National Technical University of Athens

School of Naval Architecture & Marine Engineering

Laboratory for Marine Transport

"Exploring Fuel Cell Potential for Marine Power Plants Economic Feasibility Study for a Ro/Pax Vessel"

Diploma Thesis

by

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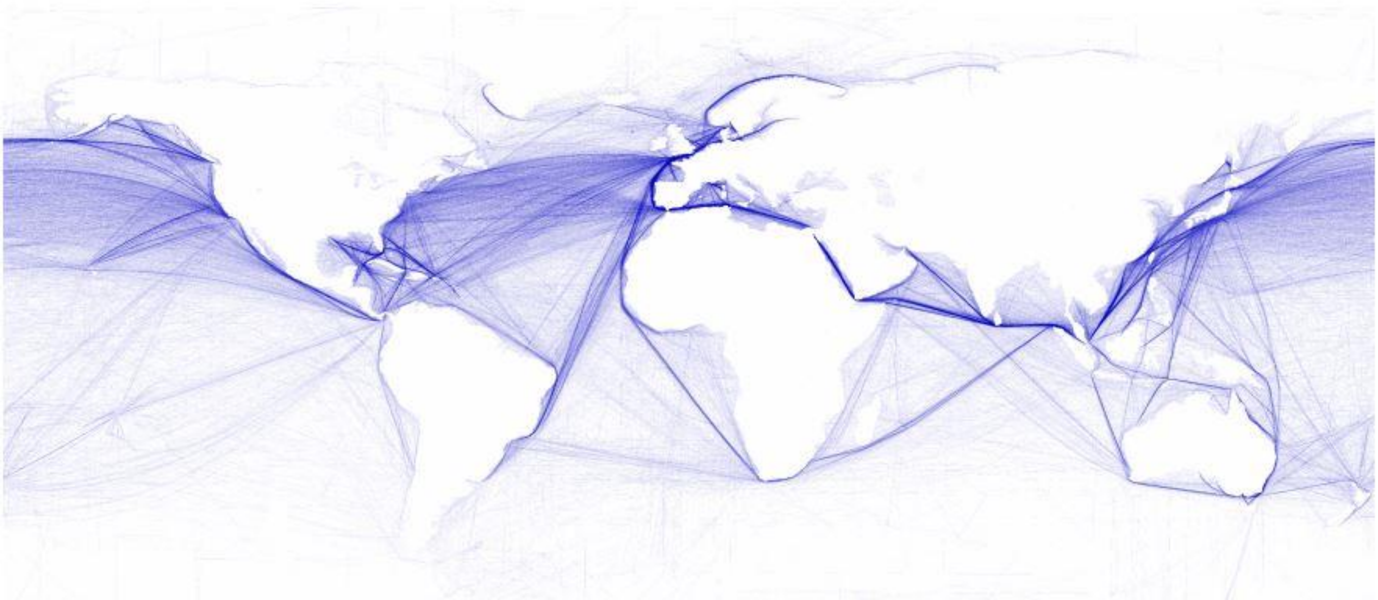

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Greece, Athens,
September 2019

“ Dedicated to all

who sacrifice anything

to keep their dreams alive.”

Ευχαριστίες

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Evangelos V. Timoleon,
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Σύνοψη Μελέτης

Θεμέλιος στόχος της παρούσας διπλωματικής εργασίας αποτελεί η διείσδυση στον κόσμο των κυψελών καυσίμου και του υδρογόνου και η έρευνα της οικονομικής τους δυναμικής στον τομέα των θαλασσίων μεταφορών.

Αρχικά, στο 1ο κεφάλαιο , παρουσιάζεται μια επισκόπηση των περιβαλλοντικών ζητημάτων που αφορούν τον ναυτιλιακό τομέα. Συγκεκριμένα, επιδεικνύεται πως οι συνεχώς αυξανόμενες ανάγκες για μεταφορά προϊόντων χάραξαν μια ρυπογόνα εξέλιξη στον τομέα των θαλασσίων μεταφορών με πρωτοφανή νούμερα τόσο σε εκπομπές ρύπων όσο και σε αερίων του θερμοκηπίου. Αυτή η δυσμενής για το περιβάλλον και την ανθρώπινη ζωή πρακτική, οδήγησε τη ναυτιλία σε ηθικά διλήμματα και περιβαλλοντικά αδιέξοδα. Αποτελεί ακριβώς εκείνη την ανάγκη η οποία επιτάσσει την θεμελίωση μιας περιβαλλοντικά φιλικής πολιτικής στον τομέα των μεταφορών, μιας ανάγκης που επρόκειτο να αναζωπυρώσει ιδέες, όπως η έννοια της βιώσιμης ανάπτυξης, οι οποίες προτείνουν την ανάδυση στον τεχνολογικό ορίζοντα νέων – φιλικών προς το περιβάλλον – τεχνολογιών για την παραγωγή ηλεκτρικής ενέργειας ή και για την πρόωση των πλοίων. Τεχνολογιών οι οποίες δύναται να φέρουν μια πραγματική επανάσταση στον τρόπο με τον οποίο ο κόσμος εξελίσσεται και προοδεύει.

Έχοντας κατανοήσει της κοινωνικές επιταγές αλλά και τις νομοθετικές προσταγές για την ανάπτυξη μιας περιβαλλοντικά φιλικής πολιτικής στον τομέα των μεταφορών , το 2ο κεφάλαιο παρουσιάζει τις βασικές αρχές των κυψελών καυσίμου; μιας τεχνολογίας με δυνατότητες για απόδοση που ξεπερνούν το κατώφλι της αρχής του Carnot και με μηδαμινούς ρύπους. Αρχικά, επιχειρείται μια σύντομη ιστορική αναδρομή στον κόσμο των κυψελών καυσίμου ενώ παράλληλα αναφέρονται κάποια βασικά στοιχεία της βιομηχανίας του. Ακολούθως, παρουσιάζονται συνοπτικά οι βασικές αρχές οι οποίες διέπουν τη λειτουργία τους, ενώ ταυτοποιούνται οι κύριοι τύποι αυτής της καινοτόμας τεχνολογίας.

Στη συνέχεια, στο 3ο κεφάλαιο επιβιβαζόμαστε στα κυριότερα πλοία - εκπροσώπους της τεχνολογίας των κυψελών καυσίμου και του υδρογόνου στο παγκόσμιο ναυτιλιακό στερέωμα. Πραγματοποιώντας μια σύντομη περιδιάβαση, αναγνωρίζεται το επίπεδο ωριμότητας της τεχνολογίας, οι δυνατότητες ορθής και ασφαλούς εφαρμοσιμότητάς της σε εμπορικά πλοία, εντοπίζεται η ενεργειακή και οικονομική της αποδοτικότητα ενώ αναδύονται τα συνολικά της ευεργετήματα – πλεονεκτήματα αλλά και οι αδυναμίες -μελανά σημεία.

Ωστόσο, καμία τεχνολογία δεν μπορεί να εφαρμοστεί στην πράξη εάν δεν διασφαλίζεται η ομαλή της λειτουργία από κατάλληλο νομοθετικό πλαίσιο. Για το λόγο αυτό, στο 4ο κεφάλαιο παρουσιάζεται μια συλλογή στοιχείων – μια βιβλιοθήκη με οδηγίες από συνομοσπονδίες Νηογνωμόνων και νομοθετήματα από παγκόσμιους φορείς (Διεθνής Ναυτιλιακός Οργανισμός & Διεθνής Οργανισμός Τυποποίησης) – με στόχο την διαπίστωση της εφαρμοσιμότητας της συνέργειας των κυψελών καυσίμου τροφοδοτούμενων με υδρογόνο. Μέσω από αυτήν την περιπλάνηση, εντοπίζονται νομοθετικά κενά και προτείνονται λύσεις για την γεφύρωση των νομικών χασμάτων σε παγκόσμιο επίπεδο.

Ακολούθως, στο 5ο κεφάλαιο πραγματοποιούμε ένα καινούργιο γνωσιακό ταξίδι με προορισμό τον κόσμο του υδρογόνου. Για το λόγο αυτό, μεταβαίνουμε σε όλα τα μήκη και τα πλάτη της Γης ώστε να αναγνωρίσουμε έργα-σταθμούς στην ανάπτυξη της οικονομίας του υδρογόνου; μιας οικονομίας που για πολλούς επιστημονικούς αναλυτές αποτελεί, σε χρονικό ορίζοντα 30 ετών, τη χρυσή τομή για την επίτευξη μιας βιώσιμης ανάπτυξης και την απανθράκωση του τομέα των μεταφορών. Στον πλου αυτόν, πληροφορούμαστε για τις μεθόδους παραγωγής υδρογόνου, τους δυνατούς τρόπους αποθήκευσης και συντήρησής του στα πλοία ενώ μέσω της παρουσίασης συνοπτικών τεχνικοοικονομικών αλλά και περιβαλλοντικών επιχειρημάτων απορρίπτονται οι περισσότερο αδύναμες ενώ προκρίνονται οι ισχυρότερες εναλλακτικές. Παράλληλα, για την σφαιρική και πολύπλευρη τριβή του αναγνώστη με το αντικείμενο, εντοπίζονται τα κυριότερα θέματα ασφαλείας που προκύπτουν από τη λειτουργία με καύσιμο υδρογόνου, ενώ προτείνονται λύσεις μέσω της προσομοιώσής τους με εφάμιλλα που έχουν ήδη καταπιαστεί ερευνητικά: όπως αυτά που αφορούν τον δεξαμενισμό και ανεφοδιασμό πλοίων με υγροποιημένο φυσικό αέριο (LNG). Κλείνοντας αυτό το κεφάλαιο, για να ολοκληρώσουμε το γνωσιακό μας πλαίσιο, εισχωρούμε στον κόσμο της οικονομίας των κυψελών καυσίμου; μιας οικονομίας η οποία έχει όλα τα χαρακτηριστικά της οικονομίας κλίμακας. Μέσω καταλόγων κατασκευαστών ενημερωνόμαστε για τις τρέχουσες τάσεις της αγοράς των κυψελών καυσίμου, εντοπίζουμε τρέχοντα και μελλοντικά χαρακτηριστικά τους γνωρίσματα και καταλήγουμε στους κυριότερους εκπροσώπους της (Κυψέλη Καυσίμου Πολυμερισμένης Μεμβράνης – PEMFC, Τηγμένων Ανθρακικών Αλάτων – MCFC και Σταθεροποιημένων Οξειδίων – SOFC).

Έχοντας στο γνωσιακό μας οπλοστάσιο όλη την απαραίτητη γνώση, είμαστε πλέον έτοιμοι για την κατασκευή του ερευνητικού μας έργου - μιας μελέτης σκοπιμότητας προσανατολισμένη στην οικονομική και περιβαλλοντική αξιολόγηση τεχνολογιών κυψελών καυσίμου εφαρμοσμένα σε ένα πλοίο-αντιπρόσωπο της ελληνικής ακτοπλοΐας. Ως πρώτος σταθμός αυτής της ανάλυσης, ορίζεται η ηλεκτρική ενεργειακή μελέτη ενός πλοίου αναφοράς; του Blue Star Paros. Έτσι, στο 6ο κεφάλαιο, αφού καθορίζεται ένα προφίλ λειτουργίας του πλοίου - για ένα δεδομένο κυκλικό ταξίδι - , πραγματοποιούνται όλοι οι απαραίτητοι ενεργειακοί υπολογισμοί με σκοπό την αναγνώριση των απαιτήσεων ισχύος και ενέργειας οι οποίες θα πρέπει να καλυφθούν από τις πιθανές προτεινόμενες τοπολογίες των κυψελών καυσίμου. Παράλληλα αναγνωρίζονται οι οικονομικές δαπάνες και ο περιβαλλοντικός αντίκτυπος από την λειτουργία της συμβατικής ηλεκτρολογικής εγκατάστασης των 3 ντιζελογεννητριών του πλοίου.

Τέλος, στο 7ο κεφάλαιο, παρουσιάζεται η σπονδυλωτή μορφή της ενεργειακής μελέτης. Αρχικά με κατάλληλη επιχειρηματολογία και εν συνεχεία μέσω αριθμητικών υπολογισμών εντοπίζονται τα περισσότερο ευοίωνα σενάρια εφαρμογής τεχνολογίας κυψελών καυσίμου με υδρογόνο ή υγροποιημένο φυσικό αέριο στην ελληνική ναυτιλία. Παράλληλα, προσδιορίζονται οι λειτουργικές δυσκολίες που παρουσιάζει το άκρως στοχαστικό περιβάλλον της θάλασσας, οι οποίες οδηγούν στην ανάγκη για συνέργεια της τεχνολογίας των κυψελών καυσίμου με κάποιο εφεδρικό σύστημα ενέργειας, ικανό να ανθίσταται στις εναλλασσόμενες και απότομες ενεργειακές μεταβολές που συνοδεύουν τη λειτουργία του πλοίου (οι οποίες κυριαρχούν κατά τις φάσεις των ελιγμών). Οι μπαταρίες ιόντων λιθίου φαίνεται να αποτελούν μια εφικτή λύση. Μέσω κύκλων φόρτισης-αποφόρτισης καθορίζεται ένα συγκεκριμένο προφίλ λειτουργίας της μπαταρίας, και ορίζεται η απαιτούμενη χωρητικότητά της. Η τεχνολογία των κυψελών καυσίμου συνοδευόμενη με την λειτουργική ασφάλεια που παρέχει η μπαταρία, κατά τα μεταβατικά φαινόμενα, δημιουργούν μια συνδυαστική δράση ικανή να καλύψει πλήρως τις ενεργειακές απαιτήσεις του πλοίου. Μαζί, συνθέτουν ένα τυπικό υβριδικό σύστημα για την κάλυψη των ηλεκτρολογικών αναγκών του

Blue Star Paros. Στη συνέχεια, και εφαρμόζοντας την κατοχυρωμένη γνώση από τα προηγούμενα κεφάλαια, μοντελοποιούνται τα τρία εναλλακτικά σενάρια εφαρμογής των κυψελών καυσίμου: 1) LH2 – PEMFC, 2) LNG – MCFC, 3) LNG – SOFC. Αφού προσδιοριστούν οι παράμετροι κάθε προτεινόμενης τοπολογίας, εκκινεί η οικονομική ανάλυσή τους. Για τον σκοπό αυτό, εφαρμόζεται η οικονομική μεθοδολογία της εκτίμησης του κόστους κύκλου ζωής τόσο για τα προτεινόμενες διατάξεις όσο και για την τρέχουσα – συμβατική. Ακολούθως, πραγματοποιείται σύγκριση και σχολιασμός των προκυπτόντων αποτελεσμάτων κάθε σεναρίου. Έπειτα, για την μελέτη της μελλοντικής δυναμικής των κυψελών καυσίμου, διενεργείται ανάλυση ευαισθησίας έχοντας ως παραμέτρους τα κυριότερα χαρακτηριστικά γνωρίσματα κάθε σεναρίου. Καταληκτικά, προσανατολιζόμενοι στην οπτική μελλοντικών επενδυτών, αναγνωρίζεται το επίπεδο ανταγωνιστικότητας των προτεινόμενων συστημάτων συγκριτικά με το συμβατικό ανάλογο, ενώ προσδιορίζονται οι συνθήκες κάτω από τις οποίες οι τεχνολογίες κυψελών καυσίμου υπερέχουν σε οικονομικούς όρους.

Λέξεις κλειδιά:

| Κυψέλες Καυσίμου | Βιώσιμη Ανάπτυξη | Οικονομία Υδρογόνου | Εξανθράκωση Ναυτιλίας |

| Μελέτη Σκοπιμότητας | Πλοίο Αναφοράς | Ηλεκτρολογική Ενεργειακή Μελέτη | |

Υβριδικό Σύστημα | Εκτίμηση Κόστους Κύκλου Ζωής | Ανάλυση Ευαισθησίας |

Research Synopsis

The fundamental purpose of this dimploma thesis encompasses the world of fuel cells and hydrogen, as well as, research in their economic potential in the field of marine transport.

The first chapter covers an overview of environmental issues concerning the field of marine industry, specifically illustrating that the continuous increasing needs to transport products have opened a polluted progression in the field of marine transport with unprecedented figures in pollutants and green house gases being unfavorable for both the environment and human life. This practice has propelled the shipping industry to moral dilemmas and environmental deadends. It consists of the need to dictate the foundation of an eco-friendly policy in transportation sector; a need which might ignite ideas such as that of a sustainable development which suggests the emergence of a technological horizon comprised of new friendly- to-the-environment breakthroughs for the production of electric energy and the propulsion of ships. Technology which has the potential to bring a tremendous revolution in world progress.

Having understood the social demands and legal regulations for the development of an eco-friendly policy in the field of marine transport, chapter 2 introduces the main principals of fuel cells; a technological breakthrough with a potential in efficiency that exceeds the threshold of Carnot while minimalizing emissions. Endeavoring into a brief historical retrospect of fuel cells and exploring the basic elements of their industry, we comprehend the current level of their technological maturity. Whereupon, this chapter introduces briefly the main principles of the operation of this pioneering technology and also identifies its major types.

In the third chapter we encounter major ships-representatives of fuel cell technology to the global marine foundation. Delving into the level of maturity in technology, the ability of righteous and safe applicability in commercial ships there is detection in their energy and economic efficiency emerging the complete advantages and disadvantages of fuel cell technology.

However, no technology can be applied in practice if its operation cannot be assured in a legal framework. For this reason, in chapter 4, a collection of data is introduced – a "library" filled with instructions – rules from the classification societies and regulations from global bodies (International Maritime Organization – IMO and International Organization for Standardization – ISO) – with the goal to ascertain the application of the hydrogen fuel cells on board. Through this we detect legal gaps and suggest solutions for their bridging on a global level.

Chapter five endeavours a journey in knowledge to the land of hydrogen. Travelling across all the corners of the globe to recognize landmarks in hydrogen economy; an economy which for many scientific analysts will bring, in a span of thirty years, the golden solution for the achievement of a sustainable development and decarbonization of the transport sector. At the same time, insight is gained about the methods of hydrogen production and the possible ways of storage and conditioning on vessels through the presentation of technoeconomical and environmental arguments, rejecting the weaknesses while qualifying the strongest alternatives. Simultaneously, for the global knowledge of the reader with the subject, the main issues of safety which arise from the usage of hydrogen as a marine fuel are detected, and solutions are suggested through their simulation with equivalent topics that arise from the usage of LNG as valuable information can be derived from related studies (especially concerning bunkering and infrastructure matters). Concluding, the world of fuel cell economy arises, an economy which has all the characteristics of an Economy of Scale. Through manufacture catalogues are informed about current trends of the market of in fuel cells, where we detect current and future distinctive features, recognize their commercial status to finally identify the primary representatives of this technology (Proton Exchange Membrane Fuel Cell – PEMFC, Molten Carbonate Fuel Cell – MCFC and Solid Oxide Fuel Cell – SOFC).

