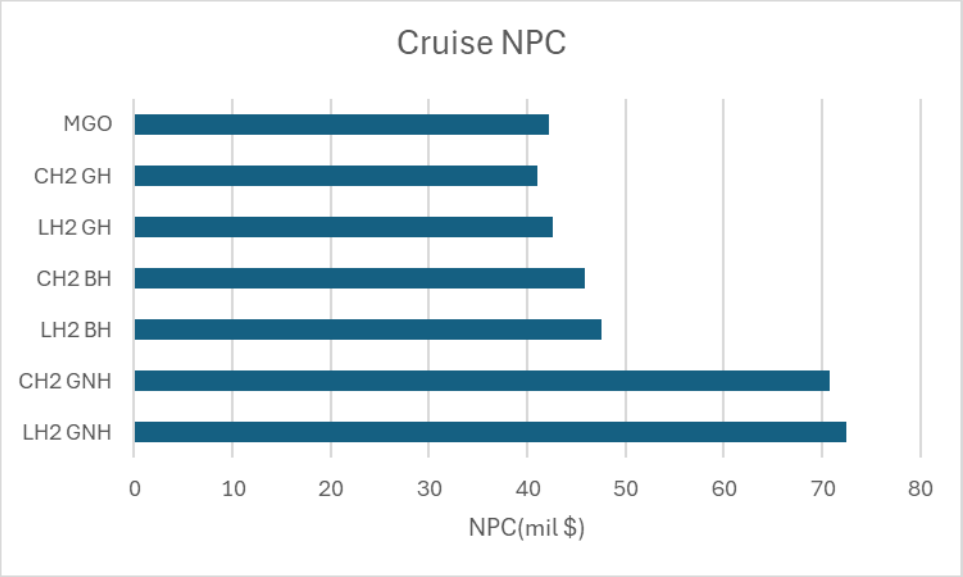




Containership						
Fuel	GH-LH2	GH-CH2	BH-LH2	BH-CH2	GNH-LH2	GNH-CH2
Emissions % differentiation	12,07%	-15,64%	-42,29%	-69,98%	-62,87%	-90,56%
NPC % differentiation	5,57%	1,49%	17,80%	13,72%	80,32%	76,24%

Cruise/passenger ship



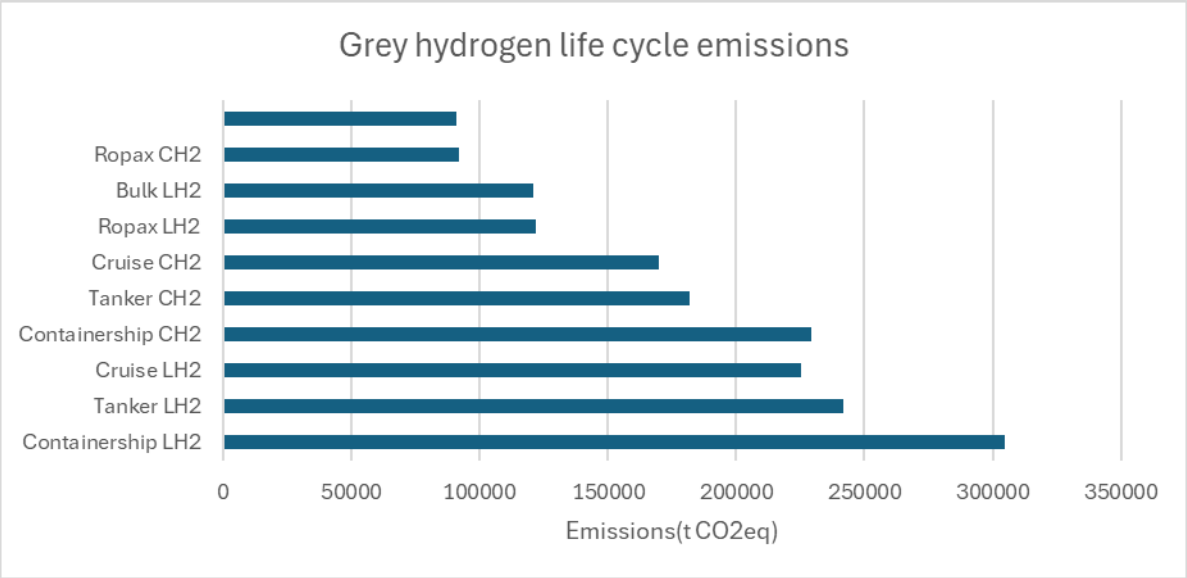


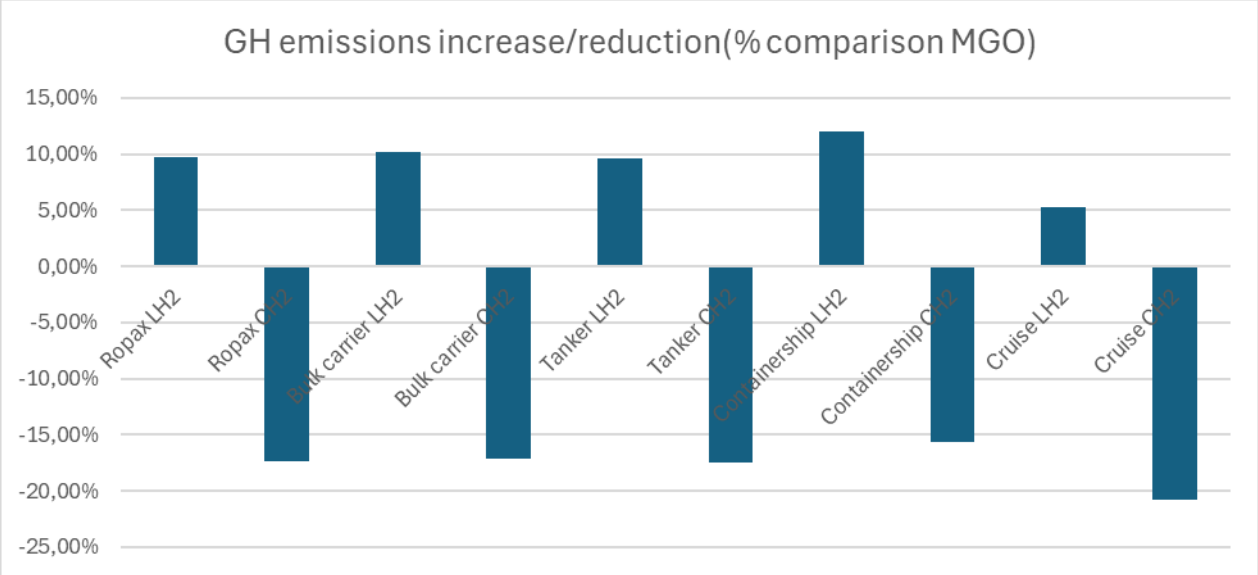
Cruise/passenger						
Fuel	GH-LH2	GH-CH2	BH-LH2	BH-CH2	GNH-LH2	GNH-CH2
Emissions % differentiation	5,31%	-20,75%	-45,80%	-71,84%	-65,16%	-91,20%
NPC % differentiation	1,14%	-2,71%	12,71%	8,86%	71,84%	67,98%

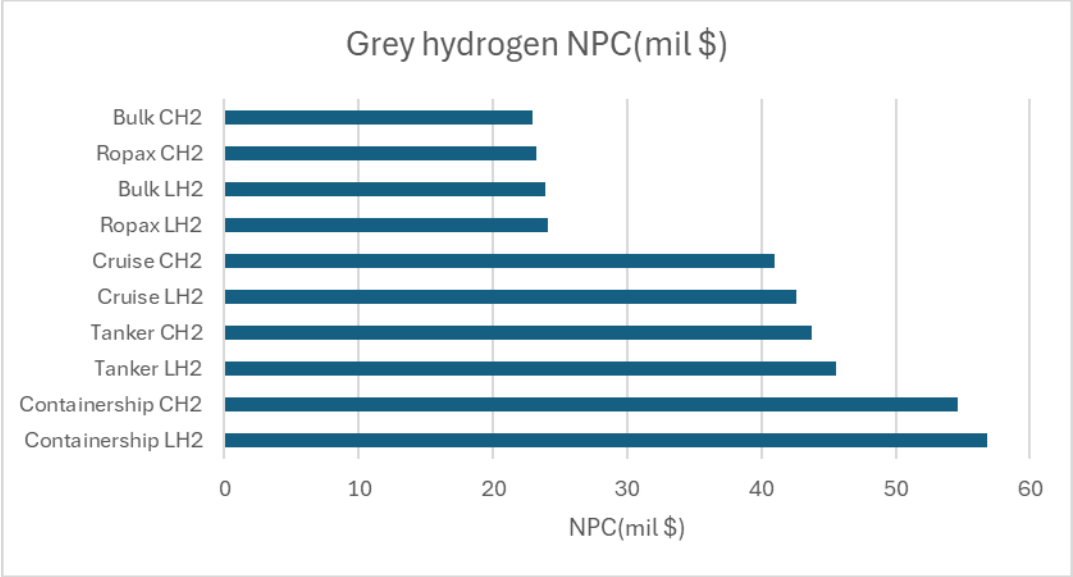
2)Grey and blue hydrogen life cycle results

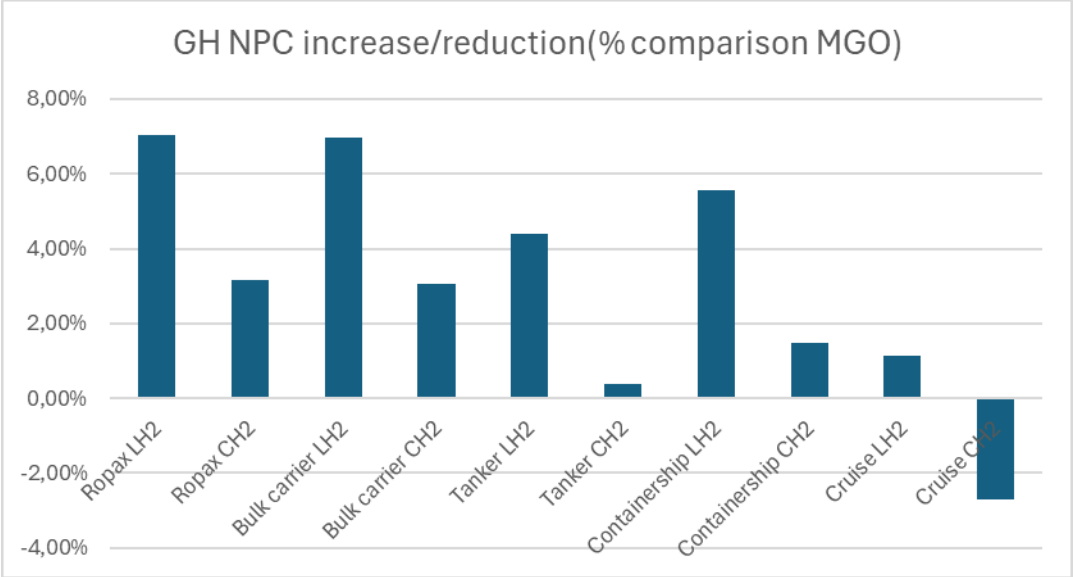
Section 6.2 included the life cycle results for green hydrogen. The results for grey and blue hydrogen are presented below.