Having acquired all this essential information, it is evident that we are ready for the realization of our research – a feasibility study, which is oriented in the economic and environmental evaluation of fuel cell technologies when applied on one of the ships of the Greek fleet. The first phase of this research is defined in an electric energy analysis of a target ship, the Blue Star Paros. So in the sixth chapter, since the profile of the ship in its operation is determined – for a specific round trip – all the energy calculations are carried out for the purpose of detecting the demands in power and energy which have to be covered by the proposed fuel cell topologies. Furthermore, the economic expenses and environmental impact is estimated from the operation of the pre-installed conventional configuration consisting of three diesel generators that united they form the electrical generation plant of the Blue Star Paros.

In the seventh chapter, the modularity of the energy analysis is introduced. Firstly, with the proper usage of argumentation and in continuation through numerical calculations the most promising scenarios of fuel cell applications powered with hydrogen or LNG are being developed for the purposes of our target ship. Furthermore, functional difficulties, found in

the stochastic sea habitat, lead to the need of a synergy between fuel cell technology with an energy storage system, are detected and addressed. This combination is capable of withstanding the alternating and steep energy variations (which are dominant during maneuvering phases) that accompany the operation of a ship. Lithium-Ion Batteries (LIBs) seem to consist a plausible and effective solution. Through charging and discharging cycles, a specific profile of operation is defined for the usage of our LIB installation for the dimensioning of its capacity. The established fuel cell technology along with the provided security that derives from the operation of the battery packs (especially during transient phenomena) create a combination of reactors which can offer an effective coverage of the complete electric energy demands of the target ship.Together, they form a typical hybrid system gathering and exploıting the merits of its components. In continuation, applying established knowledge from the previous chapters, there is a modeling if three alternative scenarios of fuel cell installations: 1) LH2 – PEMFC , 2) LNG – MCFC, 3) LNG –SOFC. After specifying the parameters of each proposed topology, economic analysis is launched. For this purpose, a Life Cycle Cost Analysis is conducted for each scenario and the pre-existing installation. Subsequently, there is a comparison and comments about the calculated results. Furthermore, for the research in the potential of fuel cells to power future on-board applications, there is a sensitivity analysis having as parameters the main characteristics of each scenario. Concluding, from the perspective of future investors, the level of competition of the proposed scenarios is recognized and compared with their conventional analog, while conditions are defined in which the technology of fuel cells prevails in economic terms.

Keywords:

| Fuel Cells | Sustainable Development | Hydrogen Economy | Decarbonization of Maritime Transport | Economic Feasibility Study | Target Ship | Electric Energy Analysis | Hybrid System | Life Cycle Cost | Sensitivity Analysis |

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KEY DEFINITIONS

Battery

A battery or voltaic cell consists of one or more electrochemical cells which store and convert chemical energy into electric energy

Carbon-free Hydrogen

Hydrogen produced from renewable feedstock with emissions below 36.4g CO_2 eq/MJ H_2, e.g., by electrolysis using renewable electricity as feedstock. This category is equivalent to “CertifHy green H2”.

Decarbonized Hydrogen

Hydrogen produced from nonrenewable feedstock with emissions below 36.4g CO_2 eq/ MJ H_2, e.g., by SMR with carbon capture technology. This category is equivalent to “CertifHy low carbon H2”.

Domestic shipping

Refers to shipping between ports of the same country, as opposed to international shipping. Domestic shipping excludes military and fishing vessels. By this definition, the same ship may frequently be engaged in both international and domestic shipping operations. This definition is consistent with the IPCC 2006 Guidelines (Second IMO GHG Study 2009).

Economy of Scale

In microeconomics, economies of scale are the cost advantages that enterprises obtain due to their scale of operation (typically measured by amount of output produced), with cost per unit of output decreasing with increasing scale. (In economics, "economies" is synonym to cost savings and "scale" is synonymous with quantity or the scale of production.). Fuel Cell economy is highly sensible to the amount of output produced, therefore consists a par excellence economy of scale.

Energy Efficiency Design Index (EEDI)

The EEDI for new ships is the most important technical measure and aims at promoting the use of more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments. The EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship.

Feedstock

Refers to raw materials (input) fed into a process for conversion into something different (output).

Fuel cell (FC)

A fuel cell is an electrochemical cell that can convert the chemical energy stored in a given fuel into electrical energy.

Gasification

Gasification is a process that converts organic carbonaceous feedstock into carbon monoxide, carbon dioxide, and hydrogen by reacting the feedstock at high temperatures (>700°C, 1290°F), without combustion, with a controlled amount of oxygen and/or steam. The resulting gas mixture *(*synthesis gas*,* syngas) is called a producer gas and is itself a fuel. The power derived from carbonaceous feedstock and gasification followed by the combustion of the product gas(es) is considered to be a source of renewable energy if the gaseous products are from a source (e.g., biomass) other than a fossil fuel.

Greenhouse Gas (GHG)

A greenhouse gas is a gas that can absorb infrared radiation in the atmosphere. As these gases take in infrared radiation, they trap heat within the troposphere, the lowest layer of the atmosphere. In turn, this will increase surface temperatures, a phenomenon known as the greenhouse effect.

Henry Hub Pricing

Consists an important market clearing pricing concept because it is based on actual supply and demand of natural gas as a stand-alone commodity. Other natural gas markets like Europe have fragmented hub pricing points. This means natural gas prices are often indexed to crude oil, which can have very different supply and demand factors affecting its price. Attempts are being made to develop European hub pricing points in the Netherlands and the UK, but this has proved difficult so far due to competition from national hubs. Asian natural gas markets are even more fragmented and have no defined hub pricing point, although Singapore would like to serve this regional role. Consequently, all Asian natural gas prices are either indexed to crude oil or linked to Henry Hub.

Internalization of Costs

Refers to the process of making societal cost effects part of the decision making process of transport users. This can be done directly through regulation, i.e. command and control measures, or indirectly through providing the right incentives to transport users, namely with market-based instruments (e.g. taxes, charges, emission trading, etc.). Combinations of these basic types are possible: for example, existing taxes and charges may be differentiated, e.g. by the EURO emission classes of vehicles.

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Life-cycle cost analysis (LCCA)

Life-cycle cost analysis (LCCA) is a method for assessing the total cost of facility ownership. It takes into account all costs of acquiring, owning, and disposing of a building or building system. LCCA is especially useful when project alternatives that fulfill the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings.

Operation & Maintenance Cost

The Operation and Maintenance cost of a component is the cost associated with operating and maintaining that component. The total O&M cost of the system is the sum of the O&M costs of each system component.

Ship Energy Efficiency Management Plan (SEEMP)

The Ship Energy Efficiency Management Plan (SEEMP) is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time. Ultimately, SEEMP urges the ship owner and operator at each stage of the plan to consider new technologies and practices when seeking to optimize the performance of a ship.

Societal Costs

Reflecting all costs occurring due to the provision and use of transport infrastructure, such as wear and tear costs of infrastructure, capital costs, congestion costs, accident costs, environmental costs.

Sustainable Development

Sustainable development is the organizing principle for meeting human development goals while simultaneously sustaining the ability of natural systems to provide the natural resources and ecosystem services upon which the economy and society depend. The desired result is a state of society where living conditions and resources are used to continue to meet human needs without undermining the integrity and stability of the natural system. Sustainable development can be defined as development that meets the needs of the present without compromising the ability of future generations.

Well-to-Tank Emission Factor

A Well-to-Tank emissions factor, also known as upstream or indirect emissions, is an average of all the GHG emissions released into the atmosphere from the production, processing and delivery of a fuel or energy vector. Of course, their average efficiency values and pollutant emission have an important impact on the economy and ecology.

ABBREVIATIONS

AC	Alternating Current	**LH_2**	Liquid Hydrogen
AMP	Alternative Maritime Power	**LIB**	Lithium-Ion Battery
CapEx	Capital Expenditure	**LLCA**	Life Cycle Cost Analysis
CCS	Carbon Capture and Storage	**LCC**	Life Cycle Cost
CO_2	Carbon Dioxide	**LNG**	Liquified Natural Gas
DC	Direct Current	**LSFO**	Low Sulfur Fuel Oil
DG	Diesel Generator	**MMBtu**	Million British Thermal Units
DRI	Direct Reduced Iron	**MRV**	Monitoring, Reporting and Verification
EBC	Electric Balance Calculation	**NECAS**	Nitrogev Oxide Emission Control Areas
ECAS	Emission Control Areas	**NPC**	Net Present Cost
EEDI	Energy Efficiency Design Index	**NOx**	Nitrogen Oxide
ECL	Electroactive Catalyst Layer	**OpEx**	Operational Expenditure
ECS	Energy Control System	**PEM**	Proton exchange membrane
EU	European Union	**PM**	Particulate Matter
ESS	Energy Storage System	**PV**	Present Value
FV	Future Value	**PWC**	Present Worth of Cost
GDL	Gas Diffusion Layer	**PWSC**	Present Worth of Societal Cost
GDE	Gas Direction Electrode	**SC**	Supper Capacitor
GHG	Green House Gases	**SECAS**	Sulfur Emission Control Areas
H_2	Hydrogen	**SEEMP**	Ship Energy Efficiency Management Plan
HC	Hydrocarbon	**SMR**	Steam Methane Reforming
HFC	Hydrogen Fuel Cell	**SOx**	Sulfur Oxide
ICE	Internal Combustion Engine	**TWh**	Terawatt Hour
IEA	International Energy Agency	**T&D**	Transport and Distribution
kWh	Kilowatt Hour	**WtT**	Well to Tank

Prelude

Technological development is the main pillar for the evolution of our societies. However, at its primary core, the concept of societal "evolution" has to be interlinked with concepts that attribute respect to both human life and ecosystems. Modern research projects, intergovernmental committees and non-governmental organizations strive to find the fine line between technological growth and environmental preservation. To this point, the term "sustainable development" is mankind's closest approach to above mentioned universal ambition. Sustainable development lays the foundation for the construction of an environmental-friendly operation of the modern world, but most importantly, infuses humankind with ideas such as that of humanism, respectfulness and mutuality. Its paramount ambition is to unify all present-day businesses, stakeholders and people in charge, across the world, so as to create a legion of noble people who are passionate about efficiency; efficiency that is not only connected with purely monetary or energetic terms but efficiency that is oriented towards anthropocentricism and ecofriendliness. A flourish by the citizens, for the citizens of the world.

In order to achieve this sustainable development, humanity has to find its callings, readjust its priorities and navigate its future framework of targets with carefulness and courtesy to areas of multidimensional prosperity. Besides, our future is the present of our children, and new generations to come. Having understood mankind's modern societal duties, there are some visionaries that endeavor to suggest down-to-earth solutions that could possibly serve all the above mentioned orientations and create a legacy for the future. Marine transportation sector, by incorporating, testing and reshaping new-developed technologies, could be a protagonist in the climate change movement. Time is the only truly universal condition and everything takes time, but it has been proved that trial-and-error procedures is what propels future developments.

Taking into consideration the commands of modern societies, this diploma thesis endeavors to explore the mystical world of a newly emerged technological and commercial venture that in the last years has attracted a lot of attention; Fuel Cells. Fuel cell technologies are hydrogen-fueled electric devices that could possibly revolutionize the transportation sector. What makes FCs so special is their high efficiency, that in some cases exceeds Carnot's theoretical threshold, and close-to-zero emissions. However, their low technological maturity, lack of international regulation, as well as limited commercial availability combined with excessively high production costs are the main obstacles in the way of FCs’ expansion. Amongst others, this diploma thesis targets to shed light upon FCs’ current technological and commercial status, compare them with preexistent topologies (using a case study of a target ship which is equipped with a conventional power configuration) to finally assess their operability, economic efficiency and bring to surface their advantages and blurry points.

Motivation/Problem Statement

In terms of environmental advantages compared to other fuels or systems, the shipping industry should consider applying Hydrogen Fuel Cells (HFCs) to commercial vessels; however, there seem to be some challenging issues for progress in application of HFCs to ships, ie technical and practical problems, cost reductions and infrastructure for supplying hydrogen.

First, technical and practical problems related to HFCs on board are existing vibrations that may affect HFCs in dynamic situations which are found in transportation areas. Vibrations may contribute to exacerbating defects such as pinholes, cracks, and delamination, which lead to performance degradation and lack of durability (Ahmeda, Banana, Zua & Bazylak, 2011). Moreover, storage of hydrogen was limited on board because of the lack of space, which led to short time running.

Secondly, it is essential to deal with costs for the purpose of commodification of HFCs. It is widely accepted that specific materials incorporated into tanks or catalysts are normally expensive. This problem could be seen in the automobile industry as well. Toyota's “Mirai”, for example, costs approximately £60,000, which is around twice as much as the standard-sized cars of Toyota (Lilly, 2017). Mass production of HFCs would provide economies of scale that may lead to decrease cost; however, it has not currently become a reality. Moreover, not only capital cost of fuel cells, but also hydrogen price should be taken into account. The price would be designed to maintain the equilibrium between demand and supply; thus, it is definitely not easy to predict the price. It would depend on production cost, supply cost, market price, and demand, storage cost, distribution cost, competing, non-energy markets for biomass (Demirbas, 2017). In order to commercialize ships with HFCs, cost effectiveness is essential for the shipping industry, compared to another alternative fuels such as LNG marine fuel.

Thirdly, the supply of hydrogen could be one of the problems. At present, even if ships with HFCs are produced, they cannot be freely operated at sea because of lack of supply fuel infrastructure. However, HFCs suppliers are unwilling to pay the capital cost of hydrogen fuel stations unless demand and supply for commercial shipping with HFCs are well developed. Furthermore, shipping companies are also unwilling to invest in ships with HFCs unless hydrogen bunkering is sufficiently prepared. In order to build hydrogen fuel stations at port, enormous cost would be necessary. This means that not only one player, but also all the relevant players should make efforts to build them together.

Finally, the lack of concrete international rules and regulations about FCs and hydrogen as maritime fuel make it almost impossible for stakeholders to invest into technologies that do not have a stable legislative basis. In this context, in order to secure a feasible future for the establishment of fuel cell technology in shipping industry, IMO's, National Maritime Authorities and Classification Societies have to rise to the occasion and make progress in the procedure of lawmaking with pertinent rules, recommendations and guidelines.

Aims and Objectives

The purpose of this research is to clarify the above mentioned issues in detail, and seek for possible solutions by establishing hypotheses through a case study. In order to achieve the aim of this research, it would be essential to:

- Identify the characteristics of HFCs which can be possibly applied to commercial vessels, and discuss related technological issues, legislative and economic policies

- Summarize and discuss all the necessary information related to Hydrogen Economy and shed light to FCs' industry.

- Seek for possible solutions to introduce HFCs in the shipping industry by modelling a case study consisting of three possible hybrid scenarios and assessing their economic potential and environmental benefits; all in comparison to a conventional three Diesel-Generator configuration.

- Propose a framework of necessary advancements through pertinent recommendations, including legislative and economic issues, that fortifies FC's position in global economy.

Methodology

This research uses a quantitative approach as research method to provide deep analysis of the topic. Quantitative data are related cost from literature review or hearing provides real examples through the case study. To evaluate HFCs in an economic way, calculation of Life Cycle Cost (LCC) of HFCs is conducted. Further, as an extension to the pure economic analysis, an environmental dimension of the case study is also included. Overall, the research approach applies the following methodology:

- Research characteristics of hydrogen and FC - Identification of advantage and disadvantage, and barriers to commercialize a vessel with HFC.

- Literature review analysis – Analysis of energy and environmental policies from the United States (US), the European Union (EU) to examine how the shipping industry addresses issues related to environmental barriers and competitiveness

- Case study - Establishment of the system boundary of LCC, identification of selecting a ship and course, justification and calculation of LCC and Net Present Cost (NPC) for three alternative hybrid scenarios.

- Sensitivity analysis - Identification of how independent variable values will impact a particular dependent variable under given assumptions in terms of capital costs and hydrogen purchase price.

Limitations

The greatest limitation of all is lack of data for LCC calculation of HFCs. Collecting data regarding cost is a challenging issue since most of the data is considered as confidential information in private companies. Confidentiality becomes a barrier in this research. Moreover, LCC calculation does not consider practical problems such as limitation of space and weather conditions.

Structure of Dissertation

The research analysis and findings will be structured according to the following layout:

- **Chapter 1 – Marine Transport & Environment**

  An overview of the impact of shipping industry in human life and ecosystems.

- **Chapter 2 – An Overview of Fuel Cell Technologies**

  Historical background, principles of operation and main types of fuel cells.

- **Chapter 3 – Fuel Cells Getting On-board**

  A summary of fuel cell projects in marine industry.

- **Chapter 4 – Regulations for Fuel Cells in Shipping**

  A summary of standards and guidelines for fuel cells and hydrogen.

- **Chapter 5 – Hydrogen and Fuel Cells in Shipping**

  The emergence of hydrogen economy and its maritime potential

- **Chapter 6 – Electric Energy Analysis through a Case Study**

  Blue Star Paros and its Aegean voyages

- **Chapter 7 – Economic Analysis through a Case Study**

  Fuel cell embarkation: a pathway for a smarter, greener world

- **Appendix - Additional Information about the studied topics.**

1st CHAPTER

Marine Transport & Environment

An Overview of the Impact of Shipping Industry in Human Life & Ecosystems

"Dum Spiro, Spero." (A Latin phrase which translation interprets "As long as I breathe, I hope.)"

Marcus Cicero (106 – 43 BC).

A noble aspiration from ancient times … but what if we can't breathe the air?

Picture 1.1 We do not inherit the Earth from our ancestors; we borrow it from our children [Chief Seattle]

1.1 Introduction

In recent years, world economy has been definitely growing due to rapid population increase. **According to the United Nations (UN), the current world population of 7.6 billion is estimated to reach 8.6 billion in 2030 and 9.8 billion in 2050 [UN, 2017]**. **In accordance with over 80% of global trade by volume and more than 70% of its value being carried on board ships** and handled by seaports worldwide; hence the importance of maritime transport for trade and development is colossal. International maritime transport has been the main mode of transport for global trade over the past century and one of the cornerstones of globalization. There have been significant improvements in the efficiency of international shipping in the past couple of decades. Ever since the industry introduced containerization and ultra-large container vessels, the unit cost of maritime transport has declined substantially due to the major improvement in economies of scale. **Shipping currently contributes to approximately 2% of the total CO_2 emissions**, yet emissions from shipping are estimated to grow between 50 and 250% by 2050, which would potentially increase shipping's emissions to up to 17% of the total greenhouse gas (GHG) emissions if no measures are taken.

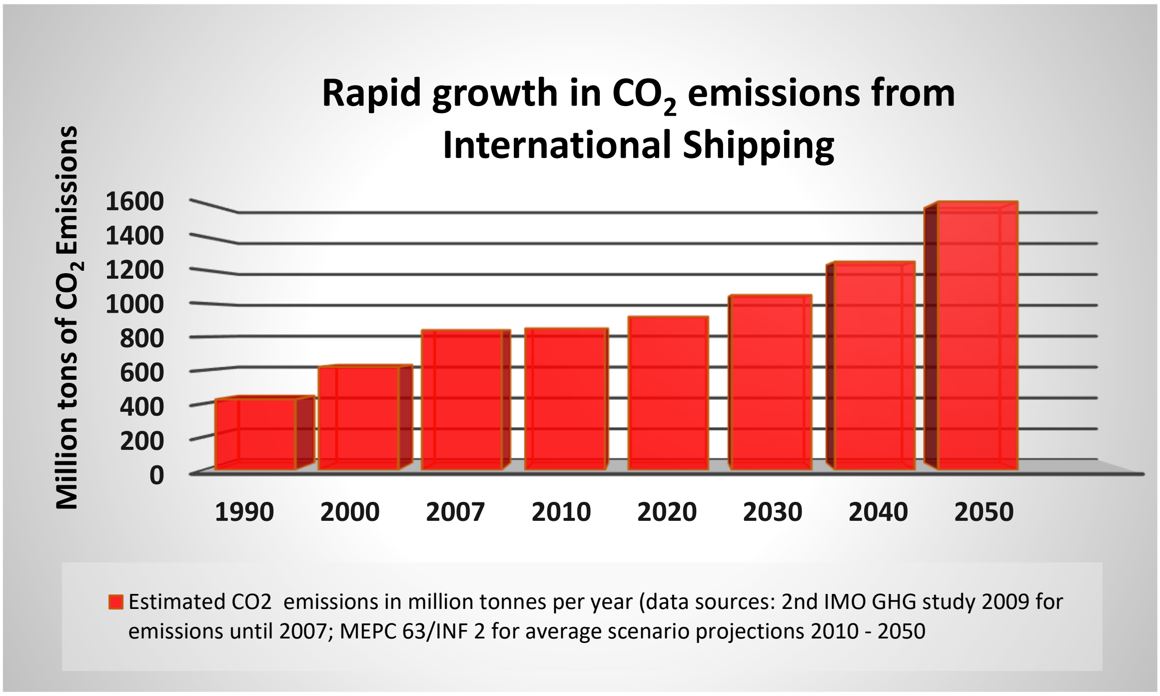


Figure 1.1 CO_2 Emissions from International Shipping [IMO, 2009]

Meanwhile, the societal pressure for the development of an eco-friendlier policy in transportation industry is currently at its zenith. Activists, non-governmental organizations and people of high status evangelize about the disastrous impacts of green-house gases on the human life and our ecosystems. There are numerous researches which highlight the unparalleled importance of establishing a great new world with complete independence in the need of fossil oils and their byproducts. A world in which great respect is attributed to every aspect of life including the flora, the fauna, their ecosystems and of course our most-valuable atmosphere.

For these reasons, it is a crucial duty for all the afflicted sectors, research community, international organizations, states, and private companies, to experiment with newly developed technologies, integrate them into their arsenal in order to identify their perks and finally realize the best possible solutions for the decarbonization of transportation sector. In times like these, dark ages for the environmental respects, **science should enlighten the world of technology with its ethics and reassure a sustainable development for the new generations to come**.

1.2 ICE's Emissions and Air Pollution

Air pollution is an issue that should be urgently addressed in the shipping industry. Pollutant emissions including NO_X and SO_X from ships might have serious impacts on human health, especially in coastal areas and port cities. To deal with these issues, innovative measures and further improvement of technologies related to energy efficiency in the shipping sector are necessary. IMO has already adopted global mandatory measures related to the reduction in GHG emissions from ships such as energy efficiency framework with a focus on Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management (SEEMP), which are considered as short-term measures in the initial Green House Gases (GHG) strategy.

The main purpose of this section is to highlight the excessively negative effects of Internal Combustion Engines (ICEs) **for both the Human Life and Ecosystems**. To succeed in this task, a brief presentation of ICEs' most noxious byproducts follows.

At present, all vehicles rely on the combustion of hydrocarbon (HC) fuels to derive the energy necessary for their propulsion. Combustion is a reaction between the fuel and the air that releases heat and combustion products. The heat is converted to mechanical power by an engine, and the combustion products are released into the atmosphere. An HC is a chemical compound with molecules made up of carbon and hydrogen atoms. Ideally, the combustion of an HC yields only carbon dioxide and water, which do not harm the environment. Indeed, green plants "digest" carbon dioxide by photosynthesis. Carbon dioxide is a necessary ingredient in vegetal life. Animals do not suffer by breathing carbon dioxide unless its concentration in air is such that oxygen is almost absent. To be realistic, the combustion of HC fuel in combustion engines is never ideal. Besides carbon dioxide and water, the combustion products contain a certain amount of nitrogen oxides (NO_X), carbon monoxides (CO), and unburned HCs, all of which are toxic to human health.

1.2.1 Nitrogen Oxides (NO_X)

Nitrogen oxides (NO_X) result from the reaction between nitrogen in the air and oxygen. Theoretically, nitrogen is an inert gas. However, the high temperatures and pressures in engines create favorable conditions for the formation of nitrogen oxides. Temperature is by far the most important parameter in nitrogen oxide formation. The most commonly found nitrogen oxide is nitric oxide (NO), although small amounts of nitric dioxide (NO_2) and traces of nitrous oxide (N_2O) are present. Once released into the atmosphere, (NO) reacts with oxygen to form (NO_2). This is later decomposed by the Sun's ultraviolet radiation back to (NO) and highly reactive oxygen atoms that attack the membranes of living cells. Nitrogen dioxide is partly responsible for smog; its brownish color makes smog visible. It also reacts with atmospheric water to form nitric acid (HNO_3), which dilutes in rain. This phenomenon is referred to as "acid rain" and is responsible for the destruction of forests in industrialized countries. Acid rain also contributes to the degradation of historical monuments made of marble.

1.2.2 Carbon Monoxide (CO)

Carbon monoxide results from the incomplete combustion of HCs due to a lack of oxygen. It is a poison to human beings and animals that inhale/breathe it. Once carbon monoxide reaches blood cells, it attaches to the hemoglobin in place of oxygen, thereby diminishing the quantity of oxygen that reaches the organs and reducing the physical and mental abilities of the affected living beings. Dizziness is the first symptom of carbon monoxide poisoning, which can rapidly lead to death. Carbon monoxide binds more strongly to hemoglobin than oxygen. The bonds are so strong that normal body functions cannot break them. People intoxicated by carbon monoxide must be treated in pressurized chambers, where the pressure makes it easier to break the carbon monoxide–hemoglobin bonds.

1.2.3 Unburned Hydrocarbons (HCs)

Unburned HCs are a result of the incomplete combustion of HCs. Depending on their nature, unburned HCs may be harmful to living beings. Some of these unburned HCs may be direct poisons or carcinogenic chemicals such as particulates, benzene, or others. Unburned HCs are also responsible for smog; the Sun's ultraviolet radiation interacts with the unburned HCs and NO in the atmosphere to form ozone and other products. Ozone is a molecule formed by three oxygen atoms. It is colorless but very dangerous and poisonous because it attacks the membranes of living cells, causing them to age prematurely or die. Toddlers, older people, and asthmatics suffer greatly from exposure to high ozone concentrations. Annually, deaths from high ozone peaks in polluted cities have been reported.

1.2.4 Other Pollutants

Impurities in fuels result in the emission of pollutants. The major impurity is sulfur, mostly found in diesel and jet fuel but also in gasoline and natural gas. The combustion of sulfur (or sulfur compounds such as hydrogen sulfide) with oxygen releases sulfur oxides (SO_X). Sulfur dioxide (SO_2) is the major product of this combustion. On contact with air, it forms sulfur trioxide, which later reacts with water to form sulfuric acid, a major component of acid rain.

It should be noted that sulfur oxide emissions originate from transportation sources but also largely from the combustion of coal in power plants and steel factories. In addition, there is debate over the exact contribution of natural sources such as volcanoes.

Petroleum companies add chemical compounds to their fuels to improve the performance or lifetime of engines. Tetraethyl lead, often referred to simply as "lead," was used to improve the knock resistance of gasoline and, thereby, produce better engine performance. However, the combustion of this chemical releases lead metal, which is responsible for a neurological disease called saturnism. Its use is now forbidden in most developed countries, and it has been replaced by other chemicals.

1.3 Global Warming

Global warming is a result of the greenhouse effect induced by the presence of carbon dioxide and other gases, such as methane, in the atmosphere. These gases trap the Sun's infrared radiation reflected from the ground, thus retaining the energy in the atmosphere and increasing the temperature. An increased Earth temperature results in major ecological damage to ecosystems and in many natural disasters that affect human populations.

Considering the ecological damage induced by global warming, the disappearance of some endangered species is a concern because this destabilizes the natural resources that feed some populations. There are also concerns about the migration of some species from warm seas to previously colder northern seas, where they can potentially destroy indigenous species and the economies that live off those species. This may be happening in the Mediterranean Sea, where barracudas from the Red Sea have been observed.

Natural disasters command our attention more than ecological disasters because of the magnitude of the damage they cause. Global warming is believed to have induced meteorological phenomena such as El Niño, which disturbs the South Pacific region and regularly causes tornadoes, floods, and droughts.

The melting of the polar icecaps, another major result of global warming, raises the sea level and can cause the permanent inundation of coastal regions and sometimes of entire countries.

1.3.1 Climate Change and the Seas

Climate change does not only affect the human life and ecosystem. As a matter of fact, climate change is warming the oceans, causing acidification of marine environments, and changing rainfall patterns. This combination of factors often exacerbates the impacts of other human pressures on the seas leading to biodiversity loss in the oceans. Here lies a graphical depiction of the impact of global warming on the marine ecosystems.

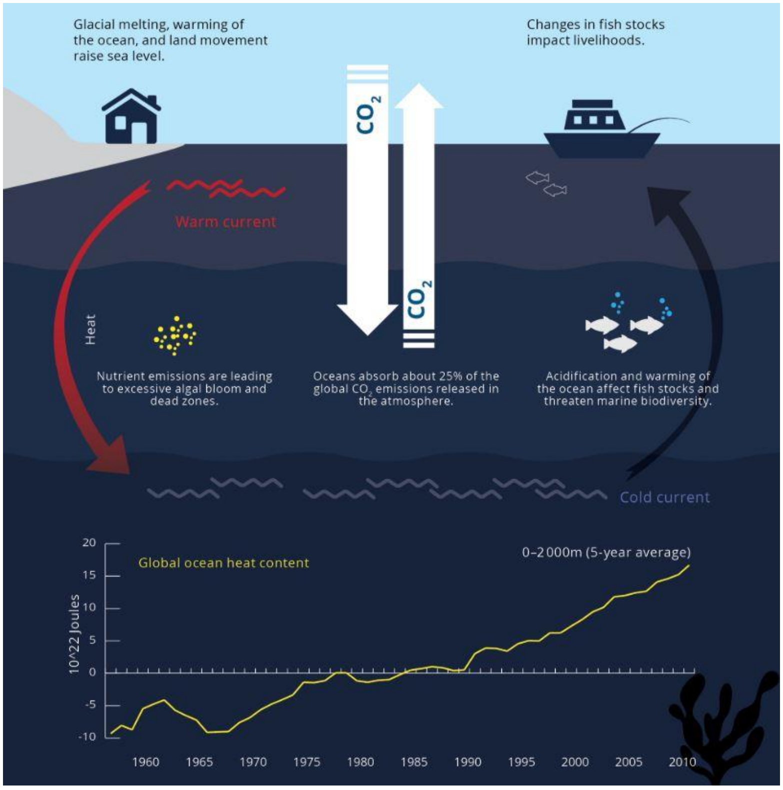


Figure 1.2 Global Warming effects on seas

To make things worse, scientists believe that climate change could possibly affect the global sea level by melting due to accelerating melting in Greenland and Antarctica. The long-held view has been that the world's seas would rise by a maximum of just under a meter by 2100. However, new studies based on expert opinions, projects that the real level may be around double that figure. In the researcher's view, if emissions continue on the current trajectory then the world's seas would be very likely to rise by between 62 cm and 238 cm by 2100. This would be in a world that had warmed by around 5 ℃ -one of the worst-case scenarios for global warming. According to the researchers, this scenario would have huge implications for the planet. They calculate that the world would lose an area of land equal to 1.79 million square kilometers – equivalent to the size of Libya.

Much of the land losses would be in important food growing areas such as the delta of the Nile. Large swathes of Bangladesh would be very difficult for people to continue to live in. Major global cities, including London, New York, Hawaii's islands, and Shanghai would be under threat. This could lead to the displacement of hundreds of millions of people and many other daisy-chain repercussions.

Picture 1.2 The southern Antarctic Peninsula shed around 56 billion tonnes of ice a year from July 2010 to April 2014.

1.3.2 Global Warming & Shipping Sector

As stated in the introduction, shipping has always been a big contributor to global warming. CO_2 is considered the largest contributor to greenhouse gases. CO_2 emission from ships is depending on the carbon content of the fuel and the fuel consumption. Therefore, the solution to reduce CO_2 emission is to switch to more efficient machinery configurations or to use alternative fuel. Today there are no good solutions to reduce CO_2 from the exhaust gas, but the industry is currently seeking improvements in this area.

1.3.2.1 Key findings from the Third IMO GHG Study 2014

[1] Shipping emissions during the period 2007–2012 and their significance relative to other anthropogenic emissions.

For the year 2012, total shipping emissions were approximately 938 million tonnes CO_2 and 961 million tonnes CO_2 for GHGs combining CO_2, CH_4 and N_2O. International shipping emissions for 2012 are estimated to be 796 million tonnes CO_2 and 816 million tonnes CO_2eq for GHGs combining CO_2, CH_4 and N_2O. International shipping accounts for approximately 2.2% and 2.1% of global CO_2 and GHG emissions on a CO_2 equivalent (CO_2eq) basis, respectively. **Table 1.1** presents the full time series of shipping CO_2 and CO_2eq emissions compared with global total CO_2 and CO_2e emissions.

For the period 2007–2012, on average, shipping accounted for approximately 3.1% of annual global CO_2 and approximately 2.8% of annual GHGs. A multi-year average estimate for all shipping totals for 2007–2012 is 1,015 million tonnes CO_2 and 1,036 million tonnes CO_2eq for GHGs combining CO_2, CH_4 and N_2O.

International shipping accounts for approximately 2.6% and 2.4% of CO_2 and GHGs on a CO2e basis, respectively. A multi-year average estimate for international shipping using bottom-up totals for 2007–2012 is 846 million tonnes CO2 and 866 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O.

These multi-year CO_2 and CO_2e comparisons are similar to, but slightly smaller than, the 3.3% and 2.7% of global CO_2 emissions reported by the Second IMO GHG Study 2009 for total shipping and international.

This study estimates multi-year (2007–2012) average annual totals of 20.9 million and 11.3 million tonnes for NO_X (as NO_2) and SO_X (as SO_2) from all shipping, respectively (corresponding to 6.3 million and 5.6 million tonnes converted to elemental weights for nitrogen and sulphur respectively). Note that NO_X and SO_X play indirect roles in tropospheric ozone formation and indirect aerosol warming at regional scales.

Annually, international shipping is estimated to produce approximately 18.6 million and 10.6 million tonnes of SO_X (as NO_2) and SO_X (as SO_2) respectively; this converts to totals of 5.6 million and 5.3 million tonnes of NO_X and and SO_X respectively (as elemental nitrogen and sulphur respectively). Global NO_X and and SO_X emissions from all shipping represent about 15% and 13% of NO_X and and SO_X from anthropogenic sources.

Table 1.1 a) Shipping CO_2 emissions compared with global CO2 (values in million tonnes CO_2) and b) Shipping GHGs (in CO_2e) compared with global GHGs (values in million tonnes CO_2e)

Third IMO GHG Study 2014 CO_2

Year	Global CO_2[1]	Total shipping	% of global	International shipping	% of global
2007	31,409	1,100	3.5%	885	2.8%
2008	32,204	1,135	3.5%	921	2.9%
2009	32,047	978	3.1%	855	2.7%
2010	33,612	915	2.7%	771	2.3%
2011	34,723	1,022	2.9%	850	2.4%
2012	35,640	938	2.6%	796	2.2%
Average	33,273	1,015	3.1%	846	2.6%

Third IMO GHG Study 2014 CO_2e

Year	Global CO_2e[2]	Total shipping	% of global	International shipping	% of global
2007	34,881	1,121	3.2%	903	2.6%
2008	35,677	1,157	3.2%	940	2.6%
2009	35,519	998	2.8%	873	2.5%
2010	37,085	935	2.5%	790	2.1%
2011	38,196	1,045	2.7%	871	2.3%
2012	39,113	961	2.5%	816	2.1%
Average	36,745	1,036	2.8%	866	2.4%

[2] Fuel Consumption and CO_2 emissions by Ship Type (2012)

Figure 1.3 presents the CO_2 emissions by ship type for 2012.

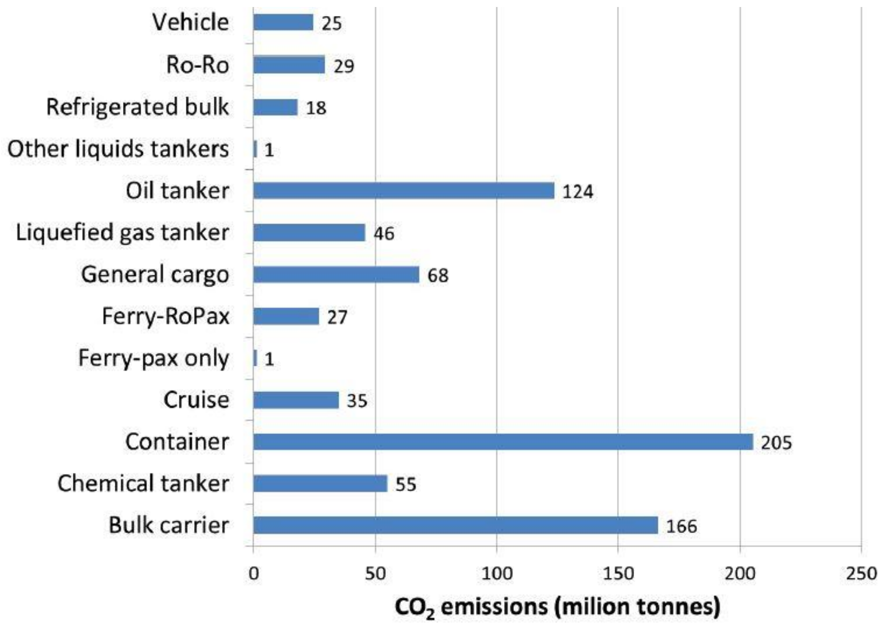


Figure 1.3 CO_2 emissions from International Shipping by ship type in 2012

Figure 1.4 shows the relative fuel consumption among vessel types in 2012 (both international and domestic shipping).