Grey hydrogen

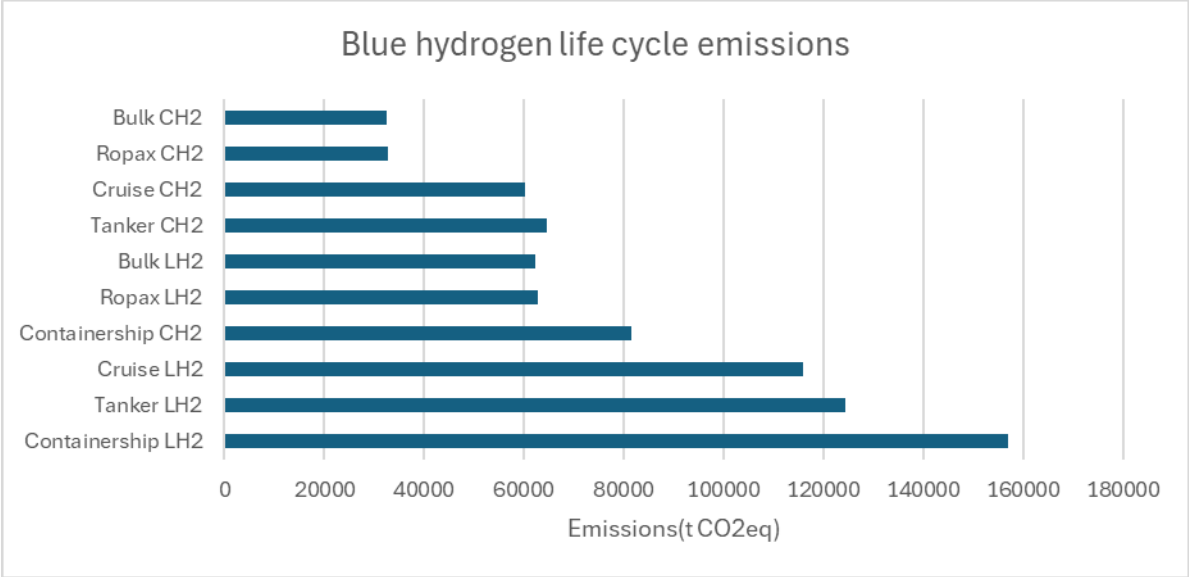


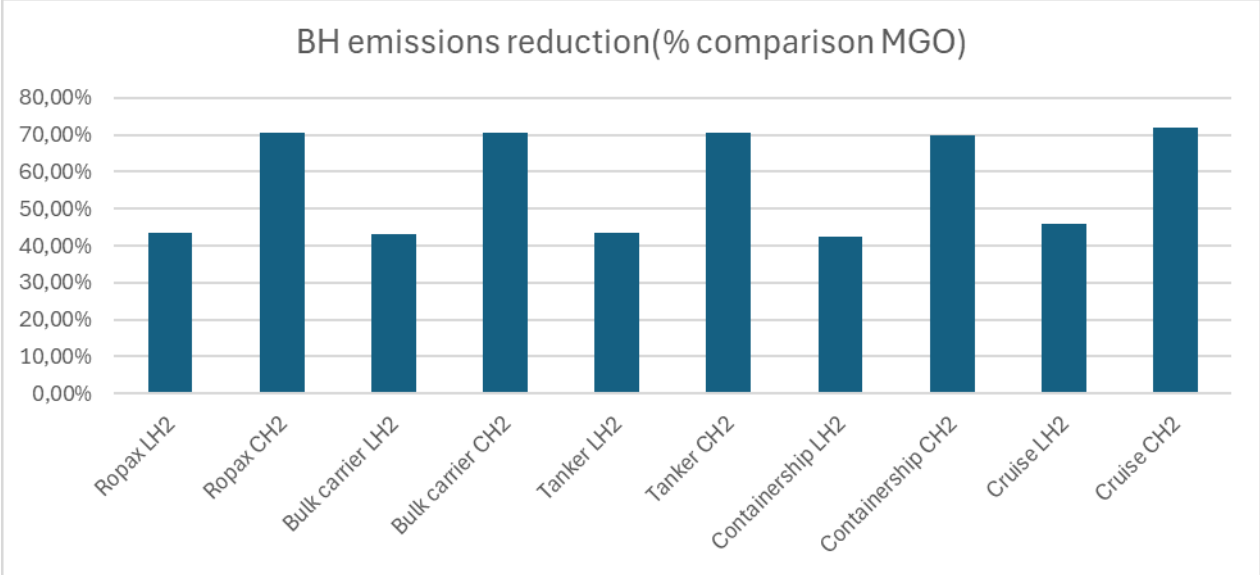


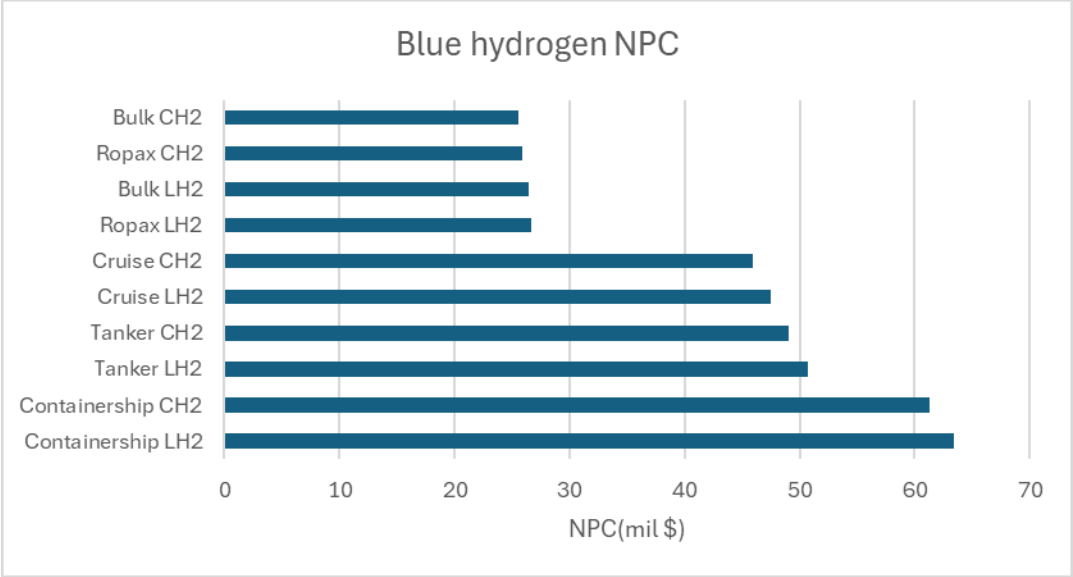

Grey hydrogen NPC(mil $)
Bulk CH2
Ropax CH2
Bulk LH2
Ropax LH2
Cruise CH2
Cruise LH2
Tanker CH2
Tanker LH2
Containership CH2
Containership LH2
0
10
20
30
40
50
60
NPC(mil $)

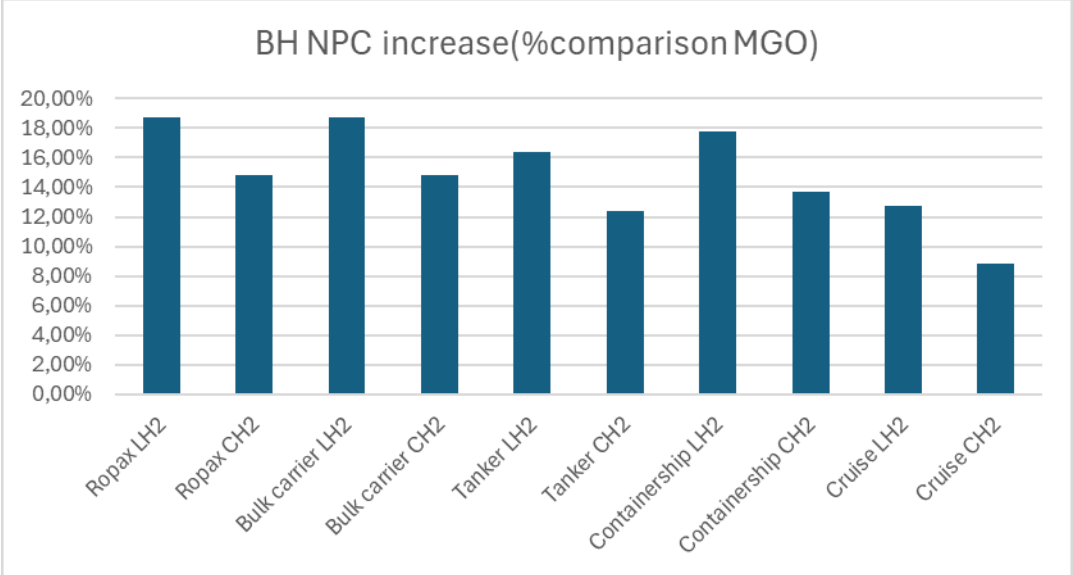

GH NPC increase/reduction(% comparison MGO)
8,00%
6,00%
4,00%
2,00%
0,00%
-2,00%
-4,00%
Ropax LH2
Ropax CH2
Bulk carrier LH2
Bulk carrier CH2
Tanker LH2
Tanker CH2
Containership LH2
Containership CH2
Cruise LH2
Cruise CH2

Blue hydrogen



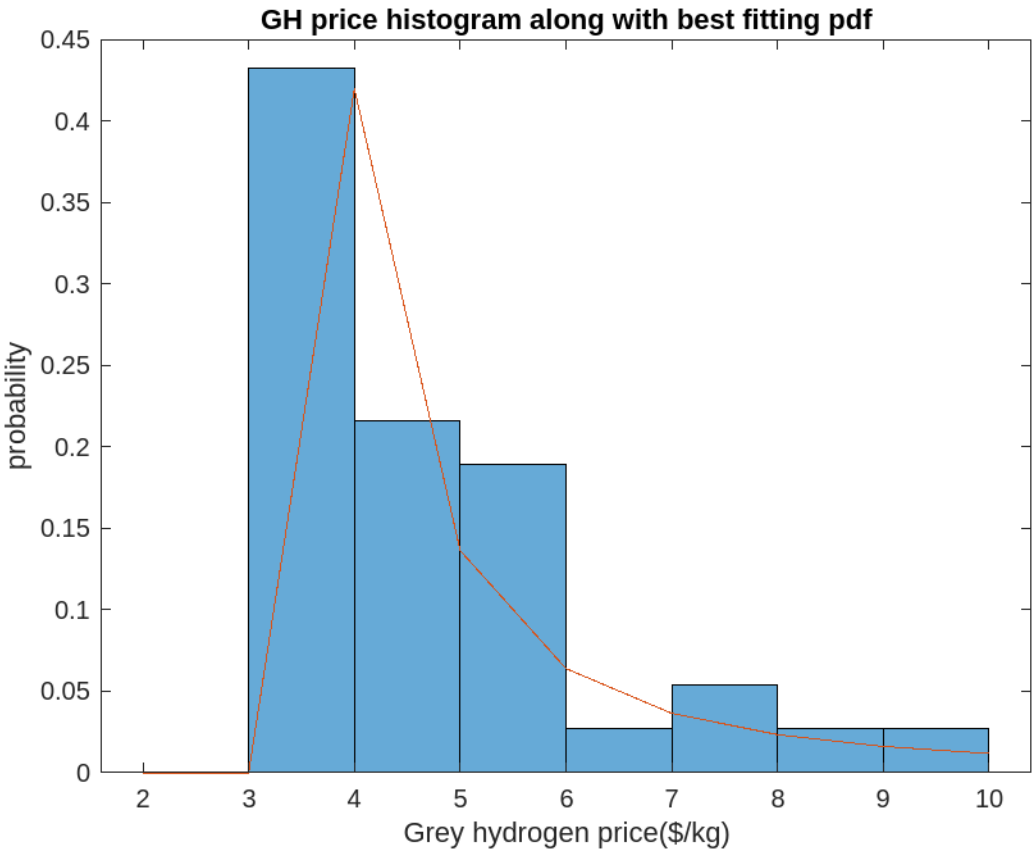


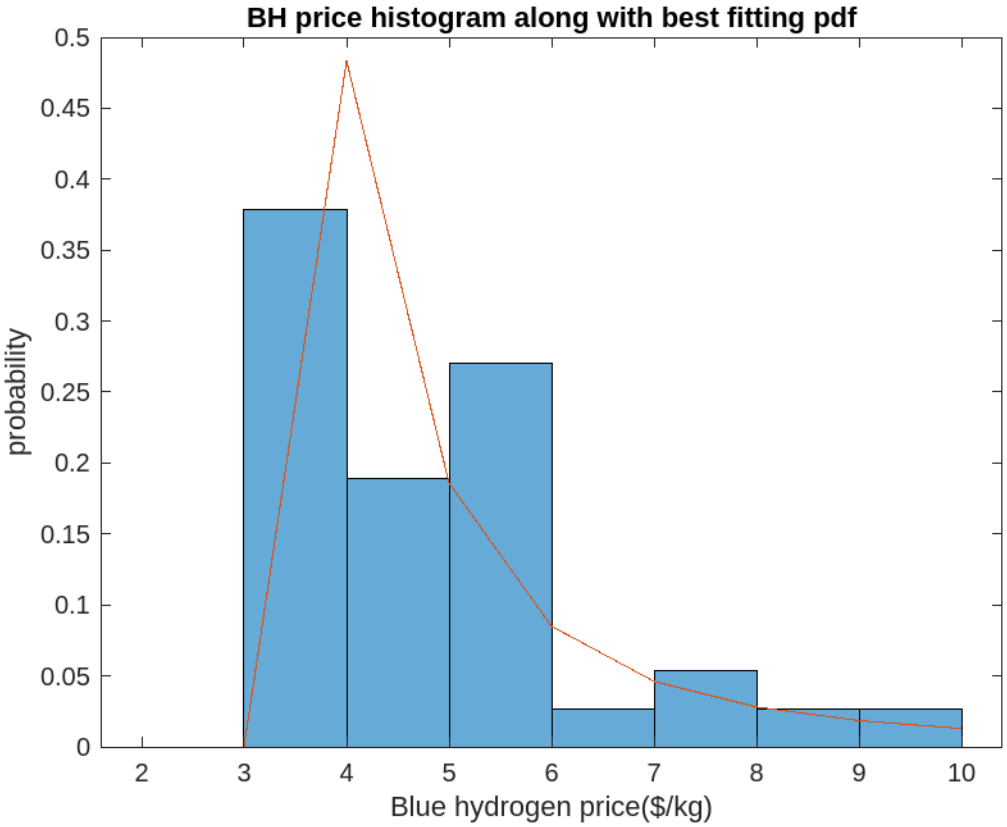

Blue hydrogen NPC
Bulk CH2
Ropax CH2
Bulk LH2
Ropax LH2
Cruise CH2
Cruise LH2
Tanker CH2
Tanker LH2
Containership CH2
Containership LH2
0
10
20
30
40
50
60
70
NPC(mil $)

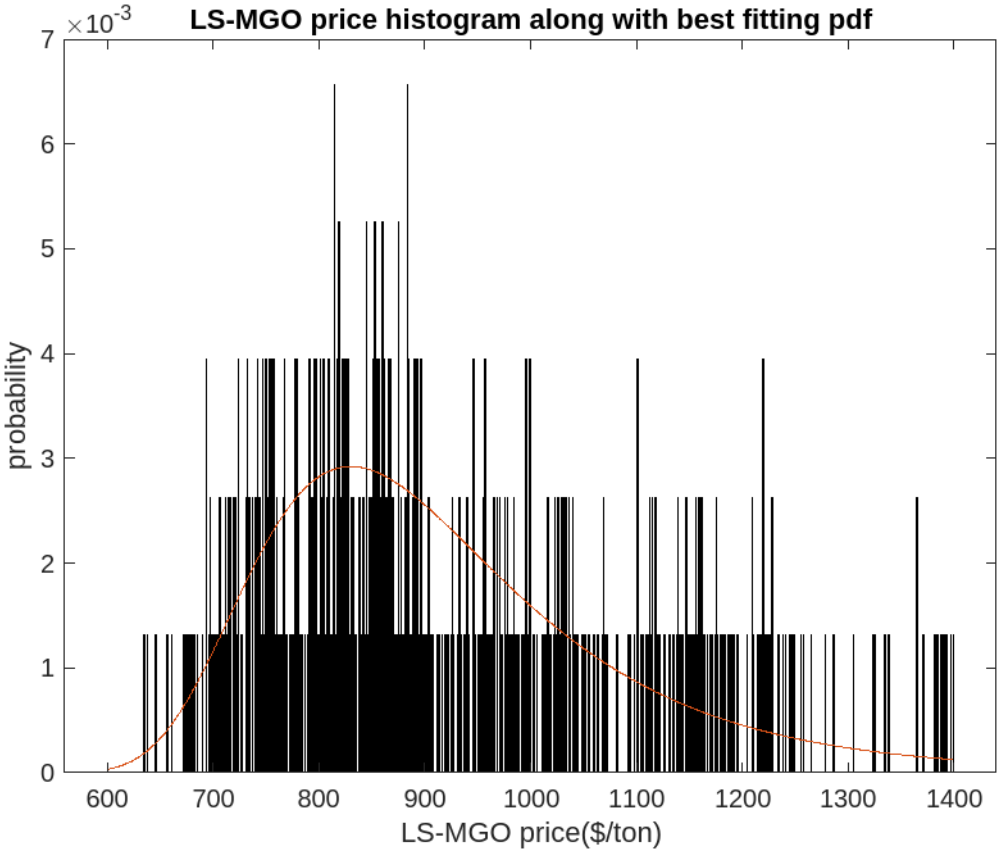

BH NPC increase(%comparison MGO)
20,00%
18,00%
16,00%
14,00%
12,00%
10,00%
8,00%
6,00%
4,00%
2,00%
0,00%
Ropax LH2
Ropax CH2
Bulk carrier LH2
Bulk carrier CH2
Tanker LH2
Tanker CH2
Containership LH2
Containership CH2
Cruise LH2
Cruise CH2

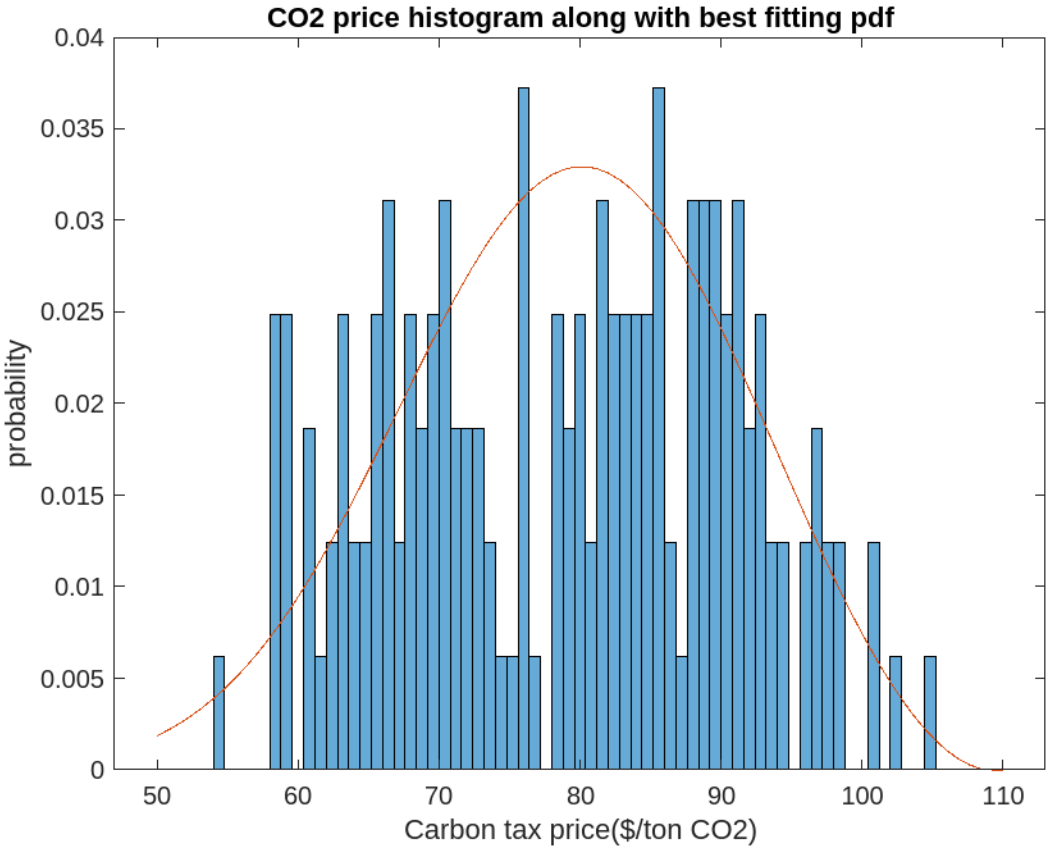
3) Rest of ship types uncertainty analysis results

Fuel prices histograms and best fitting pdf

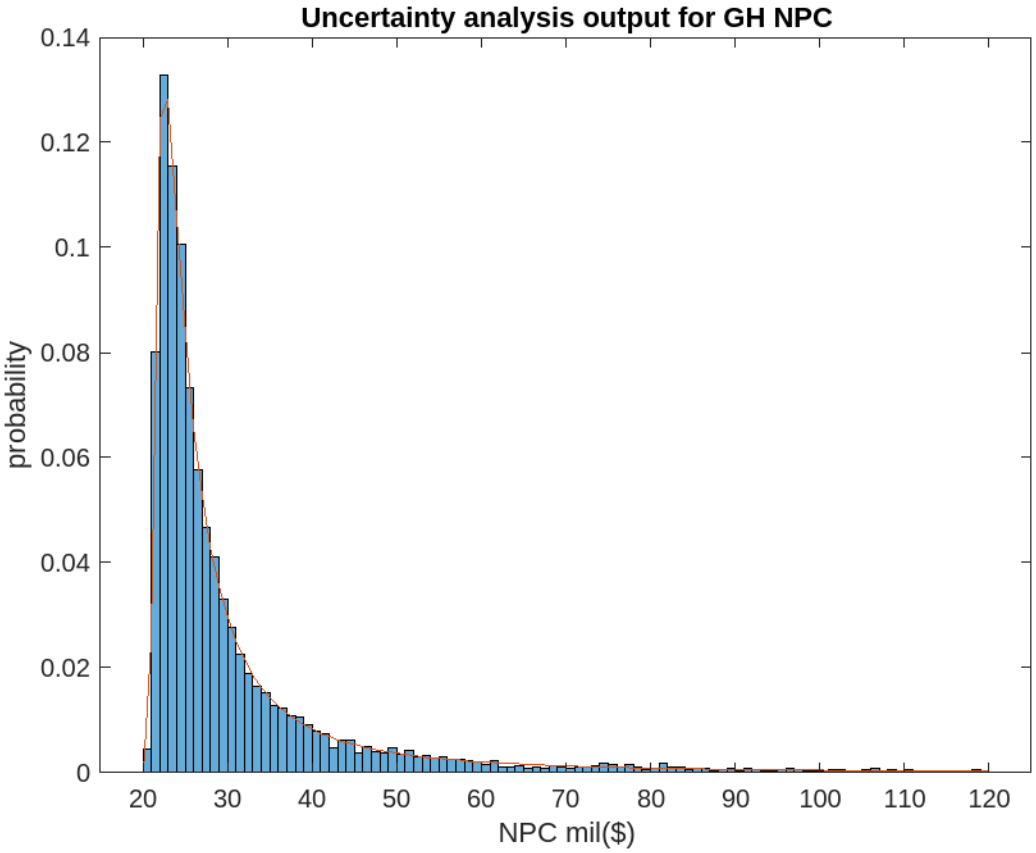


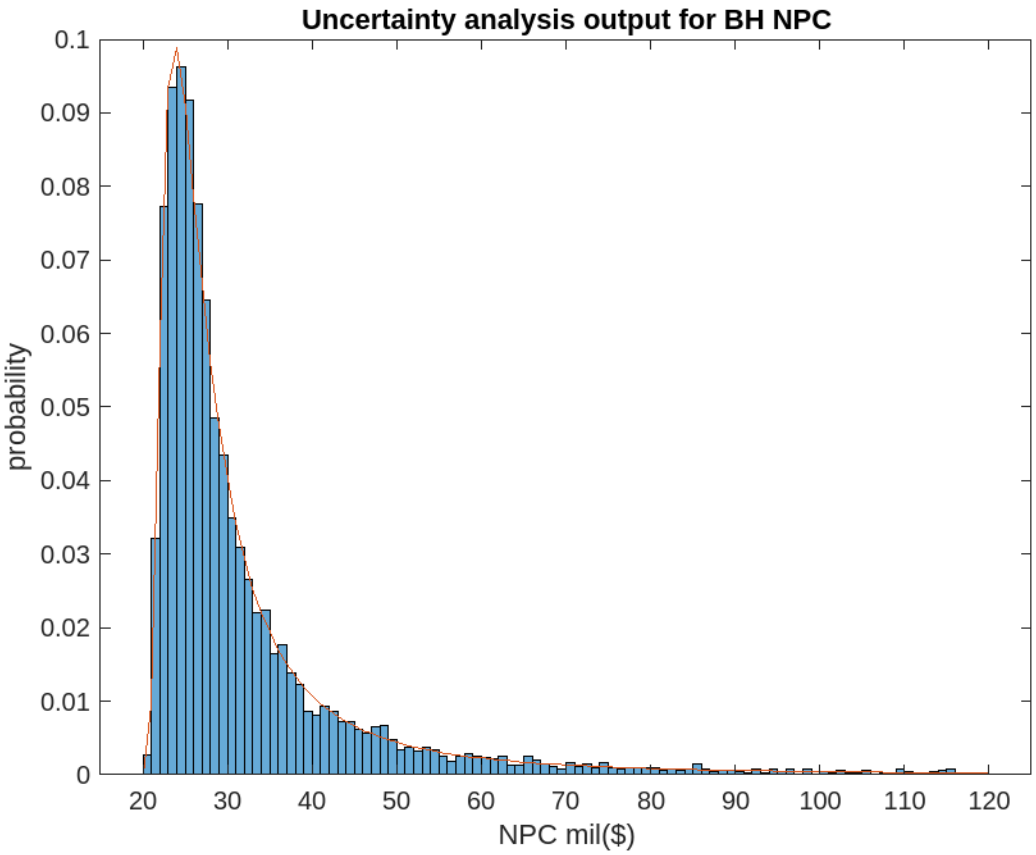

BH price histogram along with best fitting pdf
probability
Blue hydrogen price($/kg)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
3
4
5
6
7
8
9
10

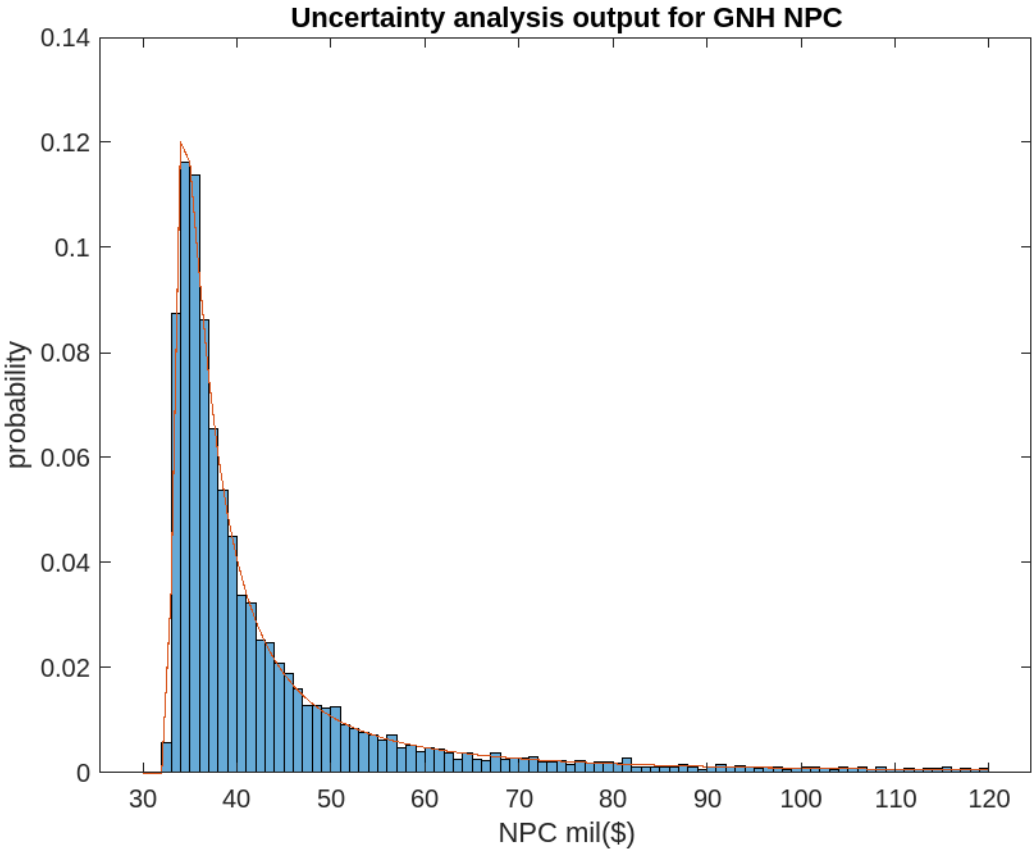

LS-MGO price histogram along with best fitting pdf
×10-3
probability
LS-MGO price($/ton)
7
6
5
4
3
2
1
0
600
700
800
900
1000
1100
1200
1300
1400

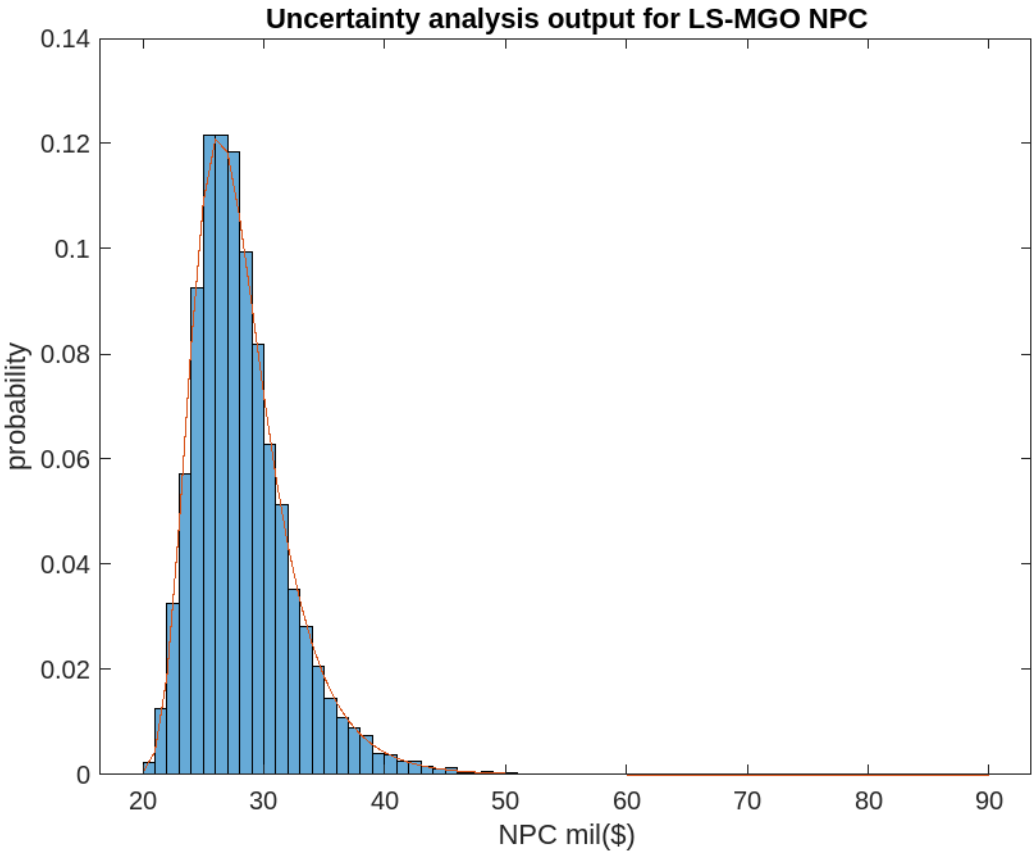

CO2 price histogram along with best fitting pdf
probability
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
50
60
70
80
90
100
110
Carbon tax price($/ton CO2)