The figure also identifies the relative fuel consumption of the main engine (predominantly for propulsion purposes), auxiliary engine (normally for electricity generation) and the boilers (for steam generation). The total shipping fuel consumption is shown in 2012 to be dominated by three ship types: oil tankers, bulk carriers and container ships. In each of those ship types, the main engine consumes the majority of the fuel.

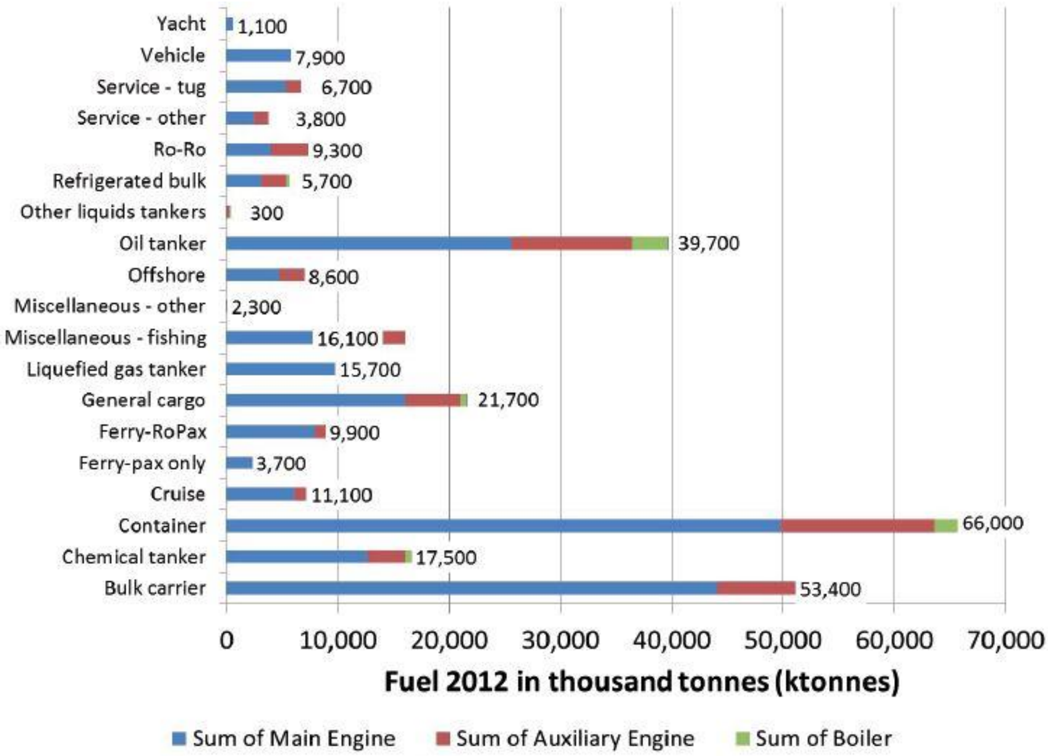


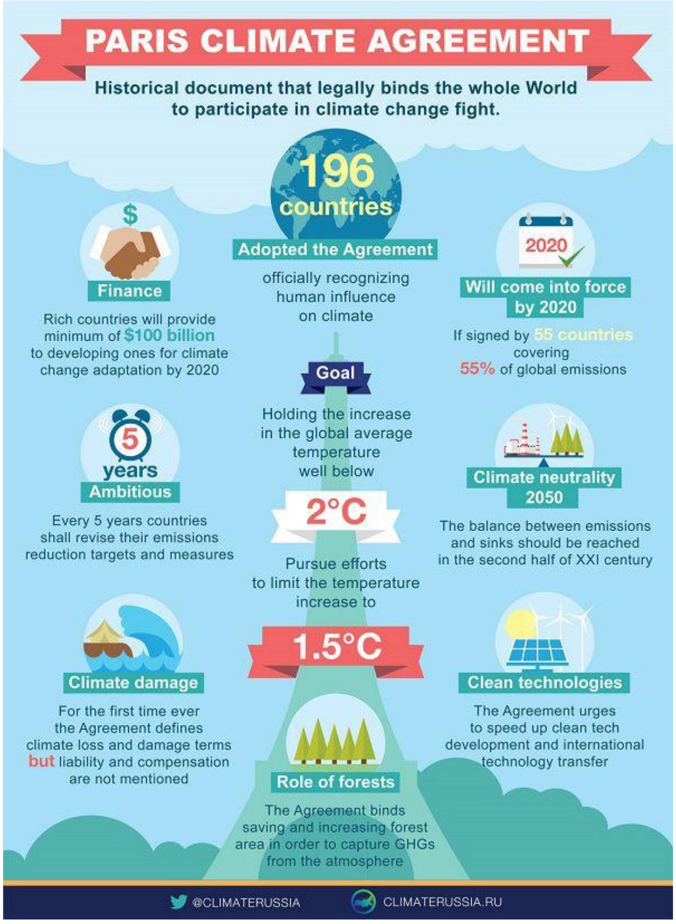
Figure 1.4 Summary graph of annual fuel consumption broken down by ship type and machinery component (main, auxiliary and boiler) in 2012

Without reference to the findings of this Third IMO GHG Study 2014, it would be extremely difficult for to demonstrate the steady and ongoing improvement in ships' energy efficiencies resulting from the global introduction of the mandatory technical and operational measures. Furthermore, the study findings demonstrate that IMO is best placed, as the competent global regulatory body, to continue to develop both an authoritative and robust greenhouse gas emissions control regime that is relevant for international shipping while also matching overall expectations for climate change abatement. **Besides, among other things, IMO's best interest should be to secure a safe and efficient shipping on clean oceans.**

1.3.2.2 Paris Climate Agreement

At a Conference of the Parties (COP), in 2015, 21 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) **adopted a landmark agreement**

(Paris Agreement) to address climate change and to require the actions and investments needed for a reduction of GHG emissions. Meanwhile, international shipping has significant impact on GHG emissions.



Picture 1.3 Paris Climate Agreement; a colossal win for the planet

As mentioned beforehand, according to the Third IMO GHG study (2014), international shipping has exhausted approximately 961 million tons of GHG emissions in 2012, which accounts for approximately 2.1% of total amounts of GHG emissions on a CO2 equivalent (CO2eq) basis in the world, respectively (IMO, 2014). The possible increase of shipping emissions becomes a concern under the context of global sustainable development.

This concern is well described in Bows-Larkin et. al. (2015); **Figure 1.5** shows a chart from this study that compares the shipping emissions scenarios from Smith et. al. (2015) with four Representative Concentration Pathways (RCPs). As explained in Bows-Larkin et. al. (2015), each pathway has been estimated so that it corresponds to a different climate outcome; for example, RCP2.6 pathway has an estimated $0.9 - 2.3℃$ of warming by 2100, while on the other side RCP8.5 has an estimated $3.2 - 5.4℃$.

Moreover, each shipping emissions scenario is defined by two major parameters; the first concerns the utilization of LNG (high or low usage) and other alternative fuels in marine industry while the second processes the opportunity for the IMO to establish more ECA's or to stay consistent with the current regulations. **The main conclusion was that none of the anticipated shipping scenarios is close to the pathway RCP2.6 which ensures a**

proportionate contribution for shipping to avoid 2℃ of warming. Therefore, the sustainability of the shipping system has become very important in order to bridge this gap, which highlights the need to investigate new policy and technology solutions, particularly in the mid-to-long term, after 2020.

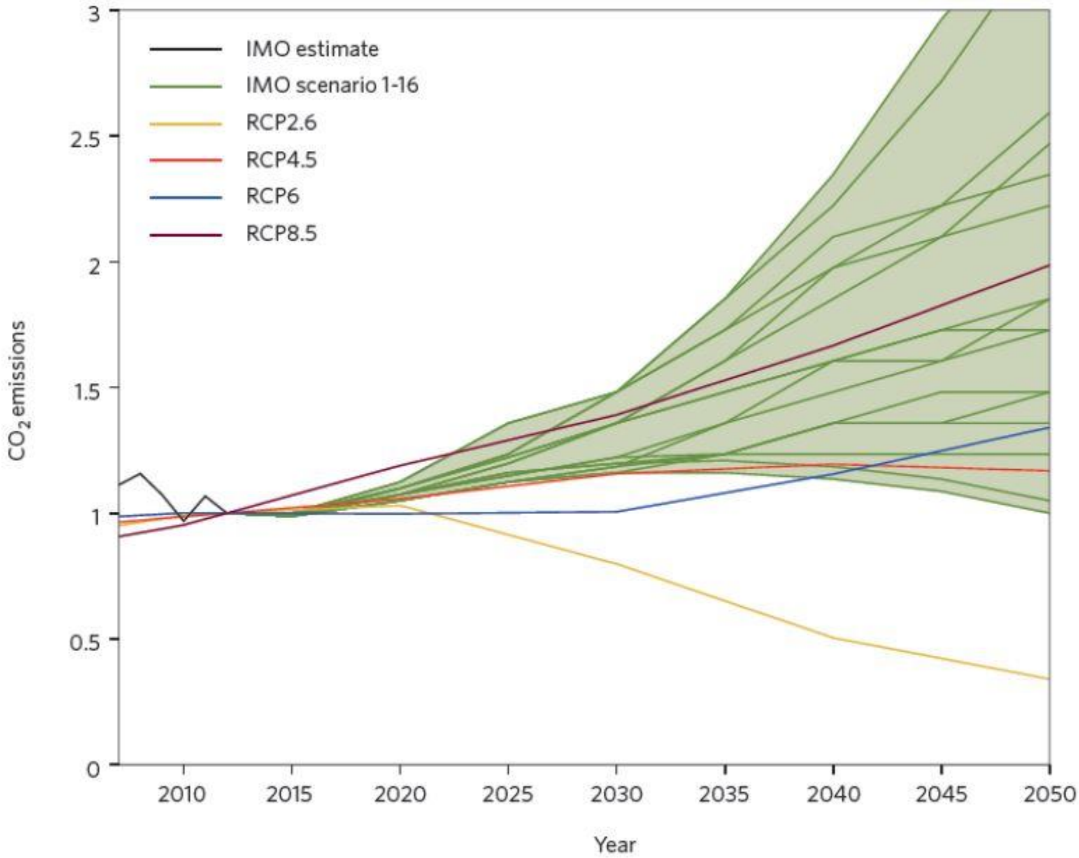


Figure 1.5 Comparison of 16 GHG scenarios from the IMO and the RCP marker scenarios for a range of climate outcomes. All scenarios are indexed to 2012 emissions (CO_2 emissions in Mton). [Bows Larkin et. al., 2015]

In the context of current situation and Paris Agreement, the Marine Environment Protection Committee (MEPC) of IMO has established an initial strategy that provides possible measures for reduction of CO_2 appropriate to timelines at MEPC 72, in accordance with a roadmap approved by IMO member States [IMO, 2018a].

The current IMO GHG reduction roadmap indicates a decision-making process that is sluggish in implementing the necessary measures and regulations.

An important milestone of the roadmap is the adoption of a strategy to reduce GHG emissions, including a level of ambition and candidate short-, medium-, and long-term measures, which were announced at the 72nd IMO Marine Environment Protection Committee (MEPC) meeting in April 2018. The strategy mandates a reduction in total annual GHG emissions from shipping by at least 50% by 2050 compared to the 2008 level while pursuing efforts towards phasing them out entirely.

The strategy also includes a reference to "a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals". The initial strategy will be revised in 2023 and reviewed again 5 years thereafter.

However, decarbonization of international shipping has progressed rather slowly due to fragmented and diverse ambitions and interests of stakeholders in the sector. Until recently, debates at the IMO were characterized by major disagreement as to how and whether the sector should align to the goals of the Paris Agreement.

How the regulatory framework will evolve will be very important in view of creating new incentives towards the decarbonisation of the shipping industry. The IMO appears to lead on this topic, although regional regulations on efficiency and air pollution from ships are also becoming tighter.

1.4 Environmental Legislation

Traditionally, large ships have relied on Heavy Fuel Oil (HFO) as a cost-efficient fuel that also provides high energy efficiency from a well-to-propeller perspective. However, HFO has a high sulfur content and impurities, which lead to emissions of sulfur oxide (SOx), nitrogen oxide (NOx) and particulates that have negative impacts on both human health and the environment.

This has motivated the International Maritime Organization to regulate sulfur and nitrogen emissions from shipping in North America and the Caribbean, and in the Baltic and North Seas through emission control areas (ECAs).

This chapter offers an overview of international and regional regulations, which are helping to drive the adoption of low-emissions fuels in the shipping industry

1.4.1 International Requirements

In recent years the rules and regulations for emission have become stricter due to more focus on global warming and the damaging impact on the environment and human health. The International Maritime Organization (IMO) was established in Geneva 1948. The main focus of the convention is to regulate the shipping industry. In 1973 IMO adopted The International Convention for the Preventing of Pollution from Ships (MARPOL), and is now the main regulatory mechanism for controlling marine pollution.

MARPOL regulates pollution by oil, chemicals, harmful substances in packaged form, sewage and garbage.

Today the convention regulates the following topics:

- **Annex I**
  Regulations for the Prevention of Pollution by Oil
- **Annex** II
  Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk
- **Annex III**
  Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form
- **Annex IV**
  Prevention of Pollution by Sewage from Ships
- **Annex V**
  Prevention of Pollution by Garbage from Ships
- **Annex VI**
  Prevention of Air Pollution from Ships

1.4.1.1 MARPOL ANNEX VI

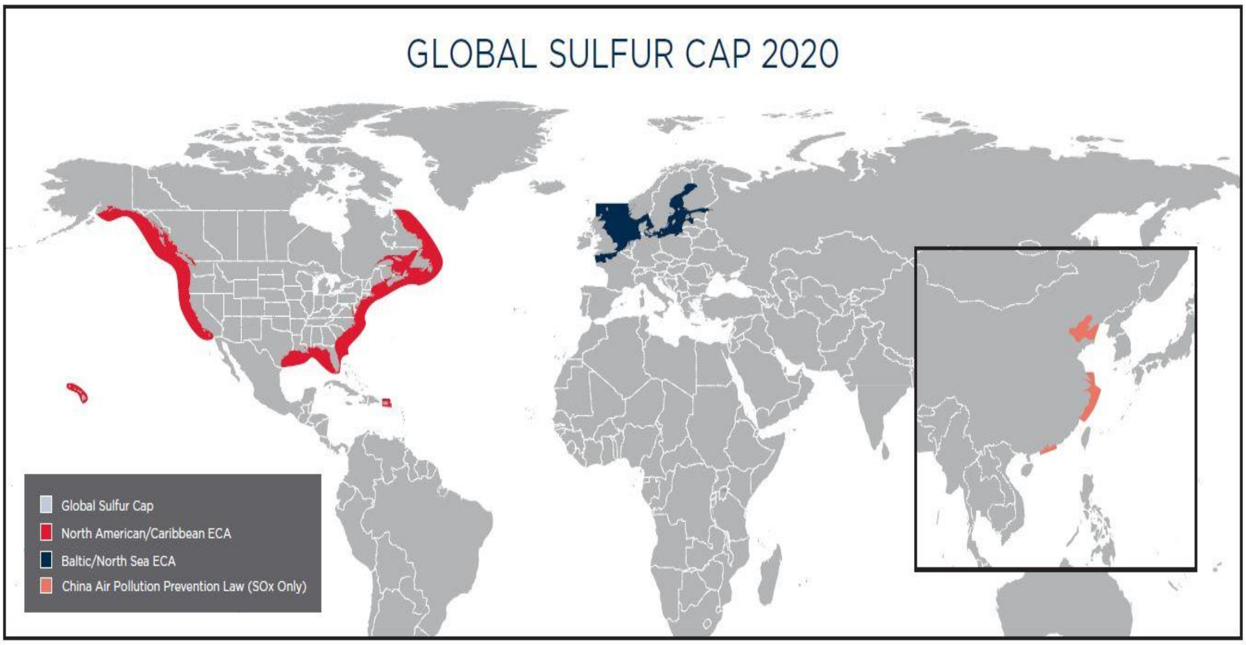
The MARPOL Annex VI (took effect on 19 May 2005) is the main regulator for emission to air. It represents worldwide acknowledgement that harmful emissions from ships should be decreased as the ability to do so develops. The Annex VI establishes limits for NO_X from marine diesel engines of more than 130 kW output, dependent on engine mean rotational speed and the ship construction date (keel-laid date of the ship). The keel-laid date determines if a vessel is beholden to Tier I, II or III:

- **Tier I** – Ships keel laid from 1 January 2000 to 1 January 2011
- **Tier II** – maximum NO_2 emission of 14,4 g/kWh for engine speed less than 130 rpm and 7,7 g/kWh for engine speed of 2000 rpm or above. - Ships keel laid on or after 1 January 2011
- **Tier III** – 3,4 g/kWh for engines speed of less than 130 rpm & 2 g/kWh for engines speed of 2000 rpm or more – Ships keel laid after 1 January 2016 operating in the North American Emission Control Area or the United States Caribbean Sea Emission Control Area.

IMO's Marine Environment Protection Committee (MEPC) 58th session in October 2008, adopted a Revised MARPOL Annex VI – Resolution MEPC.176(58), applicable from 1 July 2010. The revisions adopted include progressive reductions of SOX emissions from ships, progressive reductions of NOX emissions from marine engines and revised criteria for ECAS**.** As a result of the IMO's Marine Environment Protection Committee meeting held in October 2016 [MEPC 70] **a marine fuel sulfur cap of 0.50% effective 1 January of 2020 was confirmed**. Under this global sulfur limit, ships will have to use marine fuels with a sulfur content of no more than $0.50\ \%$ **(the current limit is $3,5\%$)** unless using approved equivalent methods under regulation 4.1. of MARPOL Annex VI, such as an Exhaust Gas Cleaning System (EGCS).

In 2013 amendments of the Annex VI were adopted by Parties to MARPOL Annex VI represented in the Marine Environment Protection Committee (MEPC), which se mandatory measures to reduce emissions of GHG in international shipping. The new chapter 4 of Annex VI made it mandatory for new ships to respect the limit imposed of an Energy Efficiency Design Index **(EEDI)**, and all ship were rewired to follow the Ship Energy Efficiency Management Plan **(SEEMP)** [IMO, 2015].

According to International Chamber of Shipping (2009), **the EEDI should lead to about a 25% - 30% reduction in emissions by 2030 compared to business-as-usual', and the SEEMP, instead, should ensure the monitoring and the improvement of several factors that can contribute to CO2 emissions**



Picture 1.4 Global Sulfur Cap 2020 [ABS, 2018]

Furthermore, in the MEPC 72th session in April 2018, the committee approved amendments to regulation 14 of MARPOL Annex VI and the form of the Supplement to the IAPP Certificate (International Association of Privacy Professionals) concerning the prohibition of the carriage of non-compliant fuel oil for combustion purposes with a sulfur content exceeding 0.50%. This action was taken with a view to adoption at MEPC 73. Exemptions for ships equipped with an equivalent arrangement were also approved

The Resolution provides controls specific to operation inside ECAs established to limit the emission of SOx and particulate matter (SECAs) and those applicable outside such areas and are primarily achieved by limiting the maximum sulfur content of the fuel oils used onboard. These fuel oil sulfur limits (expressed in terms of % m/m, that is by weight) are subject to a series of step changes over the years.