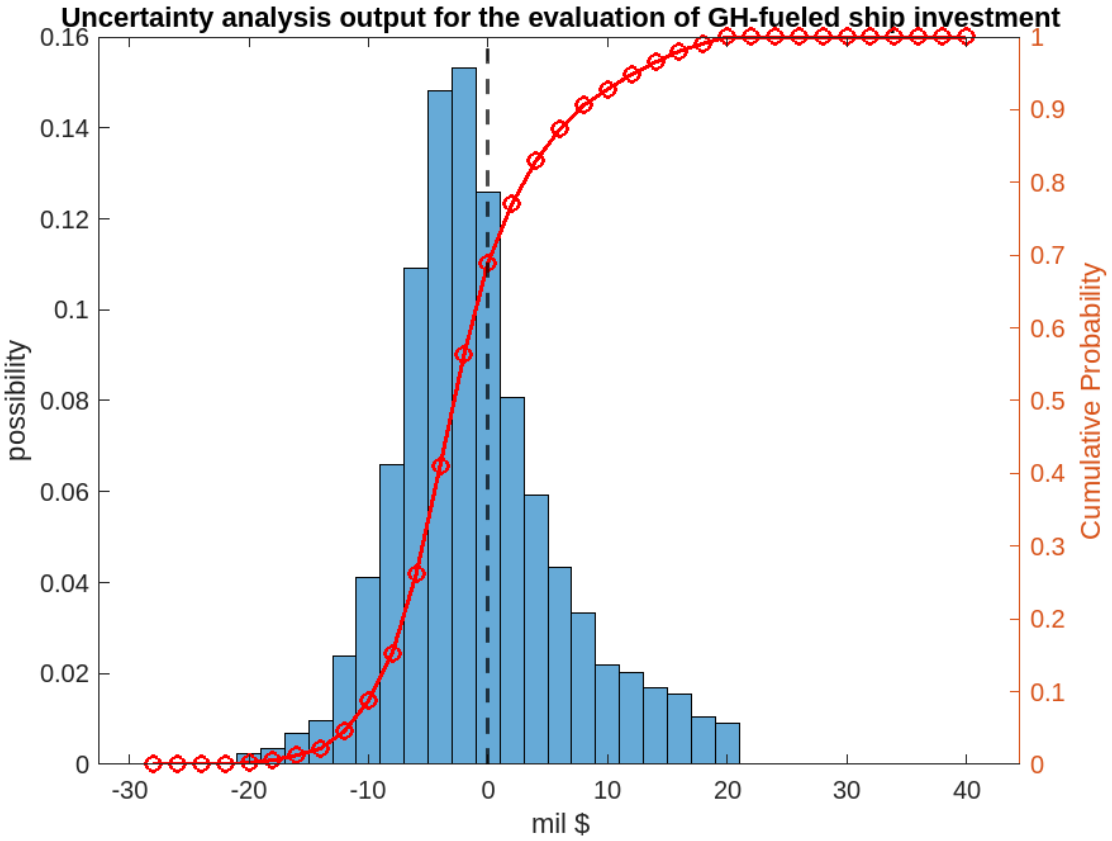
Ro-pax ship

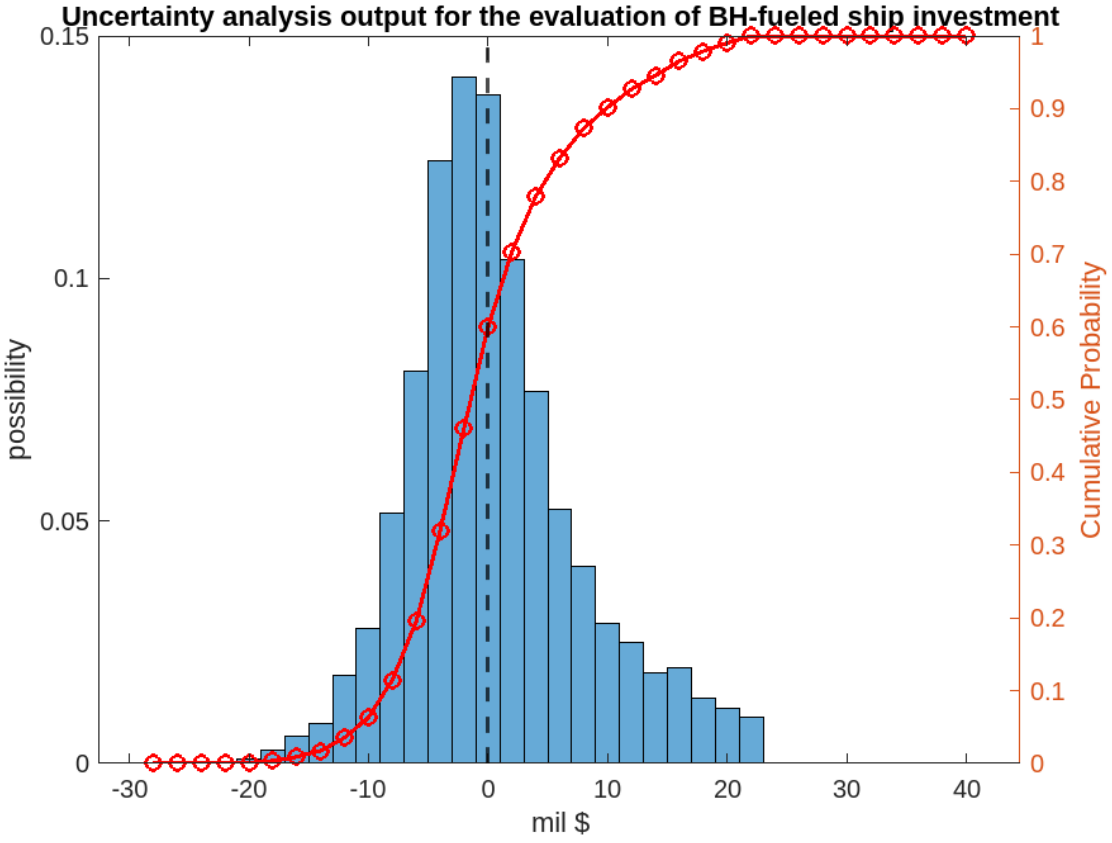

Uncertainty analysis output for GH NPC
probability
NPC mil($)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
20
30
40
50
60
70
80
90
100
110
120

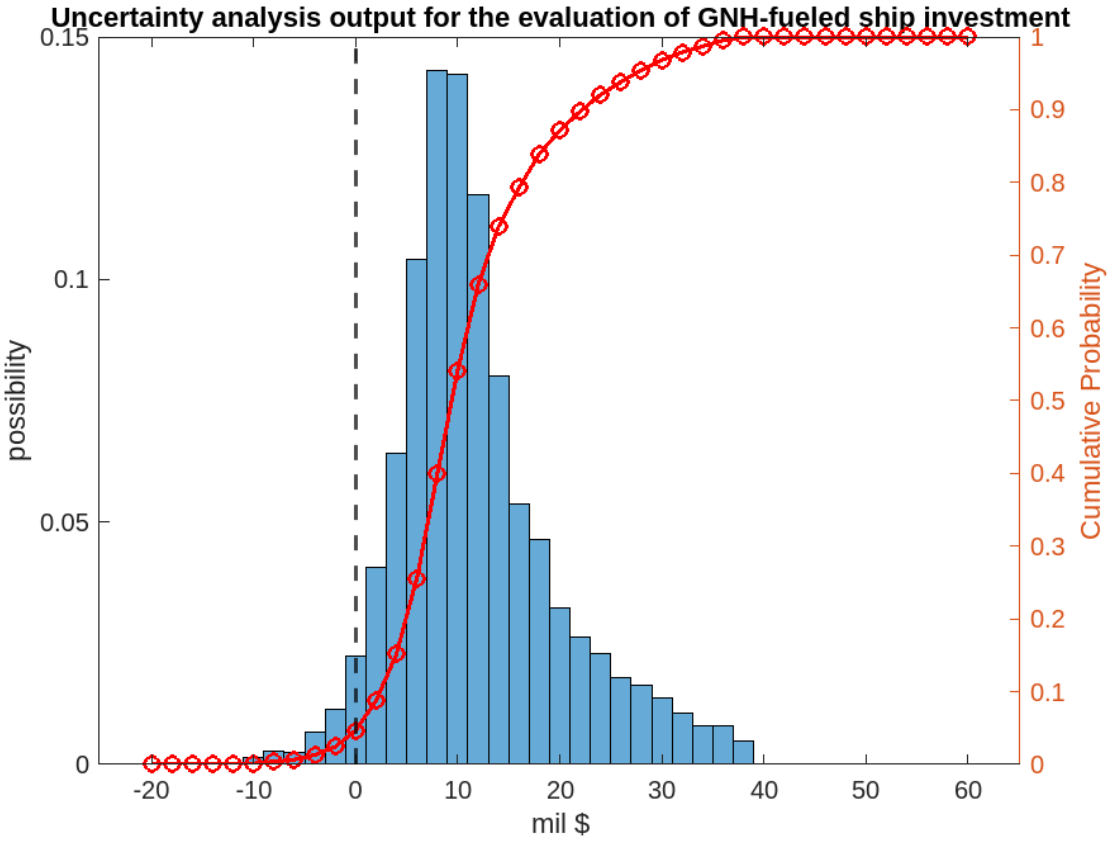

Uncertainty analysis output for BH NPC
probability
NPC mil($)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
20
30
40
50
60
70
80
90
100
110
120


Uncertainty analysis output for GNH NPC
probability
NPC mil($)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
30
40
50
60
70
80
90
100
110
120

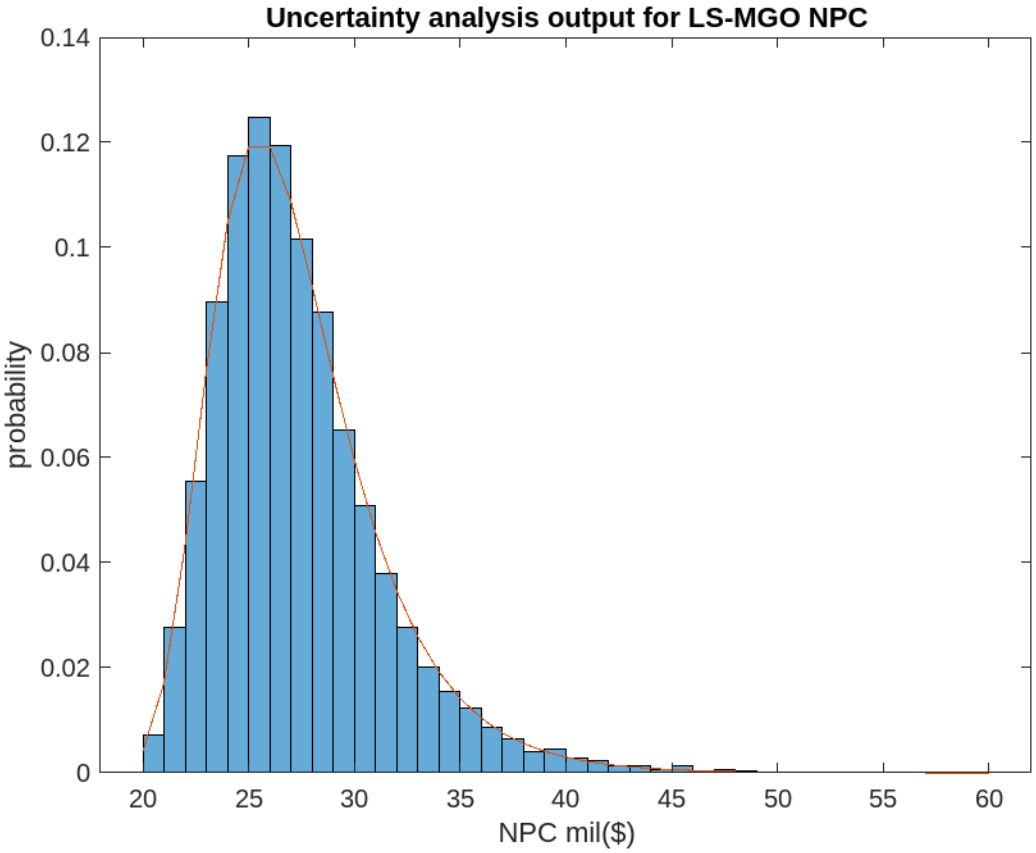

Uncertainty analysis output for LS-MGO NPC
probability
NPC mil($)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
20
30
40
50
60
70
80
90

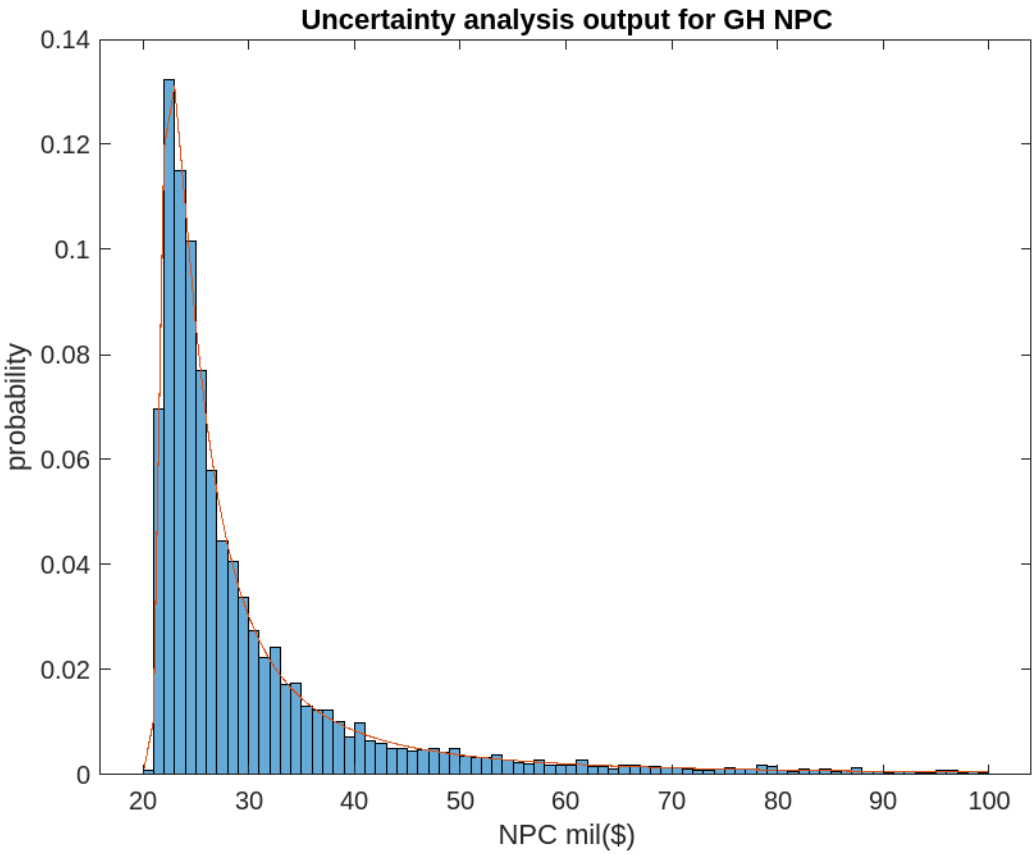

Uncertainty analysis output for the evaluation of GH-fueled ship investment
possibility
Cumulative Probability
mil $
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-30
-20
-10
0
10
20
30
40

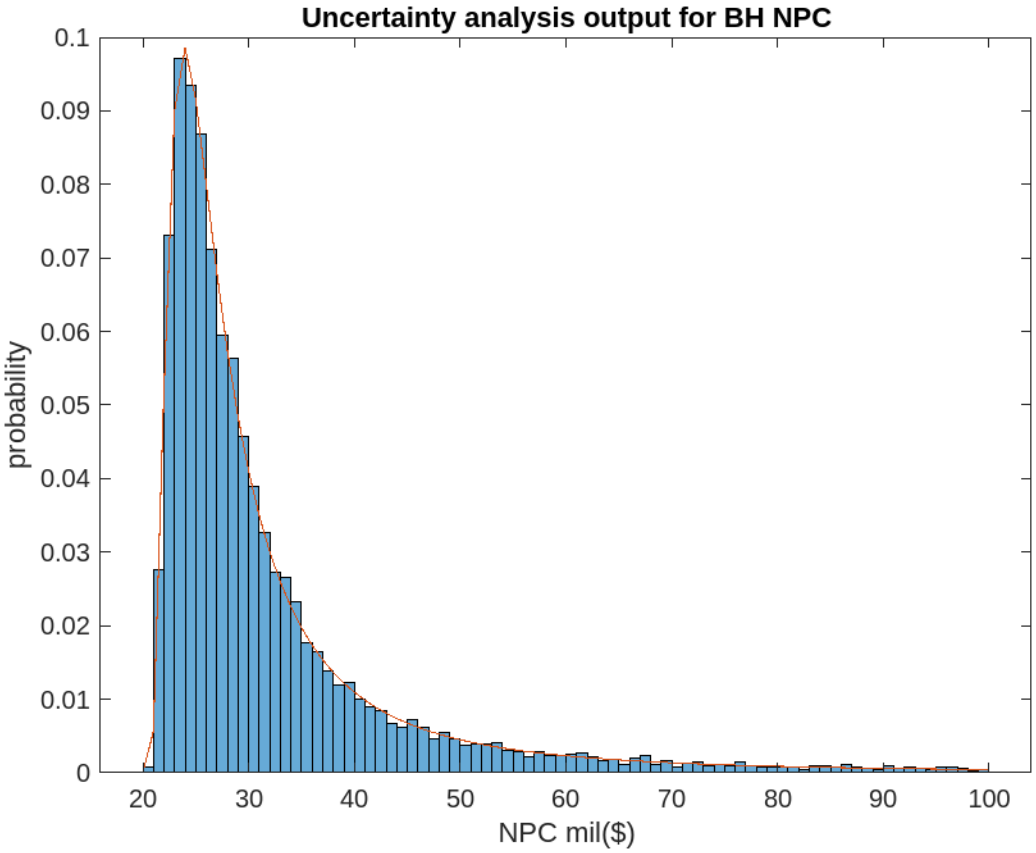

Uncertainty analysis output for the evaluation of BH-fueled ship investment
possibility
Cumulative Probability
mil $
0.15
0.1
0.05
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-30
-20
-10
0
10
20
30
40

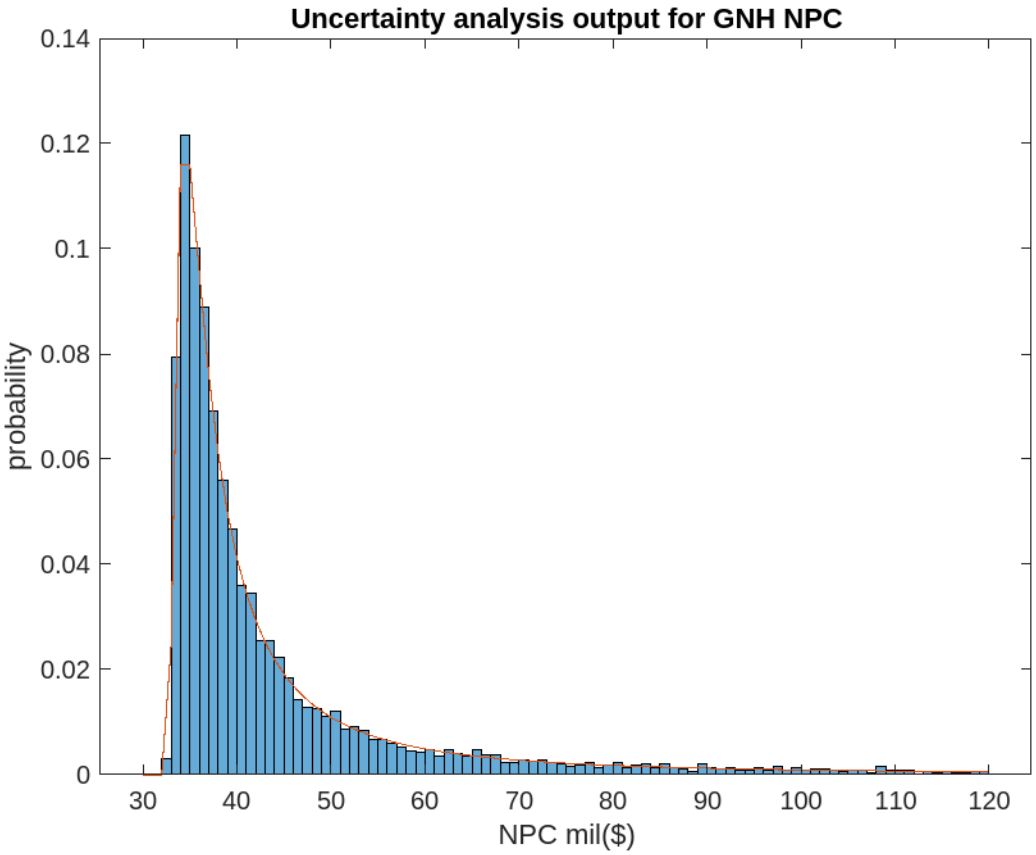

Uncertainty analysis output for the evaluation of GNH-fueled ship investment
possibility
Cumulative Probability
mil $
0.15
0.1
0.05
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-20
-10
0
10
20
30
40
50
60

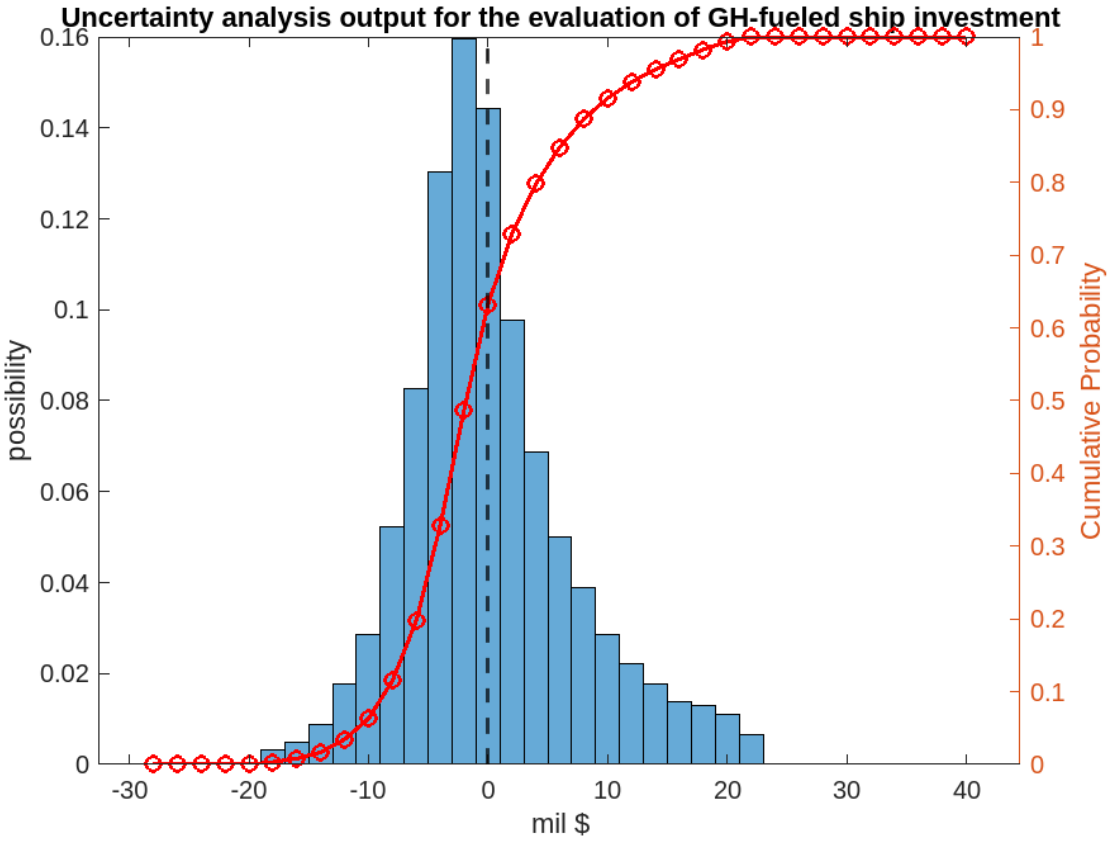
Bulk carrier ship

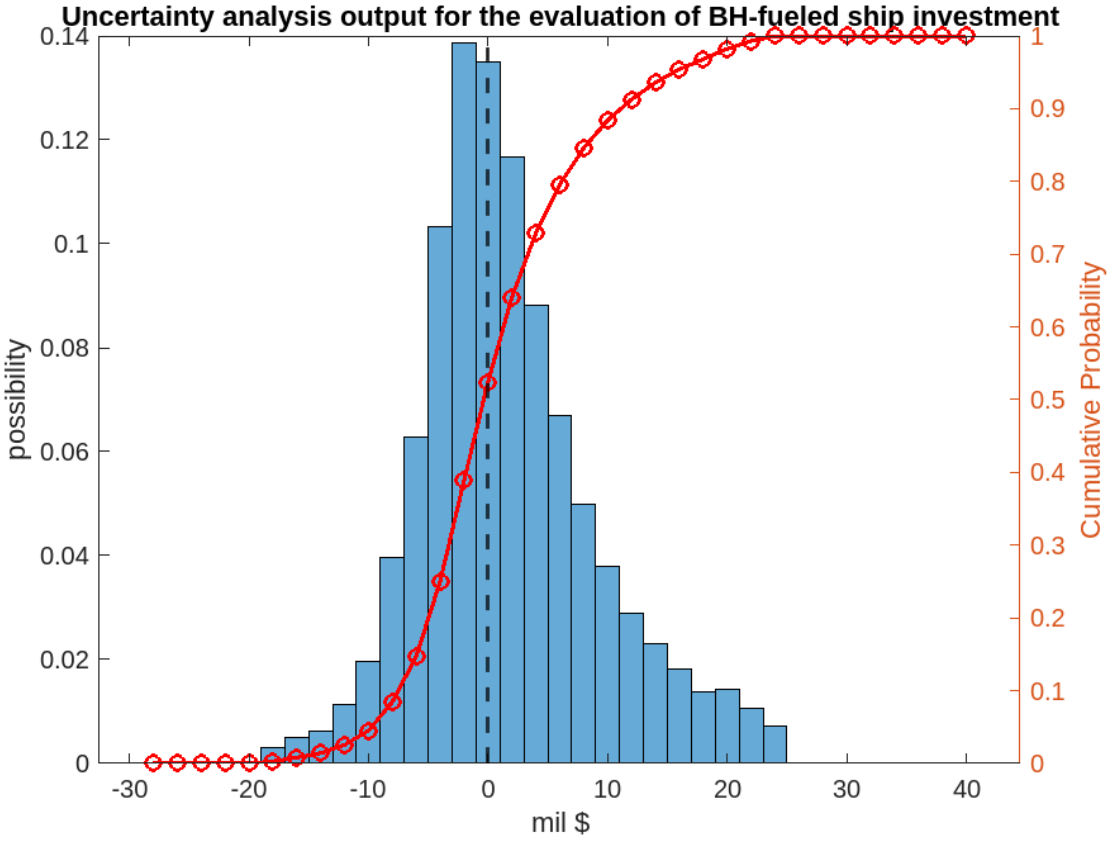


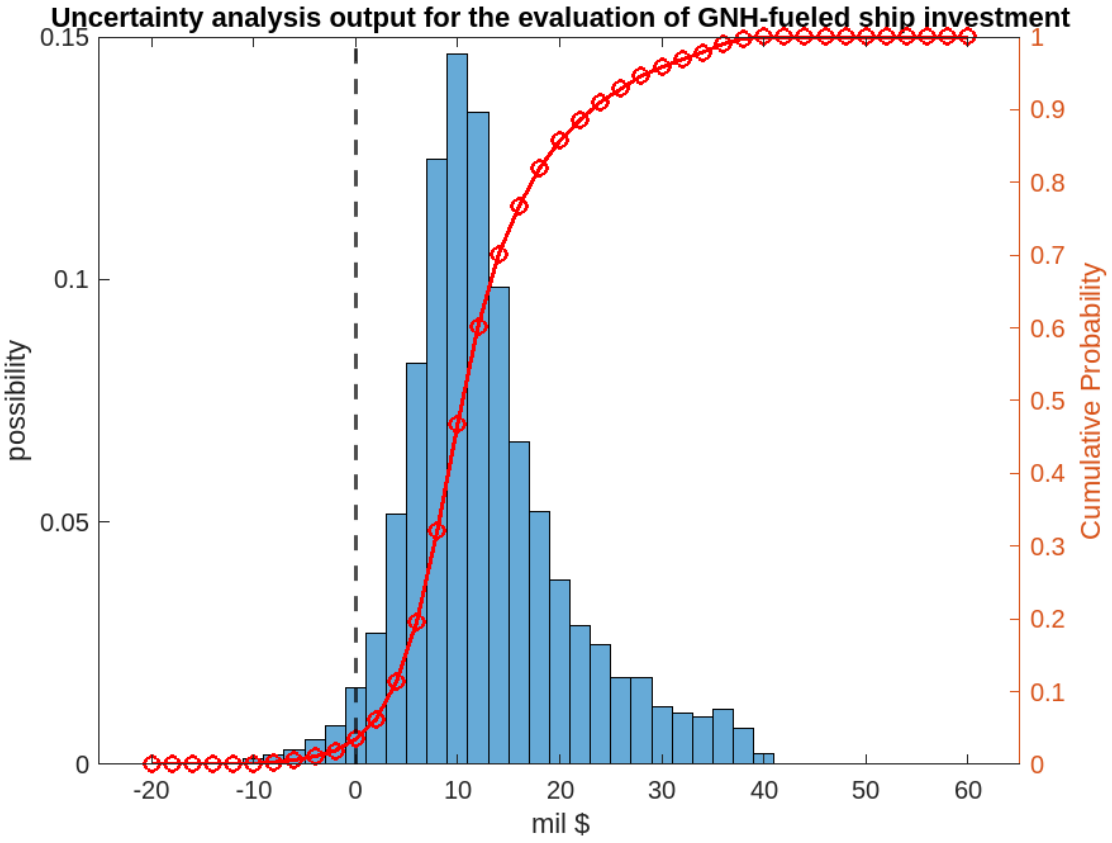



Uncertainty analysis output for BH NPC
probability
NPC mil($)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
20
30
40
50
60
70
80
90
100