Table 1.2 MARPOL Annex VI, Regulation 14 – Global Sox Compliance Date & Limits

Compliance Date	Sulfur Limit in Fuel (% m/m)
1 January 2000	4.5 %
1 July 2012	3.5 &
1 January 2020	0.50 %

The relevant NO_X emissions for each tier level as well as the present and future limits for sulfur content, SO_X of marine fuel are shown in Figure 1.6 and Figure 1.7 respectively.

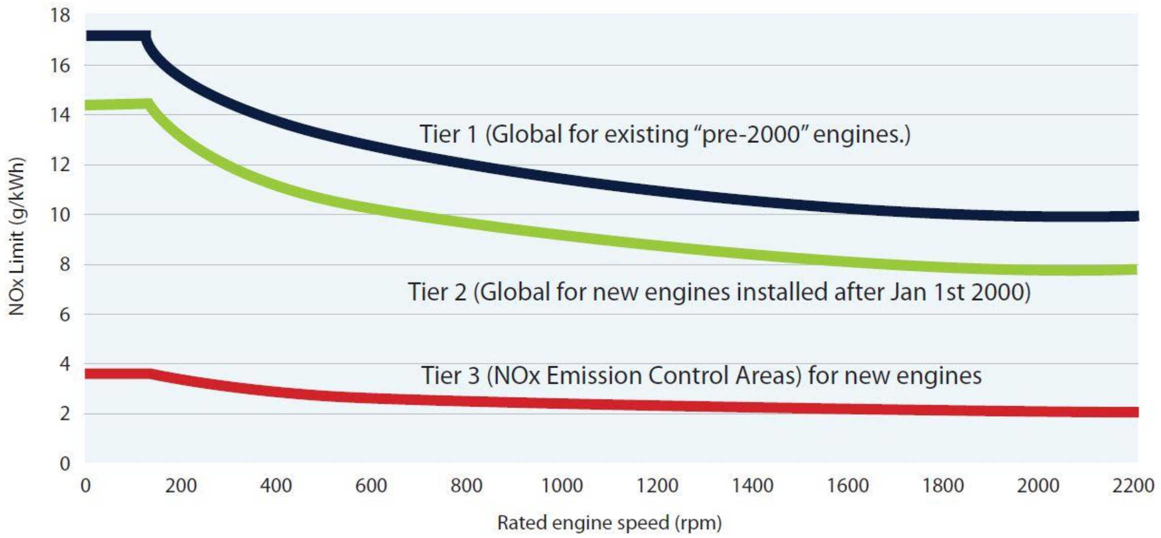


Figure 1.6 Regulations for NOx emissions for new-build ships in ECAs [ABS, 2018]

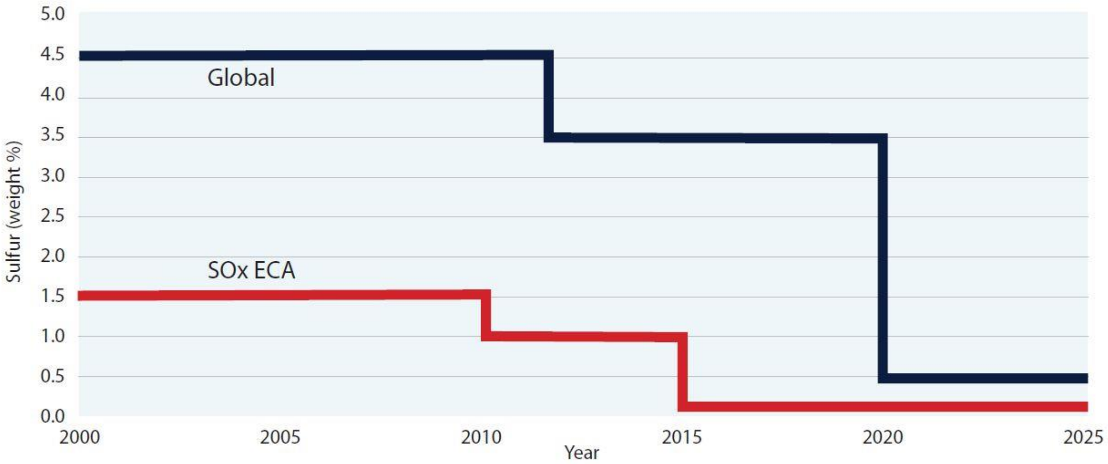


Figure 1.7 Present and future limits for sulfur content of marine fuel [ABS, 2018]

1.4.2 Emissions Control Areas (ECAs and SECAs)

The emission control areas (ECAs) are mandated by the International Maritime Organization (IMO) to regulate both sulfur oxide and nitrogen oxide emissions.

Regulation 14 of Annex VI contains provisions for nations to apply to the IMO for designation of special areas to further reduce harmful emissions from ships operating in their coastal waters. The first two ECAs approved by the IMO, known as SECAs, were the Baltic Sea and the North Sea (including the English Channel), as shown in Picture 1.5. The IMO then approved two more ECAs: US Caribbean Sea and The North American, as shown in Picture 1.6 and Picture 1.7 respectively. These ECAs include SOx emissions restrictions in addition to NOx Tier III emission restrictions. NOx Tier III emissions restriction was enforced from 1 January 2016 in these two ECAs.

During MEPC 71, the IMO adopted Resolution MEPC.286(71), amendments to MARPOL Annex VI, introducing two new NOx Emission Control Areas (ECAs). These two new NOx ECAs which were previously known as SECAs – the Baltic Sea and the North Sea – will be enforced for ships constructed (keel laying) on or after 1 January 2021, or existing ships which replace an engine with "non-identical" engines, or install an "additional" engine on or after that date.

Table 1.3 MARPOL Annex VI, Regulation 14 – Emission Control Areas

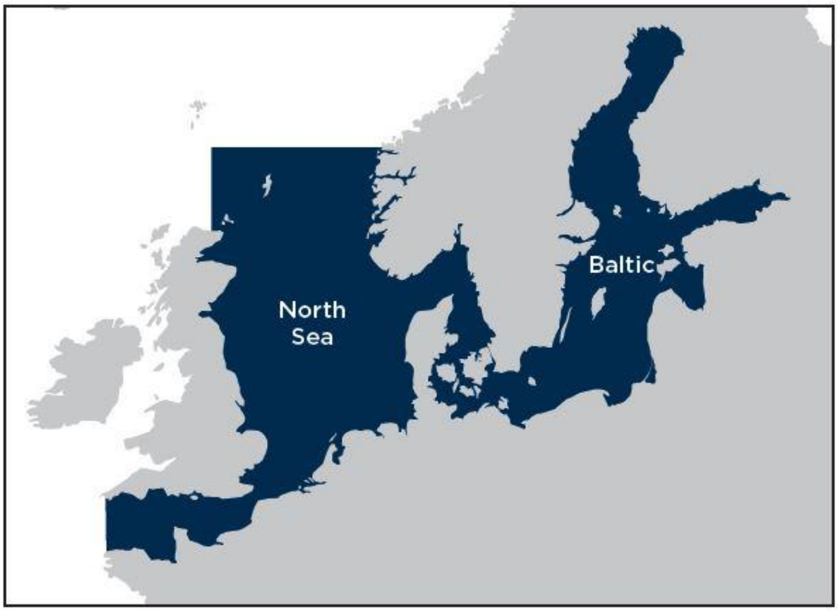
Compliance Date	ECAs - Sulfur Limit in Fuel (% m/m)
1 January 2000	1.5 %
1 July 2012	1.0 &
1 January 2020	0.10 %

The IMO Annex VI regulation 14, Special Areas are identified in Table 1.4.

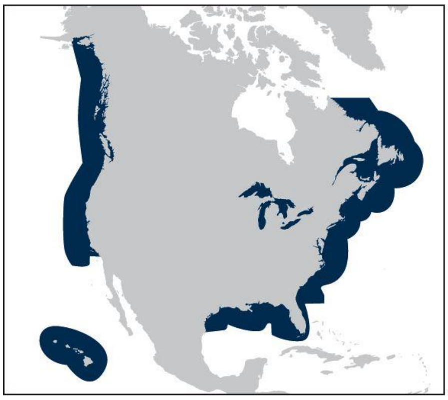
Table 1.4 Annex VI Prevention of Air Pollution by Ships (ECAs)

Annex VI Special Area	Adopted	Entry into Force Date	Effective Date
Baltic Sea (SOx)	26 September 1997	19 May 2005	19 May 2006
North Sea (SOx)	22 July 2005 (Resolution MEPC.132(53))	22 November 2006	22 May 2007
North American (SOx and PM)	26 March 2010 (Resoluton MEPC.190(60))	1 August 2011	1 August 2012
US Caribbean Sea (SOx and PM)	15 July 2011 (Resolution MEPC.202(62))	1 January 2013	1 January 2014

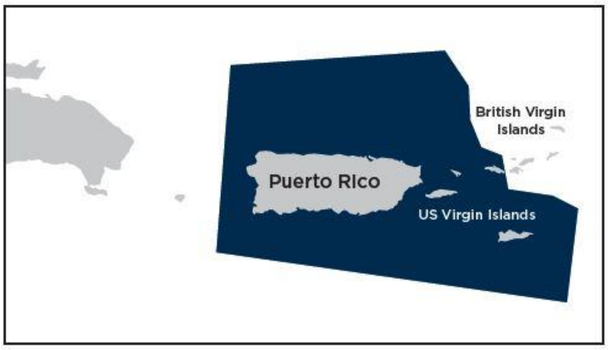
It should be noted that MARPOL Annex VI does not specifically limit PM but PM is reduced by regulating the sulfate portion of PM formation through the fuel sulfur content requirements of Regulation 14 to Annex VI.



Picture 1.5 Baltic and North Sea/ English Channel ECA



Picture 1.7 The North American ECA 200 Nautical miles offshore US and Canada, including Hawaii, St. Lawrence Waterway and the Great Lakes



Picture 1.6 The United States Caribbean Sea ECA

Beginning 1 January 2015, ships that operate in an ECA are required to use low sulfur fuel with a sulfur content no greater than 0.10%. To meet these requirements, vessels must use distillate fuel (e.g. MGO) or 0.10% Heavy Fuel Oil. Alternatively, ships can use higher sulfur HFO if operating with an approved exhaust gas cleaning system (EGCS) also known as a scrubber.

To satisfy the lower 0.10% sulfur content in ECA's, some vessels switch to lower sulfur fuels as the approach the area. In such cases, the ship shall carry on board a written procedure showing how the fuel oil changeover is to be accomplished, ensuring sufficient time will be allotted for the fuel system to be flushed of all noncompliant fuel prior to entering the ECA. The date, time and place of the fuel changeover and the volume of low sulfur fuel in each tank shall be logged when entering and leaving the ECA. The crew must be trained to carry out the fuel management and fuel switching procedure

1.4.3 European Framework about GHGs

The reduction of Green House Gasses is also high on the agenda of the European Commission. **The headline targets of the Europe 2020 strategy for smart, sustainable and inclusive growth are:**

- 20% improvement in energy efficiency
- 20% of EU energy from renewables
- 20% cut in greenhouse gas emissions (from 1990 levels)

The EU Emissions Trading System (ETS) is the EU's key tool for cutting greenhouse gas emissions from large-scale facilities in the power and industry sectors, as well as the aviation sector. Although transport and shipping are a non ETS sector, the EU member states also committed themselves to reduce greenhouse gas emissions for non ETS sectors in 2020 compared to 2005 levels. For example, in The Netherlands the required reduction for 2020 is 16%.

In July 2016 the European Commission presented a legislative proposal called the "Effort Sharing Regulation" setting out binding annual greenhouse gas emission targets for EU member states for the period 2021-2030 based on the principles of fairness, cost-effectiveness and environmental integrity.

Sectors of the economy not covered by the EU ETS are required to reduce emissions 30% by 2030 compared to 2005 as their contribution to the overall target. For the Netherlands the non ETS sectors (including transport and shipping) have a target of reducing greenhouse gas emissions with 36% in 2030 compared to 2005 levels.

The Commission's 2011 White Paper on transport suggests that the EU's CO_2 emissions from maritime transport should be cut by at least 40% from 2005 levels by 2050, and if feasible by 50% [European Commission, 2011]

Although international shipping is not covered by the EU's current emissions reduction targets, the Dutch maritime sector feels obliged to comply with these targets and present itself as a modern and sustainable industry sector.

1.5 Discussion

Many ship operators with present-day propulsion plants and marine fuels cannot meet IMO's new regulations without installing expensive exhaust after-treatment equipment or switching to low-sulfur diesel, low-sulfur residual, or alternative fuels with properties that reduce engine emissions below mandated limits, all of which impact bottom-line profits. **The impact of these new national and international regulations on the shipping industries worldwide has brought alternative fuels to the forefront as a means for achieving compliance**. The alternative fuels industry has grown dramatically for both liquid and gaseous fuels. Each of these alternative fuels has advantages and disadvantages from the standpoint of the shipping industry. It is vitally important that the nations recognize the impact that the new marine regulations will have on their marine industries and implement policies that will minimize these impacts and pave the way for smooth transitions to use of alternative marine fuels and operating procedures that will meet GHG and emissions limits without jeopardizing international maritime trade.

To deal with these issues, innovative measures and further improvement of technologies related to energy efficiency in the shipping sector are necessary. IMO has already adopted global mandatory measures related to the reduction in GHG emissions from ships such as energy efficiency framework with a focus on EEDI and SEEMP, which are considered as short-term measures in the initial GHG strategy. However, these measures might not reach at the ambitious goals in the strategy to reduce CO_2 emissions in shipping by at least 40% by 2030, seeking efforts towards 70% by 2050, compared to 2008. Moreover, in order to address air pollution, governments and private sectors have recently made efforts to introduce alternative fuel; LNG as marine fuel; however, combustion of LNG provides the reduction of CO_2 by less 20%. Although the introduction of LNG gives significant effects on air pollution, it could not be one of an effective solution for GHG reduction

Hydrogen would be one of the solutions as alternative marine fuel. Hydrogen fuel, compared to heavy oil fuel, is environmentally-friendly, which produces zero emission because it wastes only clean water. It reacts with oxygen gas within a cell that converts chemical potential energy into electrical energy. **The system is widely called HFCs which can generate low-carbon heat and electricity while avoiding environmental impacts faced by other low-carbon technologies**. Technology maturity and commercial viability of HFCs are enough, and the level of technologies is continuously improving for many applications.

For instance, as for transport sectors, HFCs have been already being used in many applications such as cars, forklifts, emergency backup systems and light-duty trucks, among others. Currently, for example, two type of hydrogen powered fuel cells electric vehicle models have already been commercialized - Hyundai's ix35 fuel cell and the Toyota “Mirai” - though these will be joined by Honda's Clarity Fuel Cell later in 2017. However, even though FC technology is used as maritime application in the offshore vessel, Viking Lady, hydrogen is not utilized as marine fuel**. Fuel cells as a main propulsion system could be a possibility for new ships as they can be used in combination with a reformer with a number of hydrocarbons such as LNG and methanol**. However, their environmental benefits could be higher when they are used in combination with hydrogen The development of such technology is still at an early stage for maritime applications, but there already exist prototypes of auxiliary power unit (APUs) operating on board ships. The investigation on further technological developments is an important factor that will influence the way future ships are developed. **The uptake of hydrogen as fuel for shipping will also depend on such developments**

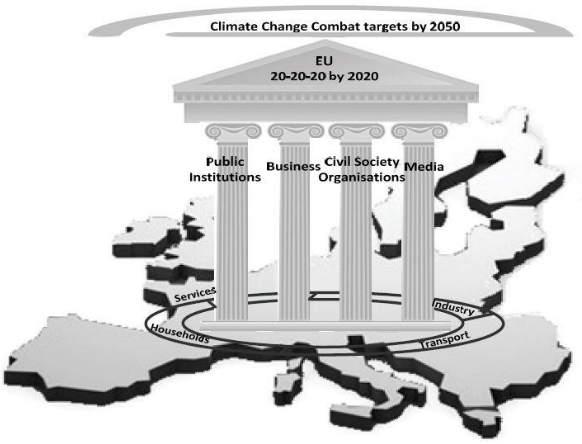


Figure 1.8 Main Pillars of implementing an environmental friendly and efficiency energy policy amongst E

2nd CHAPTER

An Overview of Fuel Cell Technologies

Historical Background, Principles of Operation & Main Types

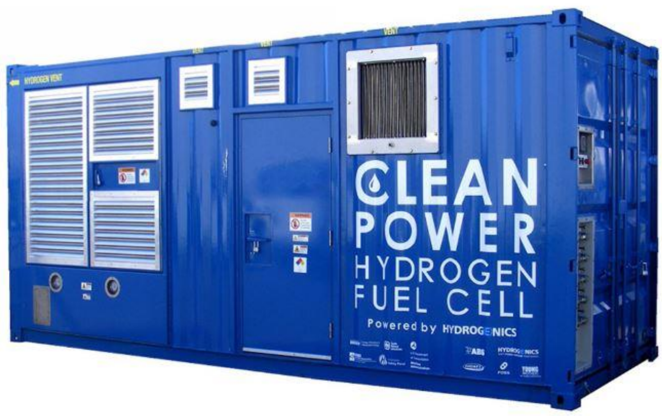
-Yes, but water decomposed into its primitive elements, *replied Cyrus Harding*, and decomposed doubtless, by electricity, which will then have become a powerful and manageable force, for all great discoveries, by some inexplicable laws, appear to agree and become complete at the same time.

Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable … I believe, then, that when the deposits of coal are exhausted we shall heat and warm ourselves with water. **Water will be the coal of the future**.

-I would like to see that*, observed the sailor*.

- You were born too soon, Pencroft*, returned Neb.*

From the Mysterious Island, Jules Verne, 1874



Picture 2.8 **Fuel Cell Module Powered by Hydrogenics**

2.1 Introduction

Fuel cell technologies have seen a revival in recent years, due to several reasons. Global warming and local air pollution caused by various energy utilization processes have created a multitude of environmental concerns, promoting the development of novel technologies with high conversion efficiencies and low emissions, possibly zero emission, with respect to greenhouse gases and other. Peak oil is another reason for the renewed interest in fuel cell technologies, in particular for automotive applications. Although this fact is discussed in a highly controversial manner, limitation in crude oil supply is obvious in the long-term perspective. This particular aspect of fossil fuel resources is strongly interlinked to the future perspective of the “oil price” and, hence, its economic competitiveness to other fuels, e.g., fuels from renewable sources. Further, the geographical distribution of oil reserves causes concerns about the supply security in industrial centers around the world.