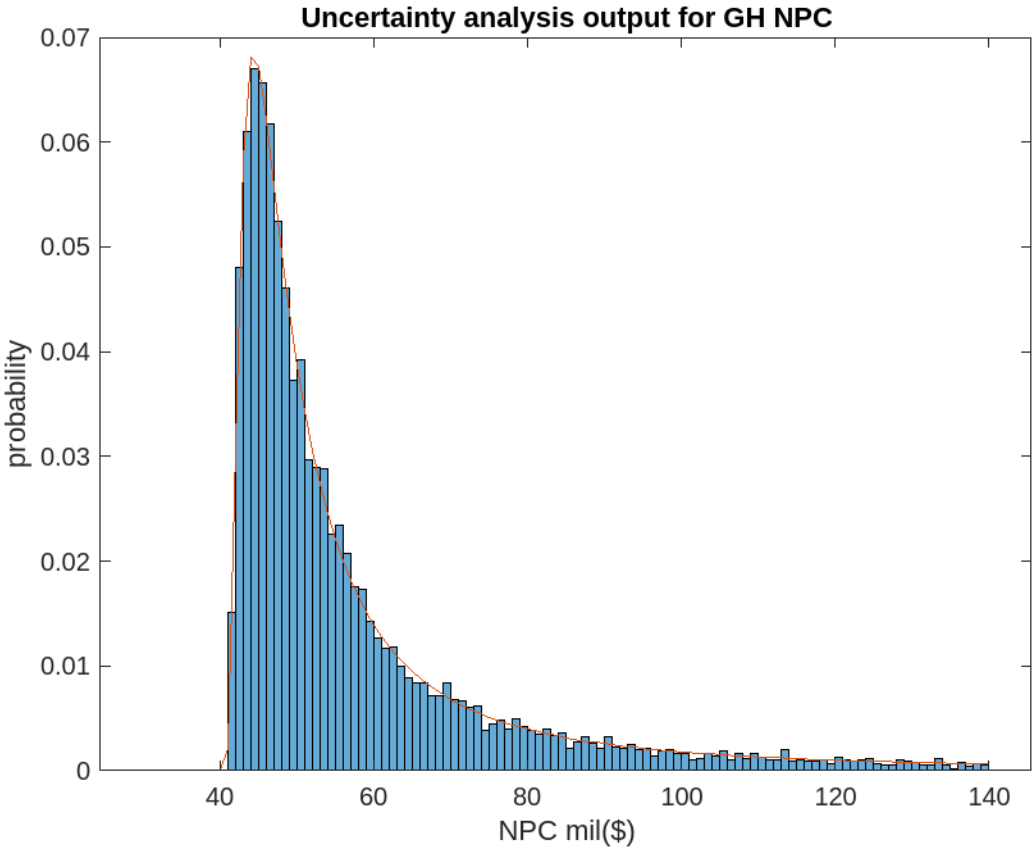

Uncertainty analysis output for GNH NPC
probability
NPC mil($)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
30
40
50
60
70
80
90
100
110
120

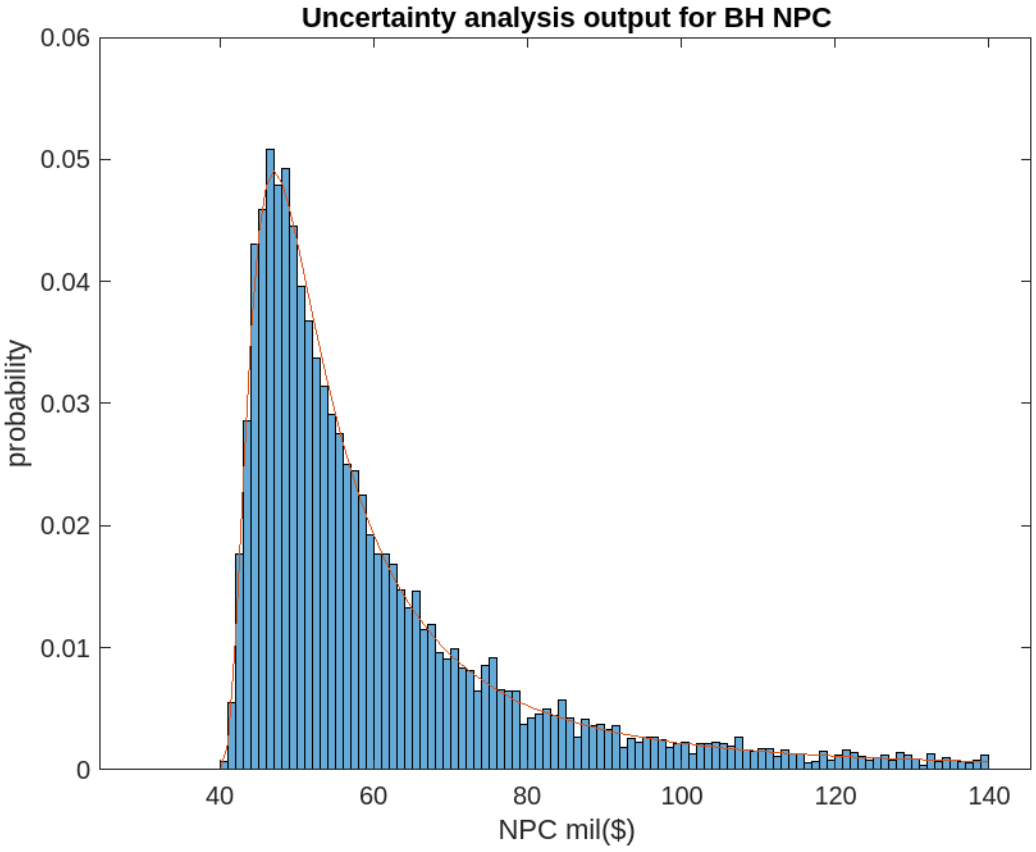

Uncertainty analysis output for the evaluation of GH-fueled ship investment
possibility
Cumulative Probability
mil $
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-30
-20
-10
0
10
20
30
40

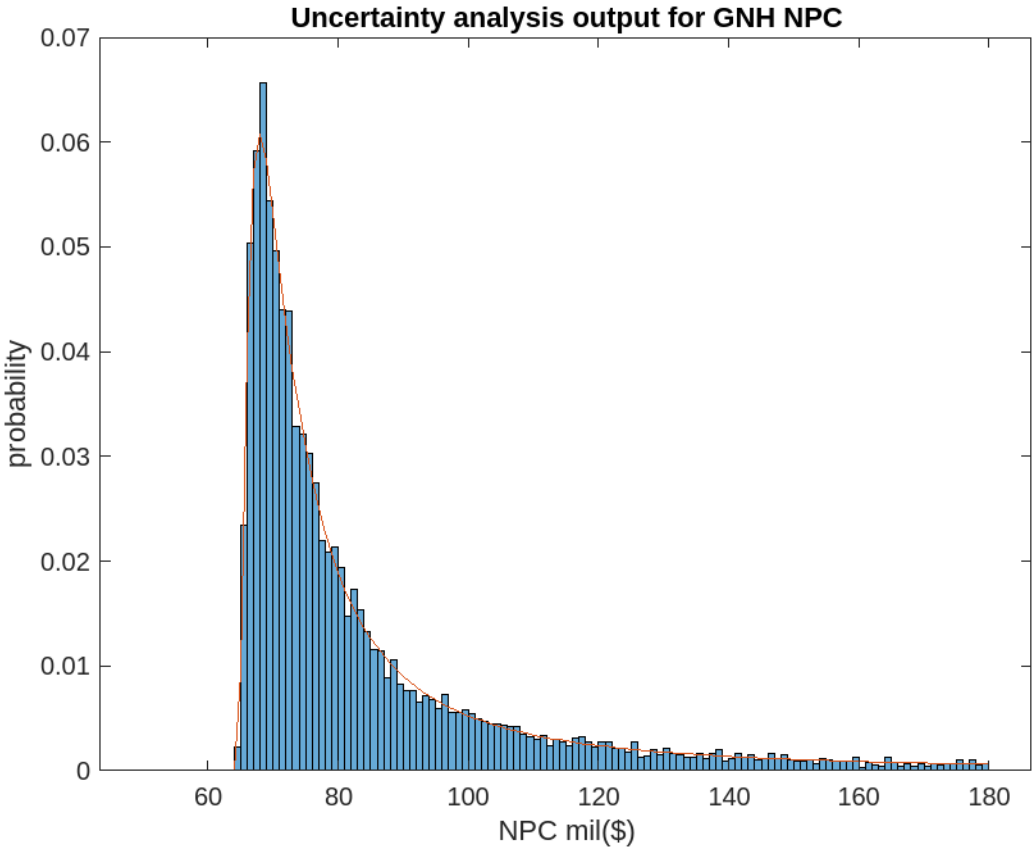

Uncertainty analysis output for the evaluation of BH-fueled ship investment
possibility
Cumulative Probability
mil $
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-30
-20
-10
0
10
20
30
40

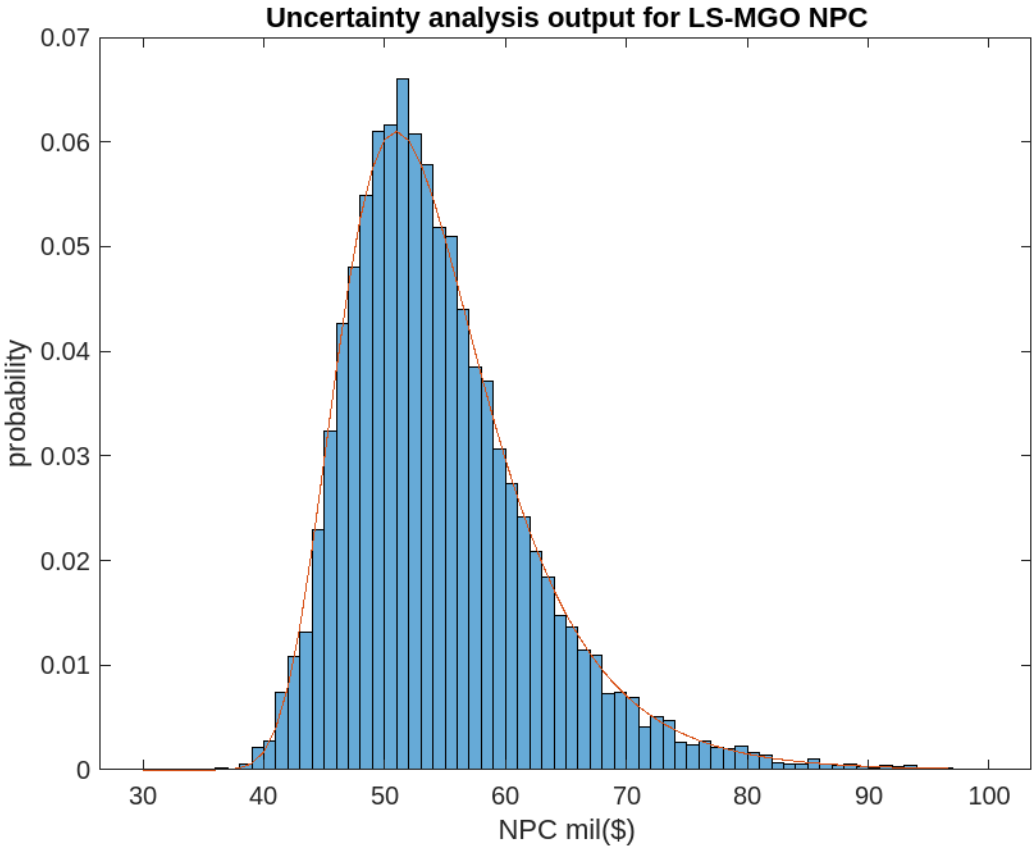

Uncertainty analysis output for the evaluation of GNH-fueled ship investment
possibility
Cumulative Probability
mil $
0.15
0.1
0.05
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-20
-10
0
10
20
30
40
50
60