In this context, **the installation of new supply infrastructures for alternative fuels, e.g., H_2 is an important additional economic and political factor**. Dedicated analysis has clearly shown that energy conversion in fuel cells has to be based on fuels, in particular hydrogen, derived from renewable sources. Apart from hydrogen, which is the ideal fuel for fuel cells, LNG, methane, methanol, ethanol and sulphur-free diesel are possible options. **We have come a long way, and still have a long but rewarding path ahead of us until these fuels are in widespread use in shipping.**

Overall, there exist several reasons to ask for novel efficient conversion technologies for mobility (electromobility) and combined heat and power systems (CHP) with independence on fossil fuels, in particular crude oil. **Another area of interest in fuel cell technology is portable electric and electronic applications**, where the argument of potentially higher energy density as compared to today’s available battery technologies, hence, longer time of operation, is of prime interest.

As will be mentioned further down, the use of the fuel cell as an electricity generator was invented by William Grove in 1842 [Vie stich et al., 2001]. Due to the success and efficiency of combustion engines, fuel cells have not been widely considered for general use, and, until recently, fuel cells have been applied only for special purposes, such as space exploration and submarines.

However, **rising and fluctuating fuel prices and a strong focus on reduction of global and local emissions have led to an increasing focus on the development of fuel cells** for application in other areas as well. **Market studies** [Fuel Cell Today, 2013] have revealed that **fuel cells should no longer be considered as a technology for the future; they are already commercially available today for a diverse range of applications** (e.g. portable electronics, power plants for residential use, and uninterruptible power supply). During 2014 and 2015 the stationary fuel cell sector became overall substantially more sustainable, with a broader range of fuel cell system suppliers, increasing growth capital flowing to the sector, price drops across the board and an increase in the number of companies with overall annual revenue above $100 million. When looking at the maritime industry in particular, as this current report discloses; a wide range of maritime fuel cell projects are ongoing, and the application of the fuel cell in commercial shipping projects is increasing.

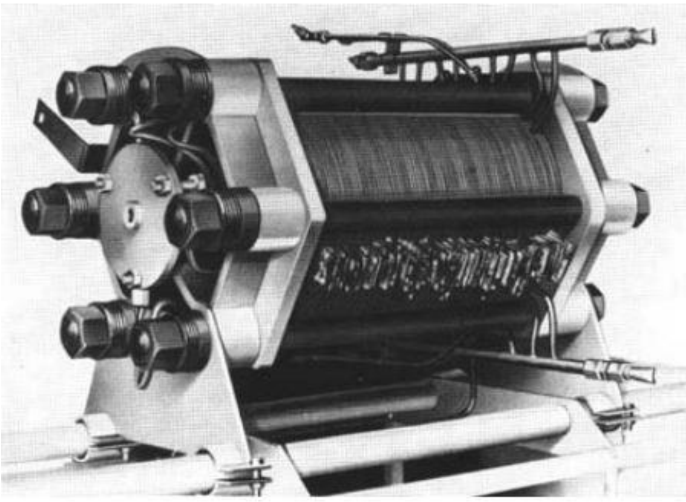
FCs are efficient energy converters, based on electrochemical principles. They convert the chemical energy (heating value) of a fuel directly into electricity, circumventing the various steps of thermal conversion and electricity generation. Fuel cells can be designed and constructed on the basis of a multitude of material combinations for electrolyte and electrodes, opening the choice of different fuels. The electro - catalytic reactions of fuel and oxygen are major challenges to obtain high conversion efficiency. The electrochemical basics of different fuel cell types considered today for technical applications are described in this contribution.

The Hydrogen and FC technology if developed appropriately can surpass the conventional fossil fuels and revolutionize the transportation section. When managed rigorously, this combination can be the epitome of a Sustainable Marine Development in a prosperous and environmentally relieved world.

This chapter provides a comprehensive review of fuel cell science and engineering with a focus on hydrogen fuel cells in marine applications. It provides a concise, up-to-date review of fuel cell fundamentals; history; competing technologies; types; advantages and challenges.

2.2 The History of Fuel Cells

Research and development that eventually led to a functional fuel cell goes back to the early 1800s. Sir William Grove, a chemist and patent lawyer, is broadly considered to be the father of fuel cell science due to his famous water electrolyzer / fuel cell experimental demonstration. Sir William Grove used his background of electrolysis to conceptualize a reverse process that could be used to generate electricity. Based on this hypothesis, Grove succeeded in building a device that combines hydrogen and oxygen to produce electricity (instead of separating them using electricity). The device, originally labeled a gas battery, came to be known as a fuel cell. Further research continued into the twentieth century. In 1959, Francis Thomas Bacon, an English engineer, demonstrated the first fully-operational fuel cell. His work was impressive enough to get licensed and adopted by NASA. PEMFCs and Alkaline Fuel Cells (AFCs), in particular, were practically used by NASA in the 1960s as part of the Gemini and Apollo manned space programs. The NASA fuel cells were customized, non-commercial, experienced several malfunctions, and used pure oxygen and hydrogen as an oxidant and fuel, respectively.



Picture 2.9 Francis Bacon's Fuel Cell

Fuel cells nowadays; however, are used in transportation, stationary, and portable applications; are gradually being adopted by the public and private sectors; are becoming more reliable and durable for long-term operation; and can function using air and reformation-based hydrogen as an oxidant and fuel, respectively. Table 2.5 highlights the main milestones in the history of fuel cells.

Table 2.5 Milestones in Fuel Cell History

Period	Milestone
1839	W.R. Grove and C.F. Schoenbe in separately demonstrate the principals of a hydrogen fuel cell
1889	L. Mond and C. Langer develop porous electrodes, identify carbon monoxide poisoning, and generate hydrogen from coal
1893	F.W. Ostwald describes the functions of different components and explains the fundamental electrochemistry of fuel cells
1896	W.W. Jacques builds the first fuel cell with a practical application
1933 - 1959	F.T. Bacon develops Alkaline Fuel Cell (AFC) technology
1937 - 1939	E. Baur and H. Preis develop Solid Oxide Fuel Cell (SOFC) technology
1950	Teflon is used with platinum/acid and carbon/alkaline fuel cells
1955 - 1958	T. Grubb and L. Niedrach develop Proton Exchange Fuel Cell (PEMFC) technology at General Electric
1958 - 1961	G.H.J. Brothers and J.A.A. Ketelaar develop Molten Carbonate Fuel Cell technology
1960	NASA uses AFC technology based on Bacon's work in its Apollo space program
1961	G.V. Elmore and H.A Tanner experiment with and develop of Phosphoric Acid Fuel Cell (PAFC) technology
1962 - 1966	The PEMFC developed by General Electric is used in NASA's Gemini space program
1968	DuPont introduces Nafion
1992	Jet Propulsion Laboratory develops Direct Methanol Fuel Cells (DMFC) technology
1990s	Worldwide extensive research on all fuel cell types with a focus on PEMFCs
2000s	Early commercialization of fuel cells

2.3 Fuel Cell Markets & Annual Growth

Fuel cells hold promising potential to become competitive players in a number of markets due to their broad range of applications. And as a result of their high modularity, wide power range, and variation of properties among different types, fuel cells have applications ranging from scooters to large cogeneration power plants as fuel cells can theoretically be used for any energy-demanding application. Efforts towards the commercialization of fuel cells in the portable electronics, stationary power generation, and transportation sectors are well underway. In fact, worldwide shipments of fuel cells increased by 214% between the years 2008 and 2011 with fuel cells becoming an emerging competitor in the back-up power for telecommunication networks market, material handling market, and the airport ground support equipment market.

The global fuel cell industry market is expected to reach $19.2 billion by the year 2020 with the United States, Japan, Germany, South Korea, and Canada acting as the flagship countries in the development and commercialization of fuel cells.

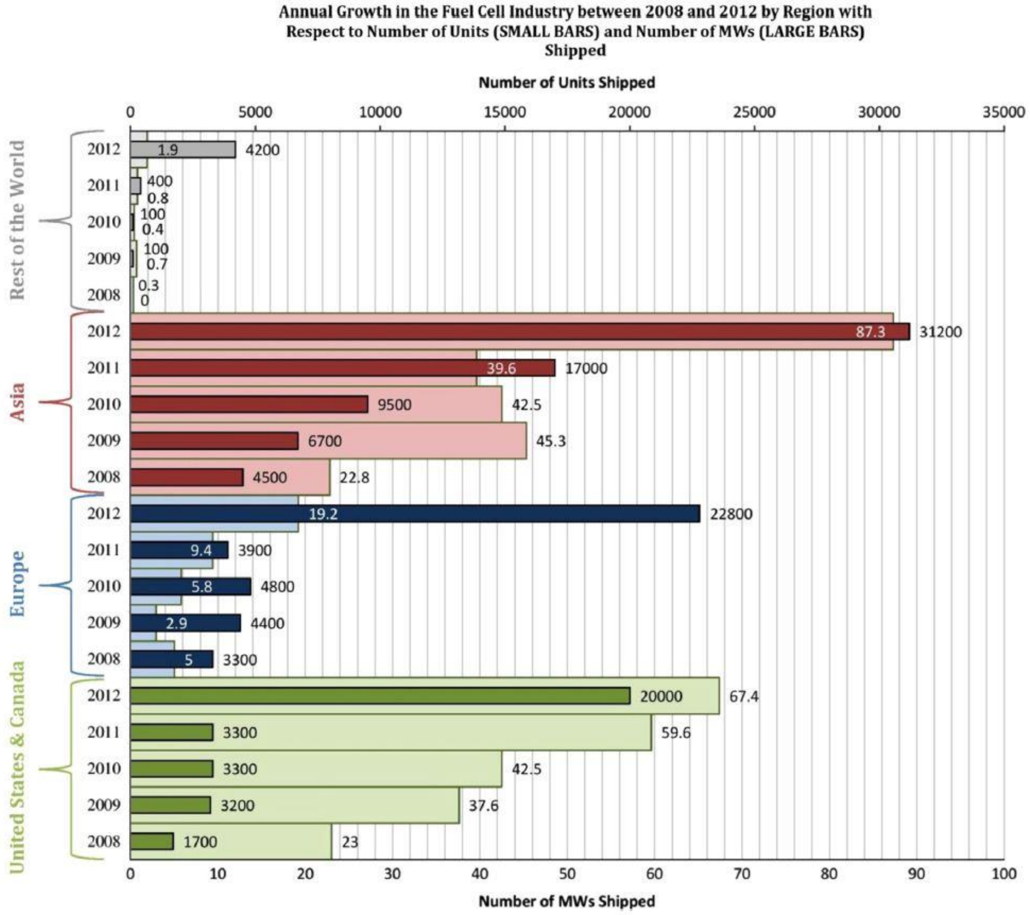


Figure 2.9 **Annual Growth of Fuel Cell Industry [Ibrahim and Ayub, 2019]**

As to what fuel cell technology have the best future prospects, the question is best answered by considering the application. Smaller and medium applications may favor low and medium temperature technology, such as proton exchange membrane (PEM) and high temperature PEM. Larger application which can more easily accommodate waste heat solutions, such as industrial and large maritime, are better for the high temperature solutions such as molten carbonate or solid oxide fuel cells.

The total shipment of fuel cells in 2015 amounts to 335 MW, with transport sector standing for 178 MW and stationary sector 157 MW. The largest manufacturers are South Korea and USA, with Japan following. Europe is behind on fuel cell manufacturing, but is leading in terms of experience and number of maritime application projects

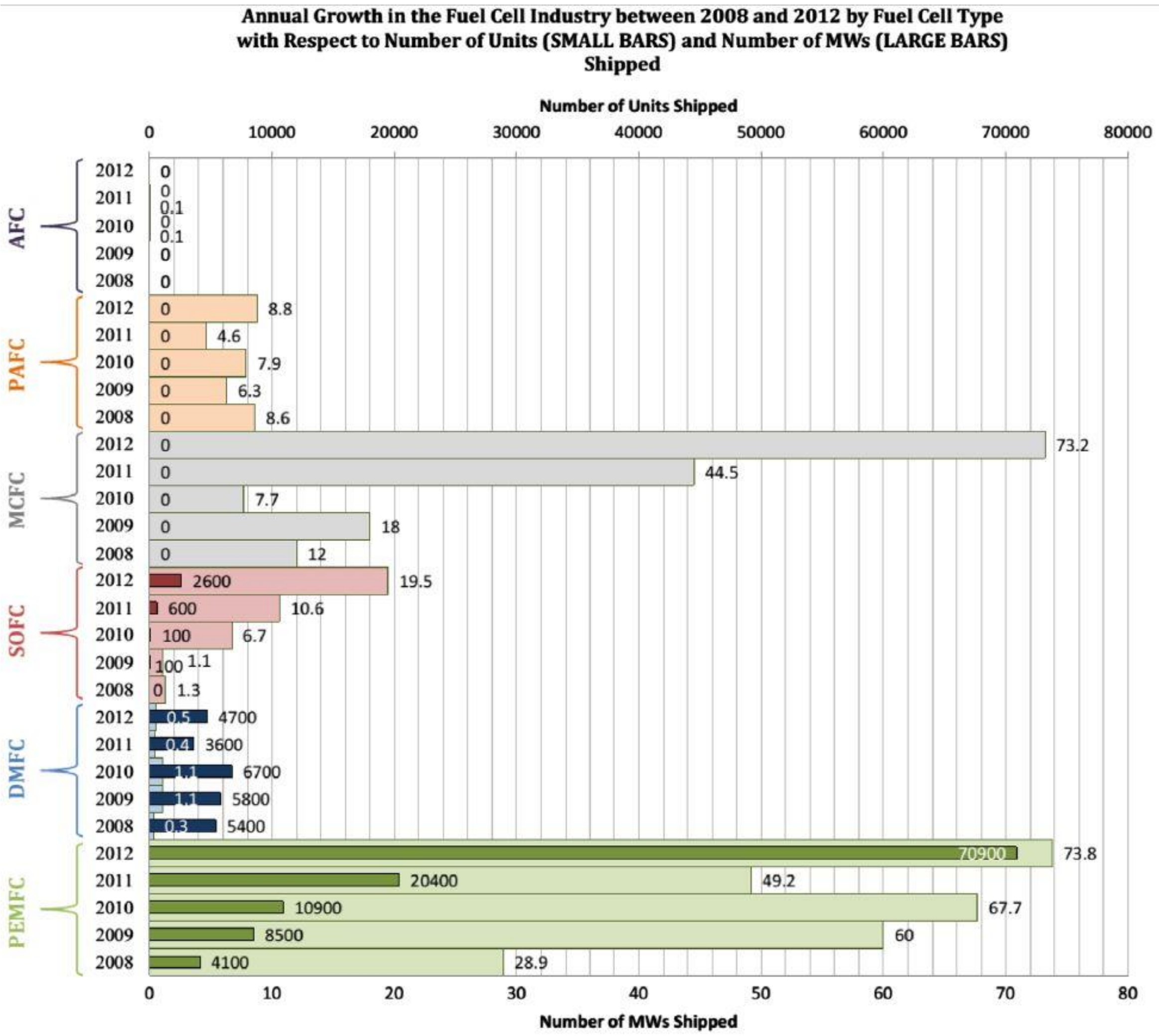


Figure 2.10 **Annual Growth of Fuel Cell Types [Ibrahim and Ayub, 2019]**

2.4 Main Principles

A fuel cell is an electrochemical device, converting the chemical energy (Gibbs free energy) stored in a gaseous or liquid fuel, e.g., hydrogen, methane, methanol, ethanol, others, directly into work of electrical energy (direct current electricity) at constant temperature (Figure 2.11). This type of energy conversion process is different from the classical thermomechanical energy conversion process and is not limited by the Carnot principle (see below).

In short, in a fuel cell, the fuel is oxidized at an electrochemical interface (electrode called anode), accepting electrons and donating these electrons at a second electrochemical interface (electrode called cathode, separated from the anode) to an oxidant, e.g., oxygen, which is reduced by accepting these electrons. Both electrochemical interfaces have to belong to a common electrochemical cell and are joined in the cell by a common medium, an ion-conducting electrolyte.

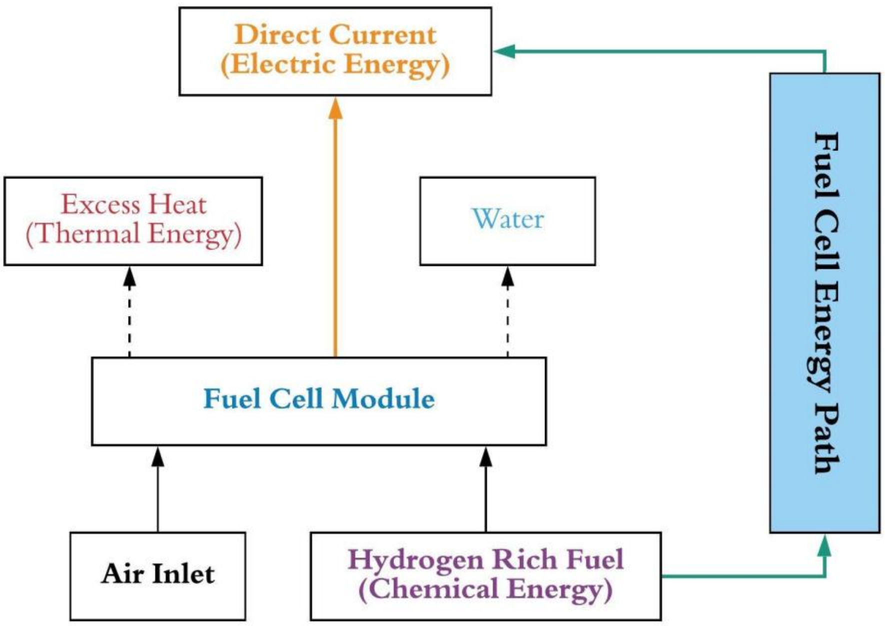


Figure 2.11 Fuel Cell's Energy Path [Author, 2019]

Both electrodes have to be connected electronically by an external circuit, containing the electrical device to be operated, in which the electrons, due to the potential difference created by the two electrode reactions, travel from the anode to the cathode delivering electrical work (Figure 2.12).

Fuel and oxidant are supplied in gas channels of the cell housing (bipolar plate in stacked cells) on the backside of the porous electrodes (not displayed in Figure 2.12) Both gases have to be transported through the porous gas diffusion layers (GDLs) with pores typically in the micrometer range (blue and red bodies in Figure 2.12) to the electroactive catalyst layers (ECLs, black dots in Figure 2.12) at the interface to the electrolyte. Colloquially, GDL and ECL together are called gas diffusion electrode (GDE).