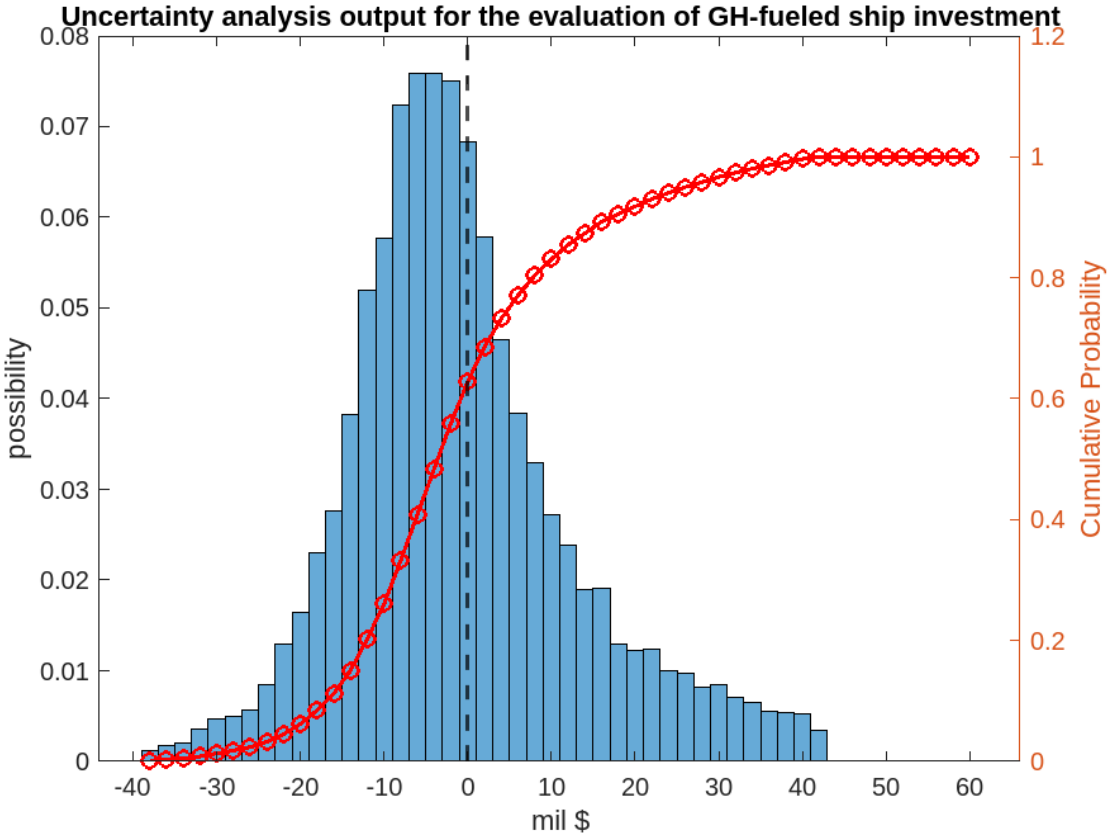
Tanker ship

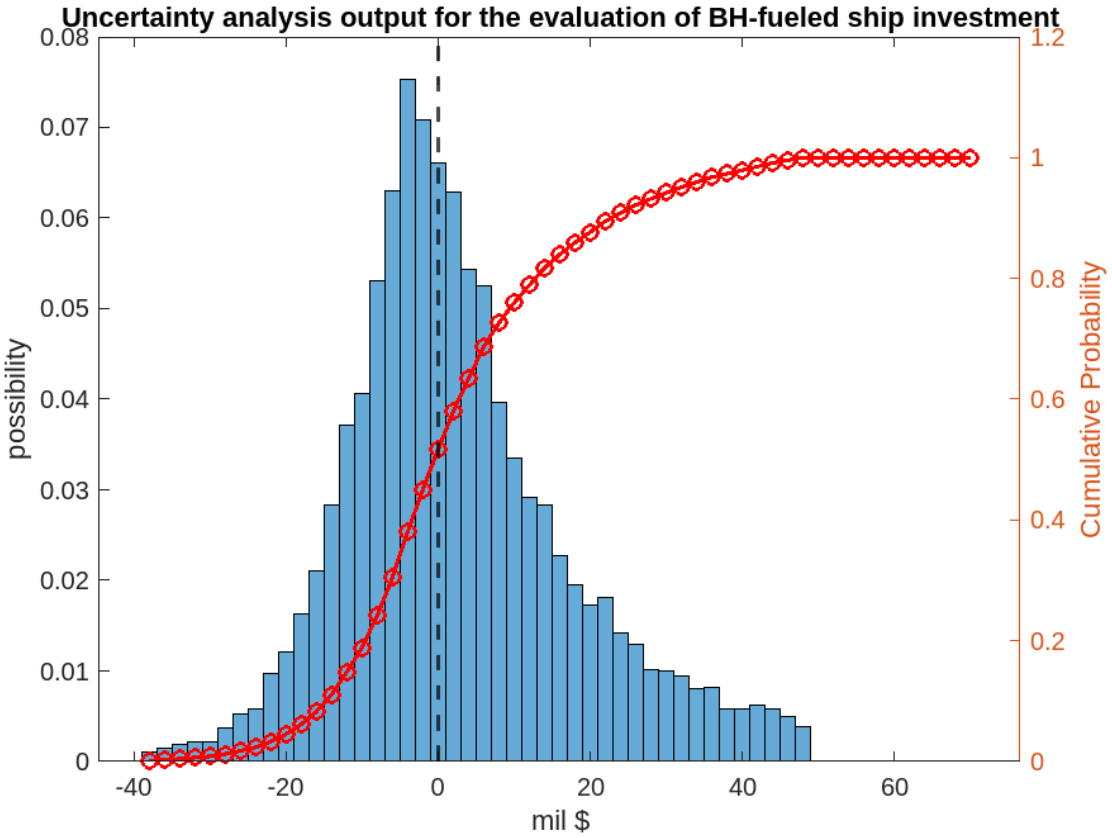

Uncertainty analysis output for GH NPC
probability
NPC mil($)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
40
60
80
100
120
140

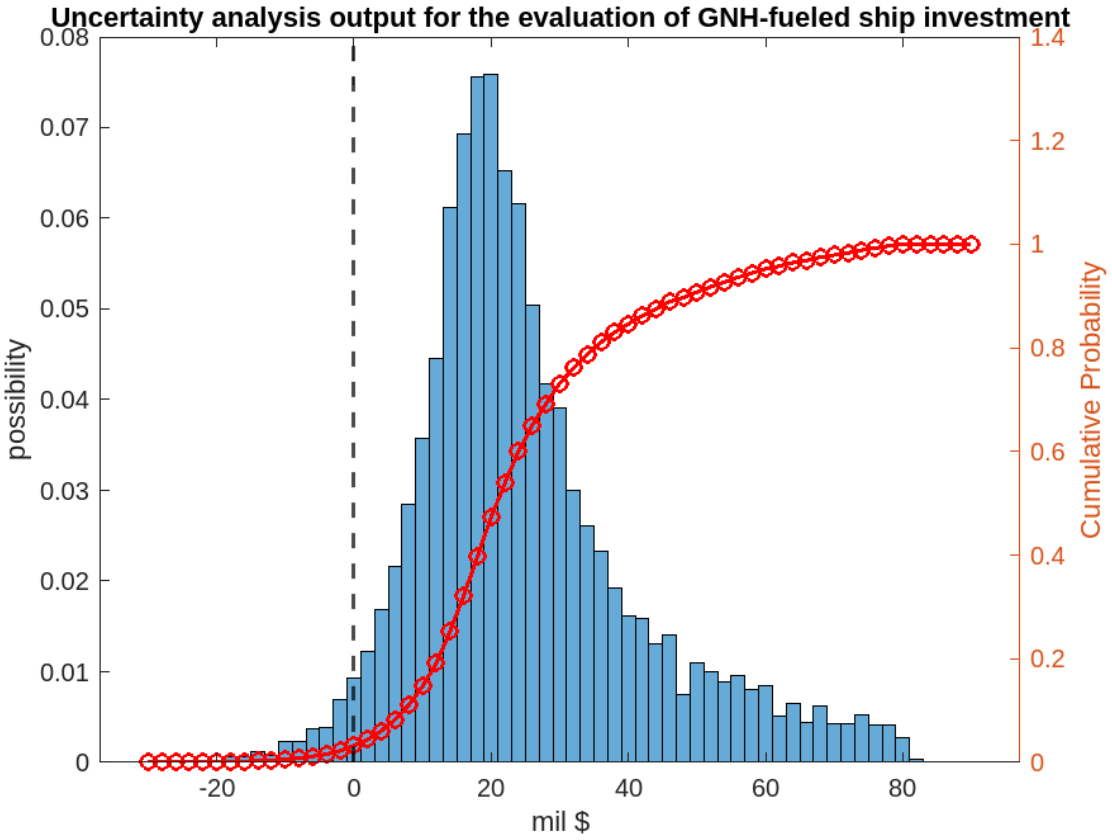

Uncertainty analysis output for BH NPC
probability
NPC mil($)
0.06
0.05
0.04
0.03
0.02
0.01
0
40
60
80
100
120
140


Uncertainty analysis output for GNH NPC
probability
NPC mil($)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
60
80
100
120
140
160
180

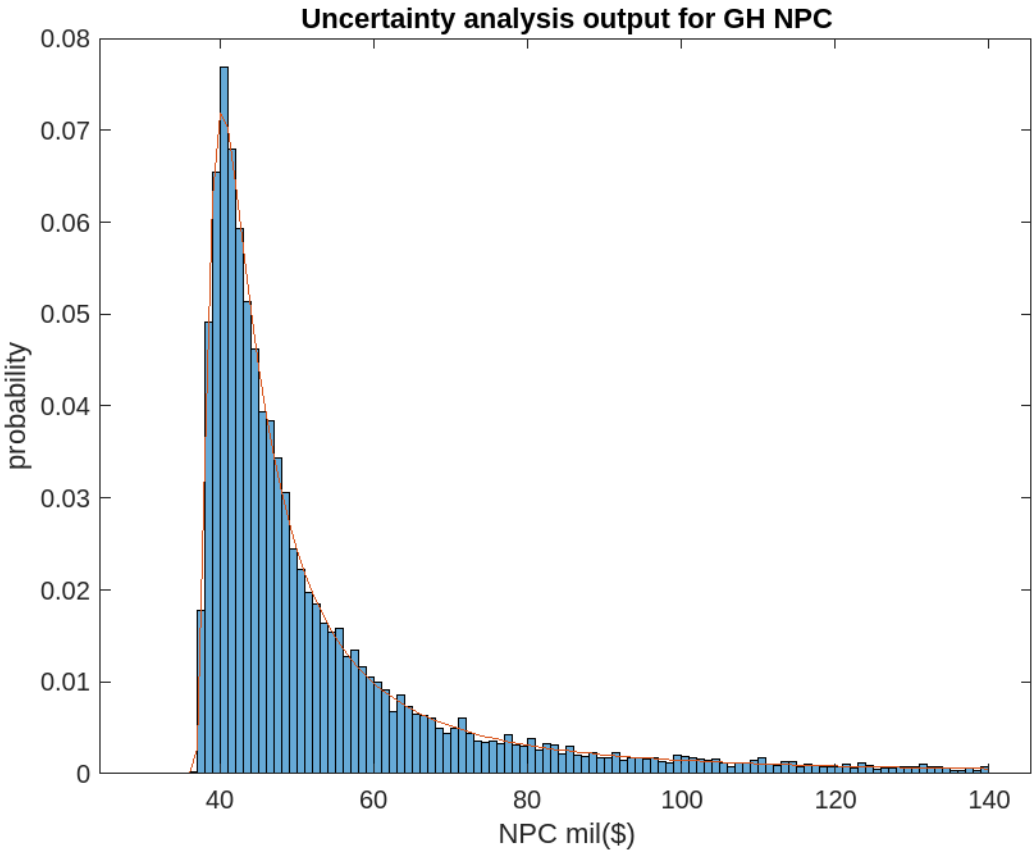

Uncertainty analysis output for LS-MGO NPC
probability
NPC mil($)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
30
40
50
60
70
80
90
100

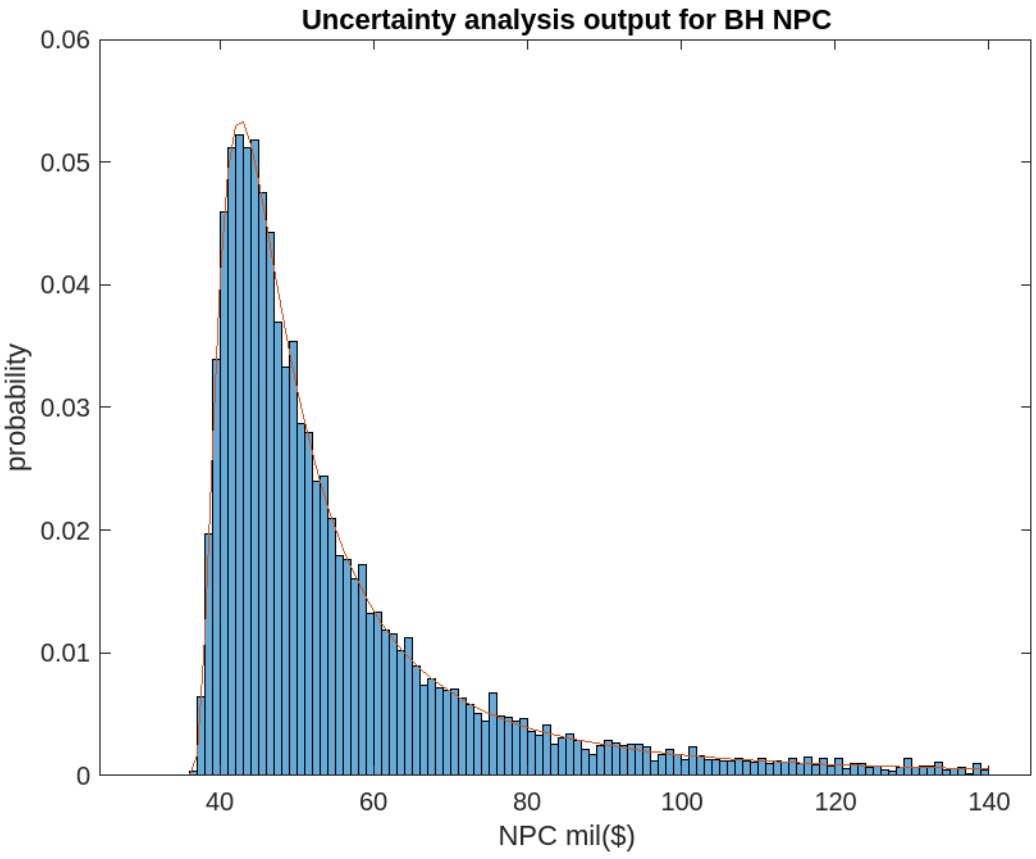

Uncertainty analysis output for the evaluation of GH-fueled ship investment
possibility
Cumulative Probability
mil $
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1.2
1
0.8
0.6
0.4
0.2
0
-40
-30
-20
-10
0
10
20
30
40
50
60

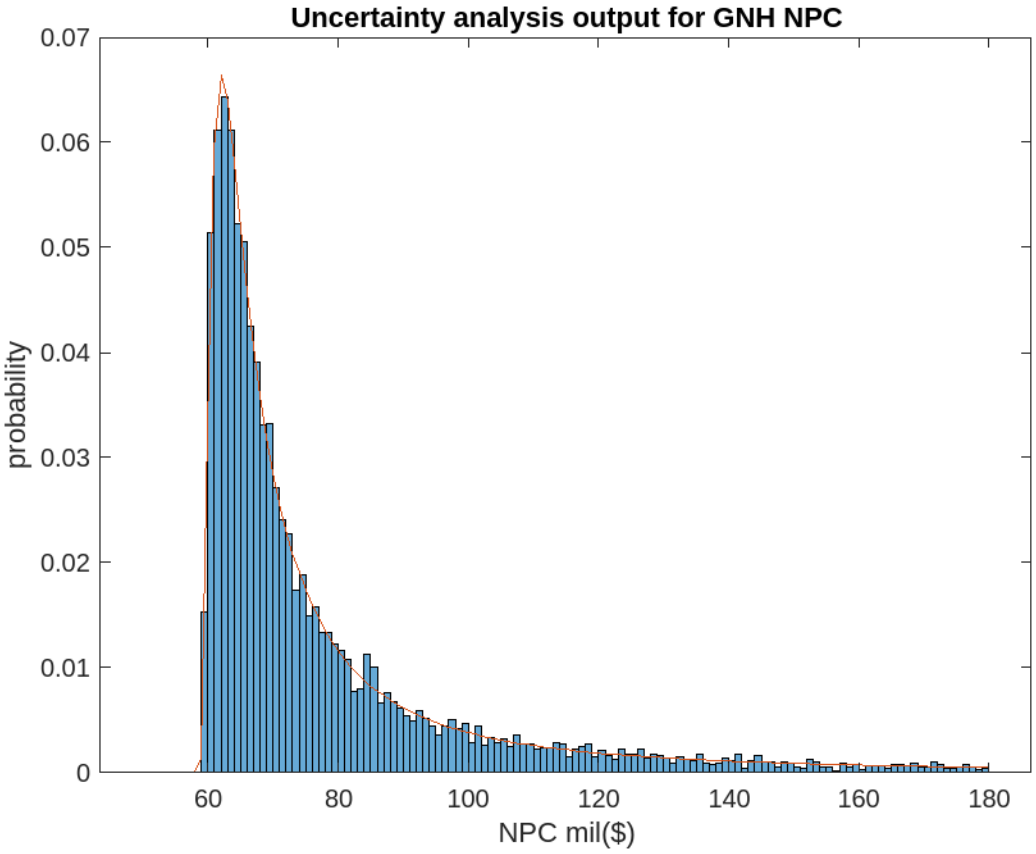

Uncertainty analysis output for the evaluation of BH-fueled ship investment
possibility
Cumulative Probability
mil $
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1.2
1
0.8
0.6
0.4
0.2
0
-40
-20
0
20
40
60

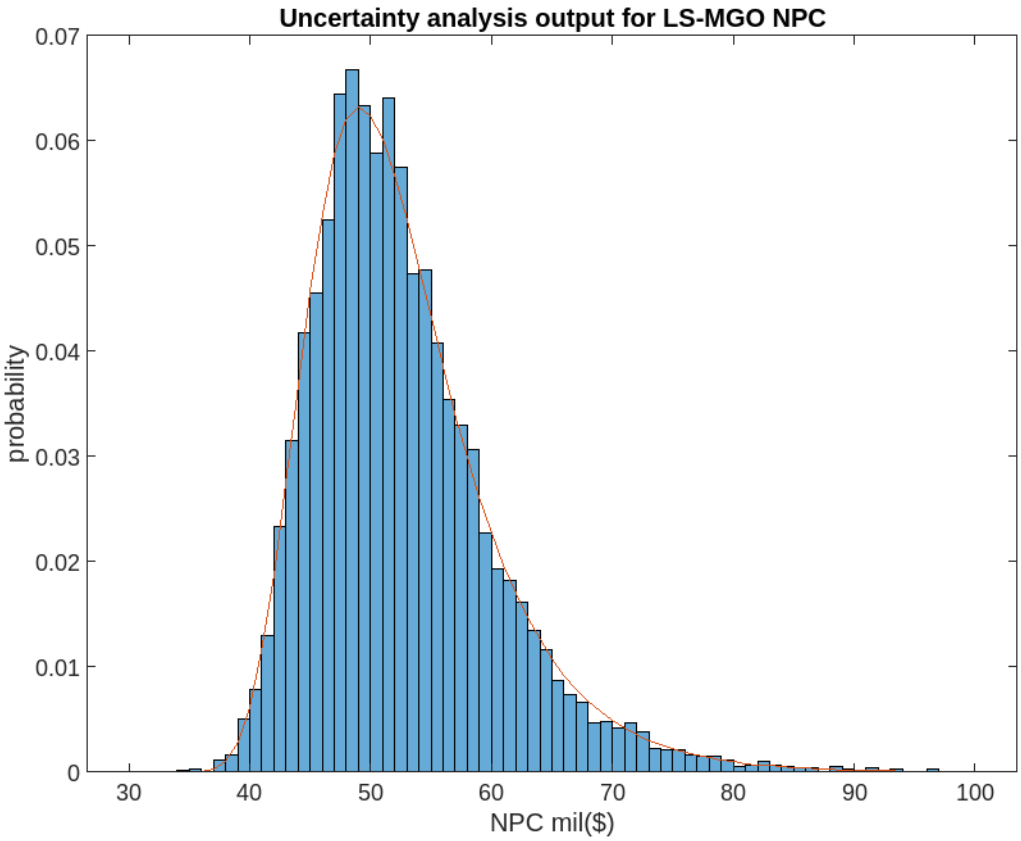

Uncertainty analysis output for the evaluation of GNH-fueled ship investment
possibility
Cumulative Probability
mil $
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-20
0
20
40
60
80

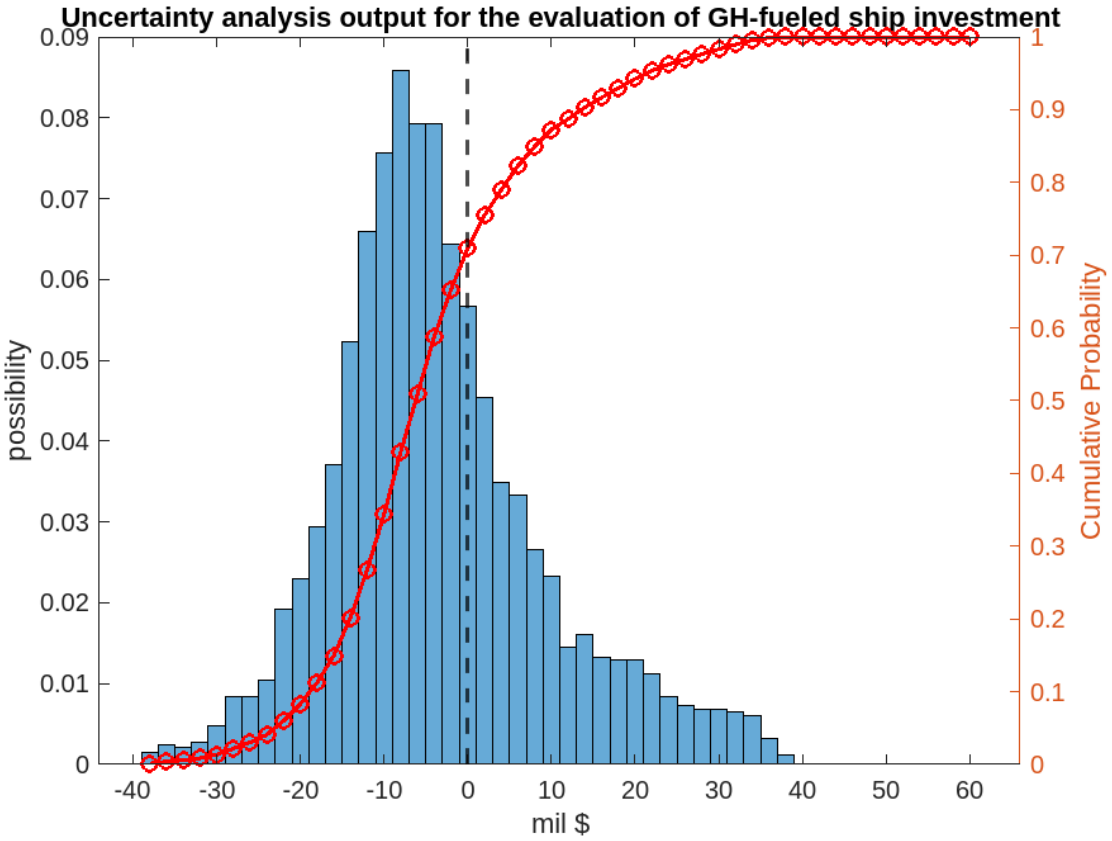
Cruise/passenger ship

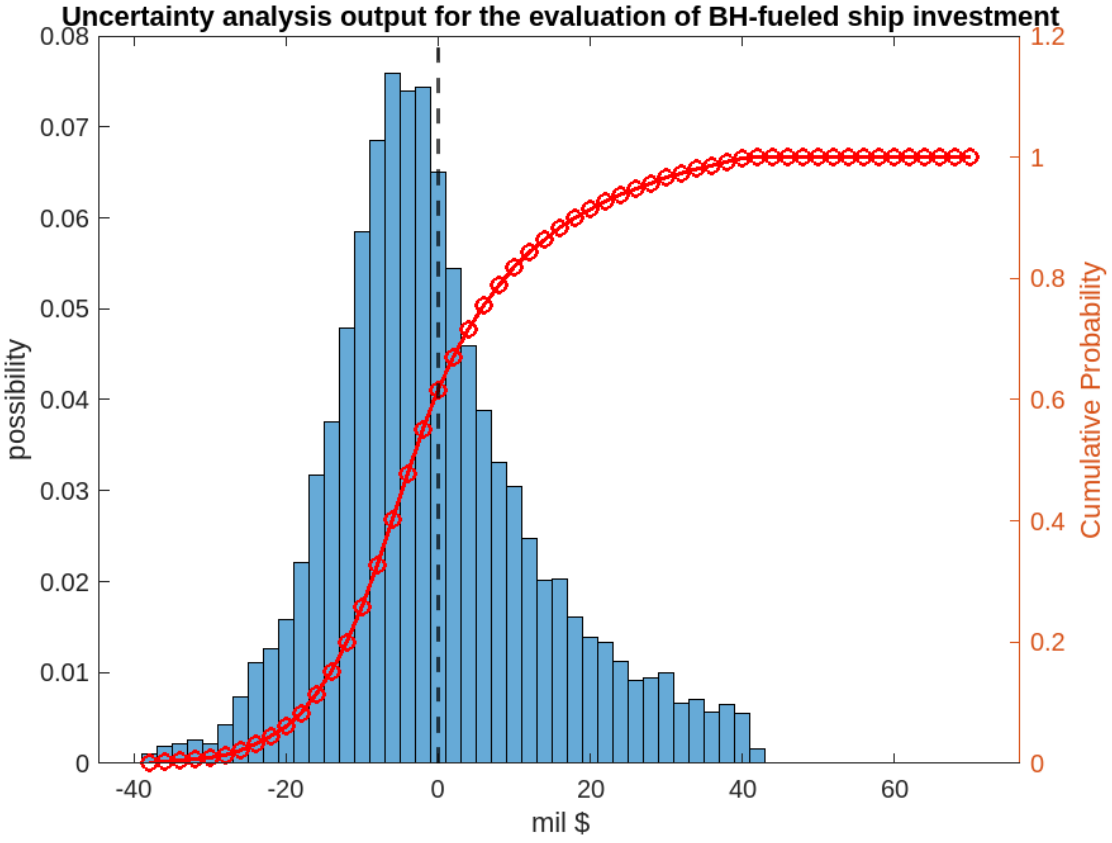


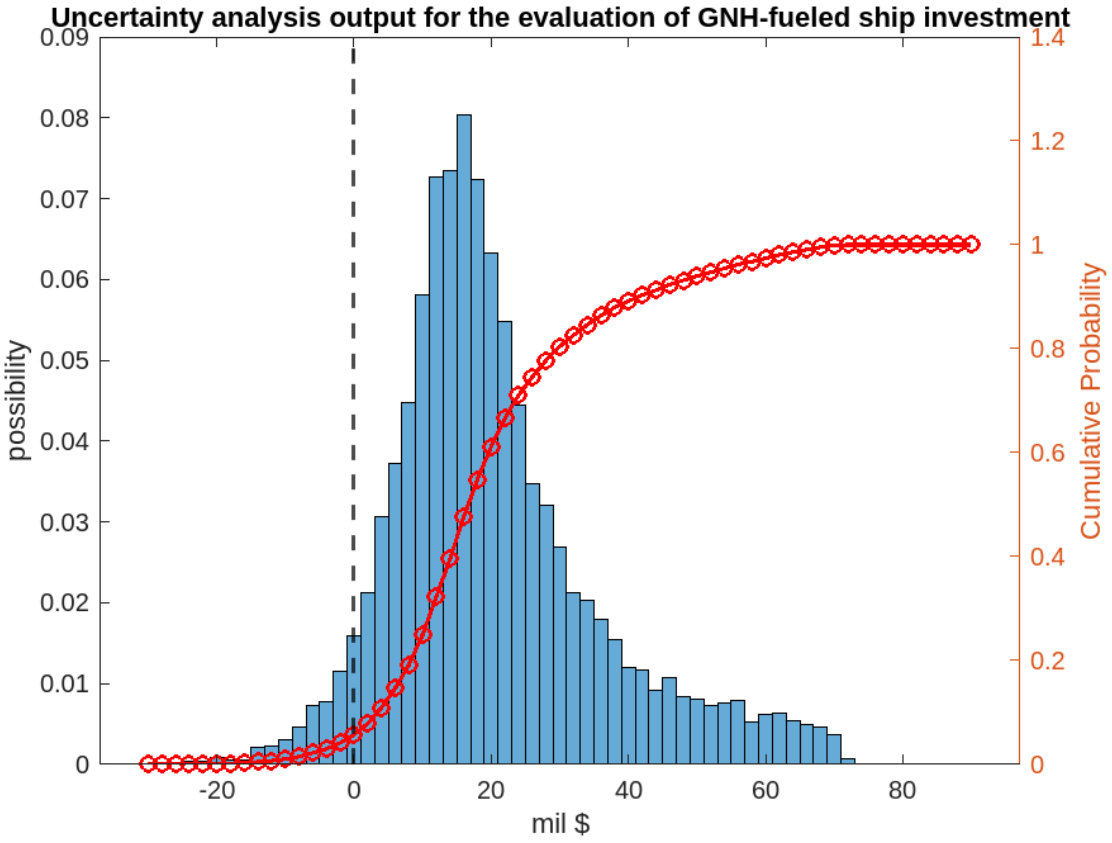



Uncertainty analysis output for GNH NPC
probability
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
60
80
100
120
140
160
180
NPC mil($)


Uncertainty analysis output for LS-MGO NPC
probability
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
30
40
50
60
70
80
90
100
NPC mil($)


Uncertainty analysis output for the evaluation of GH-fueled ship investment
possibility
Cumulative Probability
mil $
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-40
-30
-20
-10
0
10
20
30
40
50
60


Uncertainty analysis output for the evaluation of BH-fueled ship investment
possibility
Cumulative Probability
mil $
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1.2
1
0.8
0.6
0.4
0.2
0
-40
-20
0
20
40
60


Uncertainty analysis output for the evaluation of GNH-fueled ship investment
possibility
Cumulative Probability
mil $
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-20
0
20
40
60
80