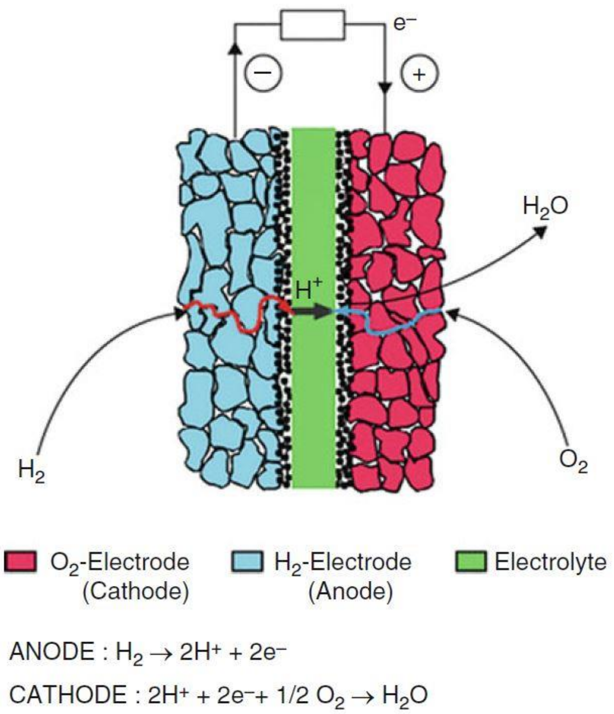


Figure 2.12 Layout of Fuel Cell's Electrochemistry

The fuel cell and its electrochemically active components, i.e., electrodes, electrolyte, etc., as well as its (electrochemically inert) structure materials, i.e., current collectors, cell housing, etc., should be as invariant as possible, i.e., they should not be consumed and, ideally, not age (corrode) over the time of operation. Hence, as an electrochemical reactor, they provide the electrochemically active interfaces (or interphases, see below) and the necessary pathways for mass transport for educts and products to and from these active interfaces through porous media (active electrode layers, gas diffusion layers, internally corrugated cell housing (flow fields) in bipolar plates) with open porosity at different scales. At the same time, it is a prerequisite that these materials are as conductive as possible because they are responsible for the collection and transmission of the electric current generated at the two interfaces. Hence, ohmic voltage losses in these materials should be as low as possible.

2.4.1 Electrochemistry Thermodynamic Analysis

The electrochemistry of the two electrode reactions is exemplified for the simplest and predominant case by the "cold" electrochemical combustion of H_2 with O_2 (pure O_2 or from ambient air) to H_2O.

The overall reaction is split into two partial reactions, occurring at the two different electrodes of the cell:

- **Anodic reaction:**

Hydrogen Oxidation Reaction (HOR)

$$\mathbf{H_2 = 2H + 2e^-} \quad \textbf{(2.1)}$$

- **Cathodic reaction:**

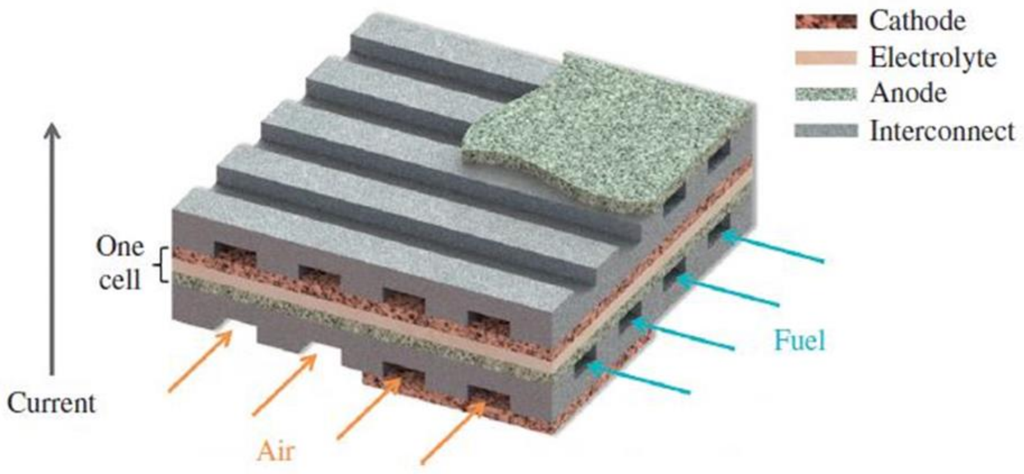
Oxygen Reduction Reaction (ORR)

$$\mathbf{\frac{1}{2}O_2 + 2H^+ + 2e^- = H_2} \quad \textbf{(2.2)}$$

The **Overall reaction** in the fuel cell produces water, heat, and electrical work as follows:

Overall Reaction (OR)

$$\mathbf{H_2 + \frac{1}{2}O_2 = H_2O + W_{ele} + Q_{heat}} \quad \textbf{(2.3)}$$



Picture 2.10 Fuel Cell Constituents

Comments

Each of the two electrode reactions creates a characteristic potential difference across the interface solid electrode/electrolyte, which is different for the two reactions according to the different reactants. The overall cell voltage between the two electrodes, which are joined by the same electrolyte, allows the electrons generated at the anode (HOR) and consumed at the cathode (ORR) to create work in the external circuit. Hence, chemical energy released by the individual electrode reactions at the locally separated electrodes is directly transferred into electrical energy. This pathway is different from the combustion step in the "classical" thermomechanical power generation, where the oxidation of fuel and reduction of oxidant occur in the same volume element, thereby generating heat only.

The heat and water by-products must be continuously removed in order to maintain continuous isothermal operation for ideal electric power generation. Hence, water and thermal management are key areas in the efficient design and operation of fuel cells.

2.4.1.1 Available Cell Voltage and Energy Conversion

Generally, the available cell voltage of electrochemical cells depends on the thermodynamics of the two electrode reactions in the prevailing electrolyte, hence the difference in the electrode potentials, and is confined, according to the series of electrochemical potentials, to a few volts. According to the individual electrode potentials of the H_2/H^+ reaction (by the International Union of Pure and Applied Chemistry (IUPAC) standard zero volt in the series of electrochemical potentials, acidic electrolyte, standard conditions of 1 atm and 25 ℃ or 298 K) and the O_2/H_2O reaction (1.23 V, respectively), **a cell with H_2 and O_2 as reactants should yield an ideal cell voltage of 1.23 V at these standard conditions.** In practice, a lower value in the range of 1 V is observed, due to different implications (side reactions, depolarization of electrodes due to crossover of gases through the electrolyte, etc.).

2.4.2 Thermodynamic Analysis

Figure 2.13 Area of Interest for FC's Thermodynamic Analysis

According to the first law for a control volume:

$$\Delta H = \Delta Q - \Delta W \qquad (2.4)$$

For a fuel cell, the work is obtained from the transport of electrons across a potential energy.

Defining the Work Term

Electrical work is, in general, described by the relation:

$$W = E.I.\Delta t \qquad (2.5)$$

Where

- E, is the cell voltage
- I, represents the current flow

In a fuel cell reaction, electrons are transferred from the anode to the cathode, generating a current. The amount of electricity (I.Δt) transferred when the reaction occurs is given by the product N.F, where:

- n, is the number of electrons transferred,
- F, is Faraday`s constant (= 96,487 coulombs/mol)

Therefore, the electrical work can now be calculated as:

$$W_{el} = n.F.E \qquad (2.6)$$

Ultimately, the First Law has the following form:

$$\Delta H = \Delta Q - F.E.\Delta N \qquad (2.7)$$

2.4.2.1 2nd Thermodynamic Law and Gibb`s Free Energy

At this point we will consider the fuel cell to be an ideal system, meaning that it is reversible and thus behaves as a perfect electrochemical apparatus. Recalling that the heat transferred during a reversible process is expressed as:

$$\mathbf{\Delta Q = T.\Delta S} \qquad \textbf{(2.8)}$$

Combining the First and the Second Law[1] analysis, the final formula for the calculation of enthalpy's alteration is:

$$\mathbf{\Delta H = T.\Delta S - F.E.\Delta} \qquad \textbf{(2.9)}$$

Defining Gibb`s Free Energy (Chemical Potential)

The free energy DG (Gibbs energy at constant pressure) of the fuel cell reaction is related to the cell voltage under open circuit conditions (open circuit voltage, OCV) E_{rev} and standard conditions according to:

$$\mathbf{E_{rev} = -\frac{\Delta G}{nF}} \qquad \textbf{(2.10)}$$

The above value is the highest theoretically attainable voltage from an isothermal fuel cell and is commonly called the Nernst Voltage.

Neglecting work done for the change of pressure and/or volume, the maximum portion of the energy input to a fuel cell that could be converted into useful electric work is found from the Gibbs free energy of formation, which is given on a mole basis using:

$$\mathbf{\Delta G_f = \Delta H_f - T.\Delta S_f} \qquad \textbf{(2.11)}$$

[1] The **second law of thermodynamics** states that the total entropy of an isolated system can never decrease over time. The total entropy of a system and its surroundings can remain constant in ideal cases where the system is in thermodynamic equilibrium, or is undergoing a (fictive) reversible process.
In all processes that occur, including spontaneous processes, the total entropy of the system and its surroundings increases and the process is irreversible in the thermodynamic sense.
The increase in entropy accounts for the irreversibility of natural processes, and the asymmetry between future and past.

It is important to distinguish that ΔG_f is the maximum useful work associated with a chemical reaction while ΔH_f is the maximum heat associated with a chemical reaction. When all the ΔG_f is converted into useful electric work by moving electrons through an external circuit, the cell voltage is termed the reversible cell voltage. Finally, it is important to realize that the $T\Delta S_f$ term grows faster than the ΔH_f term with an increase in temperature. Thus, we expect ΔG_f to decrease in magnitude as temperature is increased

2.4.2.2 Reversible Efficiency of Fuel Cells

It is worth noting that if we replace the Gibbs free energy in Equation 2.11 with enthalpy, we get what is known as the thermoneutral cell voltage, which corresponds to the complete conversion of all the energy content in the fuel to electric work (i.e., 100% thermal efficiency and no internal thermal energy generation).

Substituting Equation 2.11 into Euation 2.10 yields:

$$\mathbf{E_{rev}} = \frac{\mathbf{\Delta H_f - T.\Delta S_f}}{\mathbf{n.F}} \quad \textbf{(2.12)}$$

Hence, the reversible efficiency of a reaction under equilibrium conditions can be written as:

$$\mathbf{n_{rev}} = \frac{\mathbf{\Delta G_f}}{\mathbf{\Delta H_f}} = \mathbf{1} - \frac{\mathbf{T.\Delta S_f}}{\mathbf{\Delta H_f}} \quad \textbf{(2.13)}$$

For the case of standard conditions, we know from thermodynamics that $\Delta G_f = 237\frac{\mathrm{kJ}}{\mathrm{mole}}$ when the water is produced as a liquid (corresponding to the higher heating value, HHV) and n = 2 for the H_2/O_2 fuel cell reaction.

From thermodynamic tables we find at standard conditions that $\Delta H_f = 286\frac{\mathrm{kJ}}{\mathrm{mole}}$ .It follows that roughly 49 kJ/mole are converted into heat, and the theoretical efficiency n_{rev} of a fuel cell operating at standard conditions is:

$$\mathbf{n_{rev}} = \frac{\mathbf{\Delta G_f}}{\mathbf{\Delta H_f}} = \frac{\mathbf{237}}{\mathbf{286}} \cong \mathbf{83}\ \% \quad \textbf{(2.14)}$$

Conversion beyond Carnot

The amount of heat that could be converted to useful work in a heat engine is limited by the ideal reversible Carnot efficiency, given by the following equation:

$$n_{Carnot} = \frac{T_i - T_e}{T_i} \quad (2.15)$$

Where T_i is the absolute temperature at the engine inlet and T_e at the engine exit.

However, a fuel cell is not limited by the Carnot efficiency since a fuel cell is an electrochemical device that undergoes isothermal oxidation instead of combustion oxidation.

As mentioned above**, the maximum conversion efficiency of a fuel cell** is bounded by the chemical energy content of the fuel and is found by:

$$n_{rev} = \frac{\Delta G_f}{\Delta H_f} \quad (2.16)$$

where ΔGf is the change in Gibbs free energy of formation during the reactions and ΔHf is the change in the enthalpy of formation (using lower heating value(LHV) or higher heating value(HHV)).

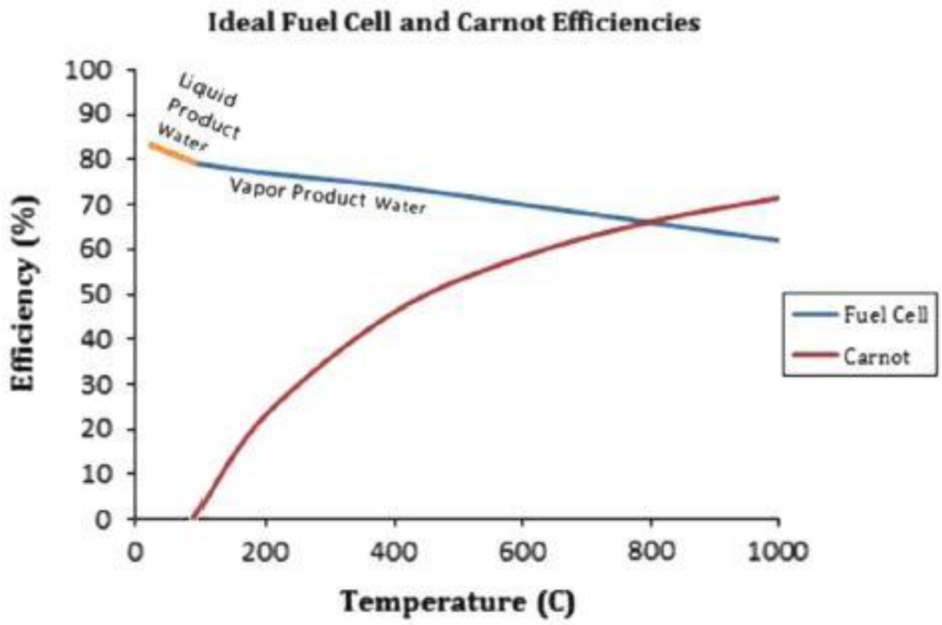


Figure 2.14 **Comparison between the Thermodynamic Efficiencies of the Carnot and the Fuel Cell process**

2.4.2.3 Nernst Law and Voltage Inefficiencies

Introducing Nernst's law[2] for the equilibrium case, the situation when no current (and hence power) is delivered by the cell, the equilibrium cell voltage **under nonstandard conditions for a H_2/O_2 cell in dependence of the respective reactant/ product concentration (partial pressures) can be expressed as:**

$$\mathbf{E_{rev} = E^{eq} = -\frac{\Delta G}{n.F} = E^{eq,c} - E^{eq,a} = E^{0} + \frac{R.T}{2F} \ln\left(\frac{[H_2][O_2]^{\frac{1}{2}}}{[H_2O]}\right)} \qquad \textbf{(2.17)}$$

Where:

- E^{eq} , is the equilibrium cell potential
- $E^{eq,c}$ & $E^{eq,a}$, is the equilibrium potential cathode and anode respectively
- E^{0} , is the equilibrium potential under standard state condition
- R , is the gas constant
- T , is absolute temperature

Mass transport and ionic conduction are faster at higher temperatures and this more than offsets the drop in the Nernst voltage. Using the definition of reversible cell voltage in Equation 2.17, we can define the voltage efficiency of a fuel cell as:

$$\mathbf{n_{vol} = \frac{E}{E_{rev}}} \qquad \textbf{(2.18)}$$

Where E is the operating voltage. That is, the voltage efficiency is the ratio of the cell operating voltage to the Nernst voltage.

As mentioned earlier, the reversible cell voltage is the voltage that can be obtained if the Gibbs free energy could be converted directly into electrical work without any losses.

---

[2] In electrochemistry, the **Nernst equation** is an equation that relates the reduction potential of an electrochemical reaction (half-cell or full cell reaction) to the standard electrode potential, temperature, and activities (often approximated by concentrations) of the chemical species undergoing reduction and oxidation. It was named after Walther Nernst, a German physical chemist who formulated the equation.

However, in reality, there are several irreversibilities within a fuel cell that cause the actual cell voltage to be less than the reversible cell voltage. These irreversibilities cause the actual voltage to decline as current density increases. Thus, it is useful to plot cell voltage against current density as a merit of characterization for a certain fuel cell. And even at the open-circuit voltage state where no load exists, the actual voltage is still less than the reversible voltage. **These irreversibilities are known as cell polarizations and could be divided into four main polarization sources; namely, crossover, activation, ohmic, and concentration losses**, as depicted in Figure 2.15. **These polarization sources are active throughout the entire polarization curve**. However, they become dominant at certain segments of the polarization curve. The polarization curve shown in FIG4 is one of the most important merits of evaluation in fuel cell science and when the four main polarizations are deducted from the reversible voltage we get what is known as the polarization equation:

$$\mathbf{E = E_{rev} - E_{a,a} - E_{a,c} - E_{o} - E_{c,a} - E_{c,c}} \qquad \textbf{(2.19)}$$

Where $E_{a,a}$ and $E_{a,c}$ are the activation and crossover losses at the anode and cathode, E_o are the ohmic losses, and $E_{c,a}$ & $E_{c,c}$ are the concentration losses at the anode and cathode. **All the terms in Eq. (31) need to be positive.**

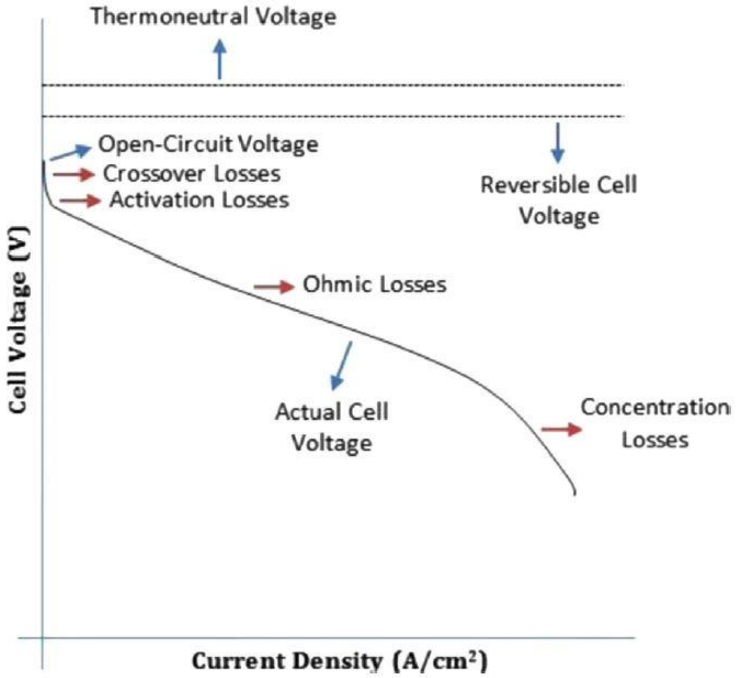


Figure 2.15 A Typical Polarization Curve with Voltage Losses

2.4.3 Fuel Cell System Overall Efficiency

The overall fuel cell system efficiency consists of a series of efficiencies.

The fuel utilization efficiency, u_{fuel}, is the fraction of the fuel consumed within a fuel cell, the power conditioning efficiency, η_{pc}, is the efficiency of the device used to condition the output power, the onboard reformer efficiency, u_{ref}, is the fraction of the raw fuel transformed into fuel cell usable fuel, and the parasitic power efficiency takes into account the amount of fuel cell power used to operate the BoP (Balance of Plant) subsystems, which is given by the following semi-empirical equation :

$$\mathbf{n_p = 1 - a - \frac{b}{E.i}} \qquad \textbf{(2.20)}$$

Where a and b are empirical constants.

When all the previously- mentioned efficiencies are combined, we get the overall fuel cell system efficiency as follows after simplification:

$$\mathbf{n_{tot} = \frac{n.F.E}{\Delta H_f}\left(.\, u_{fuel}.\, u_{ref}.\, \eta_{pc}\right)\left(1 - a - \frac{b}{E.i}\right)} \qquad \textbf{(2.21)}$$

Table 2.6 lists the parameters used in Equation 2.21

Table 2.6 Typical Efficiency Parameters for a Fuel Cell Plant

Parameter	Value	Unit
u_{fuel}	0,9	-
u_{ref}	1	-
η_{pc}	0,95	-
α	0,0499	W m^{-1}
b	0,05	-

By substituting the cell actual voltage in Equation 2.21 and using the hydrogen/air PEMFC characteristics from the previous section, we generate the total system efficiency curve in Figure 2.16.

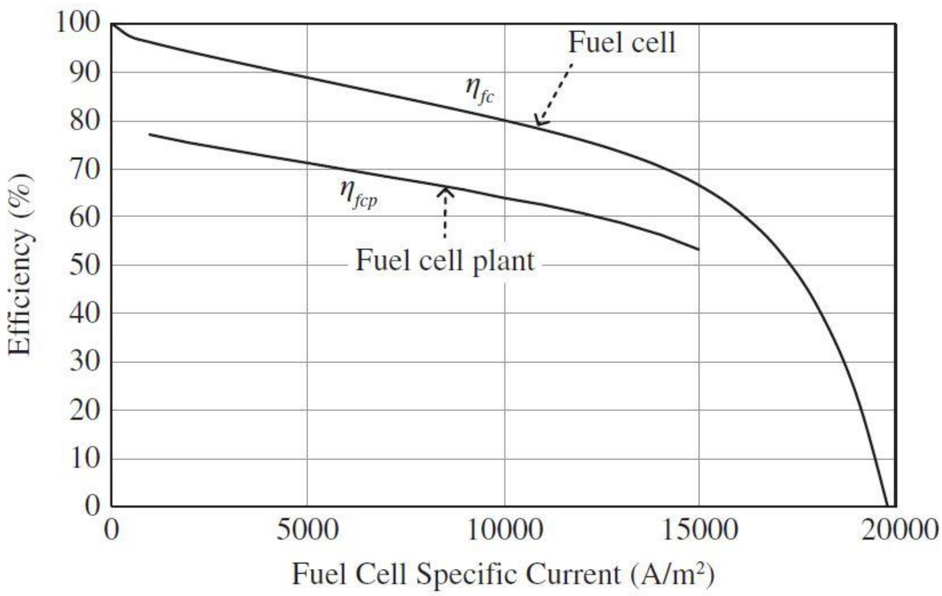


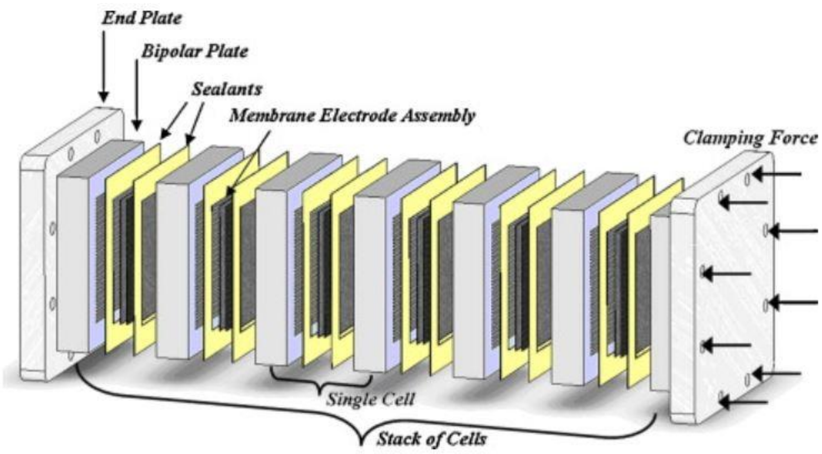
Figure 2.16 PEMFC total system efficiency curve

We observe from the figure that for the used parameter values, the efficiency is highest for a value around 0.5 of current's density. The efficiency is also very low at near-zero current densities and linearly decreases between 0.5 and 2 current densities then exponentially drops between 2 and 2.5 current densities. This implies that it is possible to optimize the design of a fuel cell by creating optimum ranges for the design parameters so as to remain within the optimum efficiency range

2.4.3.1 Discussion

Generally, the available cell voltage of electrochemical cells depends on the thermodynamics of the two electrode reactions in the prevailing electrolyte, hence the difference in the electrode potentials, and is confined, according to the Electrochemical Series of Standard Potentials, to a few volts. Cells with an aqueous electrolyte exhibit a limitation given by the stability window of water, namely 1.23 Vat standard conditions. As stated above, the H_2/O_2 fuel cell allows practical open circuit voltages of around 1.0 V. At cell voltages above 1.23 V, typically around 1.5 V, decomposition of water into H_2 and O_2 occurs.

Hence, to accumulate the necessary voltage for technical applications, e.g., 200–400 V, for an electrical power train in a car, cells must be connected in series. Dedicated bipolar arrangements of cells have been designed and put into operation for serial connection, taking into consideration also the necessary parallel mass flow of fuel and oxidant from a manifold into each individual cell and the respective removal of the product. Such an arrangement of cells is called a fuel cell stack, combining the electrical serial connection of individual cells with a parallel connection for mass flow.

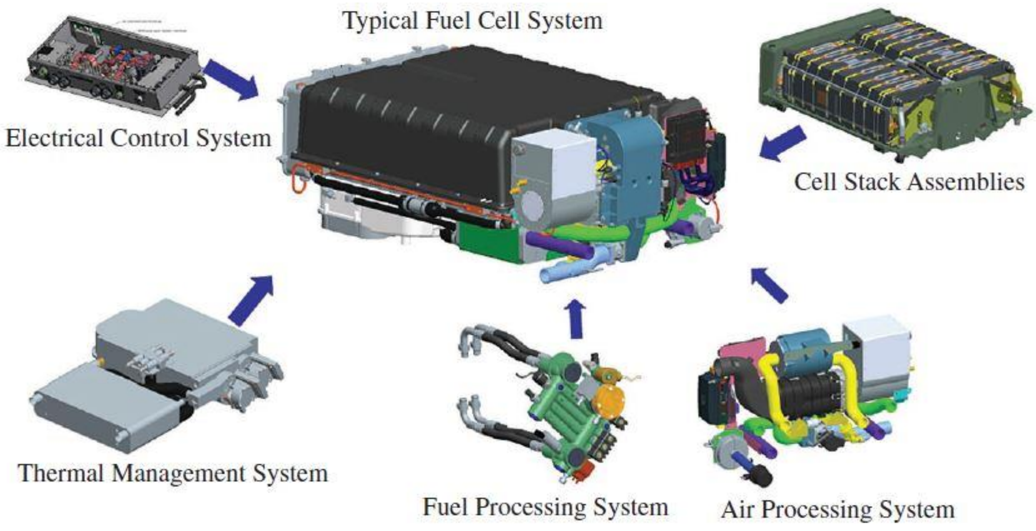


Picture 2.11 A typical Fuel Cell Stack

In contrast to batteries, fuel cells are open systems, which convert the chemical energy available in a fuel stored outside the fuel cell, the electrochemical converter. As a consequence, fuel cells need a fuel tank, also a tank for the oxidant, if the oxidant is pure oxygen and not ambient air, and auxiliaries (for temperature, pressure, etc., control) to be operated.

2.5 Fuel Cell Power System

As it is pretty obvious, a fuel cell installation is not limited to the fuel cell stack. As a matter of fact, it may correspond to a complex system with many components and ancillary equipment in order to effectively output power. These additional components and equipment, known as the balance of plant (BoP), have many responsibilities covering the fuel storage, distribution and the fuel cell power system. Moreover, the energy requirements for the balance-of-plant system can be quite high, typically consuming about 20% of the fuel cell output power for high-pressure fuel cell systems, and about 10% for low-pressure systems.



Picture 2.12 Automotive fuel cell and balance of plant [Courtesy of US Hybrid]

The main subsystems of the Fuel Cell Power System as well as their purpose are summarized below:

[1] Water Treatment System

- Ensures all parts of the fuel cell are sufficiently hydrated without flooding.
- Humidifies the incoming gases (especially to the anode).
- Ensures proper water removal from the cathode.
- Employs purge cycles and back pressure regulators for the removal of accumulated liquid water from the anode.

[2] Thermal Management System

Provides cooling and heat rejection to maintain thermal equilibrium within the fuel cell power system and assists in heating the power train during start-ups.

- Uses fans and blowers for active air cooling.
- Uses pumps for circulation of cooling liquid through cooling plates.
- Provides start-up heating in cold climates if required.

[3] Gases Management

- Employs an appropriate storage mechanism for hydrogen storage with pressure-reducing regulators.

  The pure hydrogen is stored in a compressed gas cylinder (350 + bars). There can be one or more check valves before the hydrogen enters the system. A mass flow controller would also be beneficial to monitor the flow rate.

- Uses fuel cell reformer in case of using hydrocarbons as hydrogen sources.
- Employs a pump for hydrogen recirculation.

[4] Power Conditioning

- Converts the variable low-DC voltage output to usable DC power via a step-up DC-DC converter when required.
- Inverts the variable low-DC voltage output to usable AC power via a switch-mode DC-AC inverter when required.
- Employs a battery or an ultracapacitor to meet the power spike transients.

[5] Automatic Control System

System that is composed of sensors, actuators, valves, switches and logic components to maintain the fuel cell power system parameters within the manufacturer’s specified limits including moving to safe states without manual intervention

[6] Fuel processing System

System of chemical and/or physical processing equipment plus associated heat exchangers and controls required to prepare, and if necessary, pressurize, the fuel for utilization within a fuel cell.

Other plant components, such as turbines are also useful because they can harness energy from the heated exhaust gases from the fuel cell.

[7] Oxidant Air processing System

System that meters, conditions, processes and may pressurize the incoming supply for use within the fuel cell power system. Firstly, the oxidant air is filtered for particulates as it is being pumped into the fuel cell from the atmosphere. Then, the air pressure transducer keeps track of the air pressure coming into the fuel cell. Lastly, the oxidant air is filtered again for particulates, and then humidified before it enters the fuel cell stack.

[8] Fuel Cell Modules

Equipment assembly of one or more fuel cell stacks which electrochemically converts chemical energy to electric energy and thermal energy intended to be integrated into a power generation system.

[9] Fuel Cell Stack

Equipment assembly of cells, separators, cooling plates, manifolds and a support structure that electrochemically converts, typically, hydrogen rich gas and air reactants to DC power, heat and other reactant byproducts.

[10] Onboard Energy Storage System

System of internal electric energy storage devices intended to aid or complements the fuel cell module in providing power to internal or external loads.

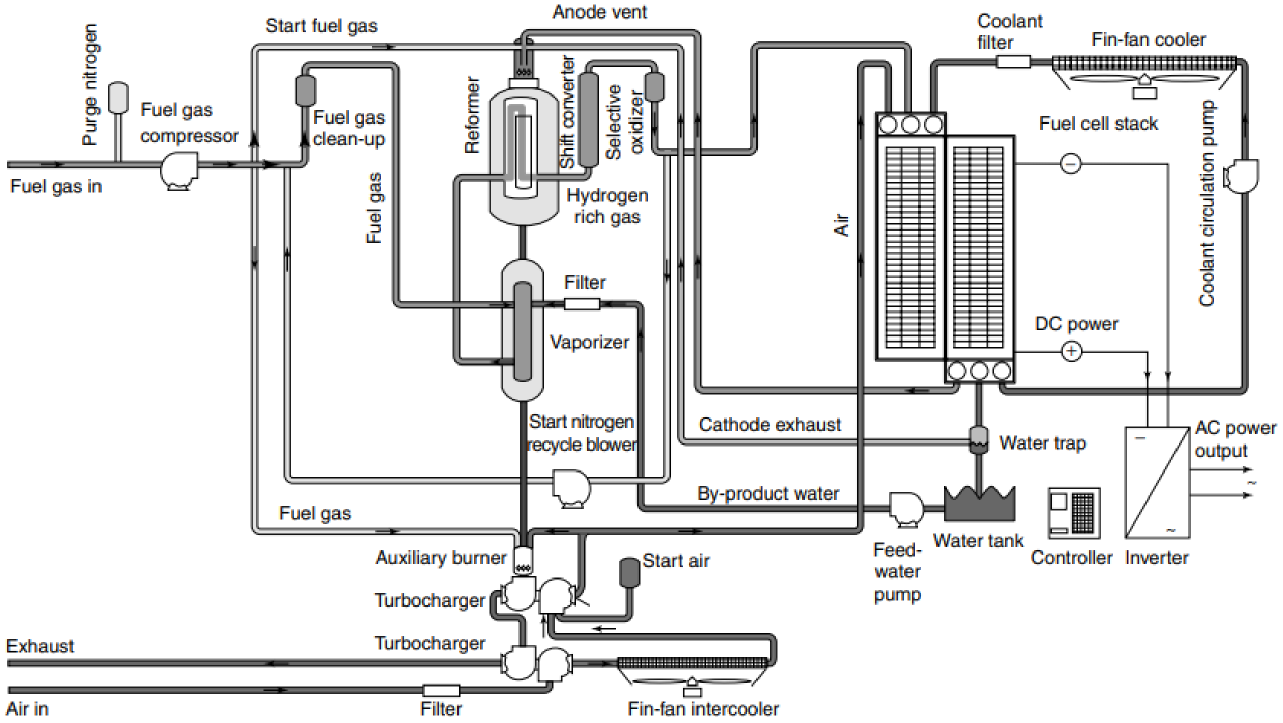


Figure 2.17 **Process flow diagram for a Ballard 250-kW PEMFC plant [Source: Larmine and Dicks (2003)]**

2.5.1 FC Power Installation on Ro/Pax Vessels

Completing the above section, it is crucial to mention the necessary systems that have to be installed for the efficient performance of a FC-powered powertrain on ships. The main components of a typical fuel cell installation on Ro-Pax Vessels or Gas Carriers include:

1. **Fuel System**
    a. Fuel tank system
    b. Distribution line between tank and fuel preparation
    c. Fuel preparation
    d. Distribution line to Fuel Cell Power System
2. **Fuel Cell Power Installation**
    a. Fuel Cell Power System
        - Piping between fuel preparation and FC power system (primary fuel line)
        - Fuel Reforming
        - Piping between reformer and fuel cell
        - Fuel Cell (FC) Module
        - Process Air
        - Afterburner
        - Heat (energy) Recovery
        - Exhaust Gas Line
    b. Electrical power output conditioning System
    c. Net integration
    d. Fuel Cell Control System
    e. Fuel Cell Safety Control System
3. **Ventilation System for possible electrostatic discharge (ESD) events in FC Spaces**
4. **Ventilation System for gas-safe fuel cell spaces**
5. **Onboard Energy buffer**
6. **Active purging system**

2.6 Fuel Cell Technologies

There are many types of fuel cells available in the market today. Fuel cells are conventionally categorized according to their electrolyte material. They differ in their power outputs, operating temperatures, electrical efficiencies, and typical applications. In technical terms, cell or single cell is more commonly used associated with fuel cell. On the other hand, battery refers to a stack. **There is a connection in series of the necessary single cells to achieve the tension adapted to a given application.**

As mentioned, the most common criterion for classification has to do with the electrolyte used. They are divided into the following types:

1. **AFC**, "Alkaline Fuel Cells"
2. **PEMFC**, "Proton Exchange Membrane Fuel Cell"
3. **DMFC**, "Direct Methanol Fuel Cell"
4. **PAFC**, "Phosphoric Acid Fuel Cell"
5. **MCFC**, "Molten Carbonate Fuel Cell"
6. **SOFC**, "Solid Oxide Fuel Cell"

Nevertheless, there is another, more generic division, which is commonly found in the literature as a whole. This division refers to the temperature in which the fuel cells operate, creating three larger groups:

1) Low Temperature fuel cells that work at approximately 65-80 ℃; the AFC, PEMFC and DMFC, appertain to this category.

2) Intermediate Temperature fuel cells that work at approximately 200 ℃; the PAFC.

3) High Temperature fuel cell which working temperature is between 500 and 1000 ℃; the MCFC and SOFC belong to this category.

Low temperature fuel cells use hydrogen with high purity. In these fuel cells, impurities, such as carbon monoxide (CO) reduce performance. High temperature fuel cells are less sensitive to fuel impurities and can even use CO as a fuel. Fuel reforming, which is used for converting hydrocarbons, such as methane or LNG into a hydrogen-rich mixture can take place directly inside these fuel cells. Start-up times and response to load transients are examples of performance characteristics that defer from one fuel cell to another: the higher the temperature of a fuel cell, the longer its start-up time. In addition, high temperature fuel cells only permit slow load changes. As a result, high temperature fuel cells are more suitable for stable units, while low temperature fuel cells are more effective as auxiliary devices. At the next paragraphs, there will be a synoptic view of the three most promising FC types; PEMFCs, MCFCs and SOFCs. For completeness sake, the rest types of FCs are developed in detail at the Appendix Part.

2.6.1 Proton Exchange Membrane FCs (PEMFCs)

Proton exchange membrane fuel cells have been used extensively in many applications. It has been used in several cars and the Alsterwasser passenger ship with a power output of 96 kW and in German Type 212A class submarines with modules from 30-50 kW each. It has also been used in other ships with power levels ranging from 12-60 kW.

The proton exchange membrane fuel cell (PEMFC) uses platinum-based electrodes and the electrolyte is a humidified polymer membrane that is an electric insulator, but permeates hydrogen ions (H+).

The operating temperature is 50-100 ℃, temperatures above 100 ℃ are not feasible as the membrane needs to stay humid. A schematic of the PEMFC is given in Figure 2.18 below.

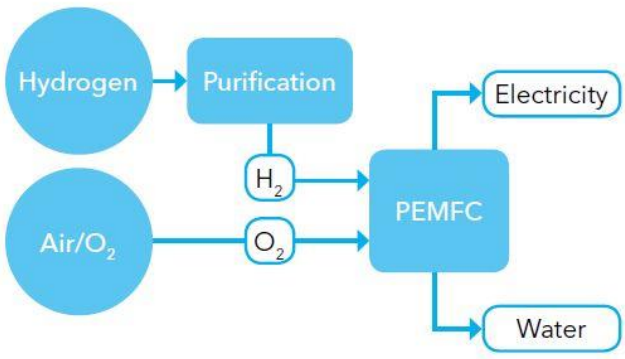


Figure 2.18 **Schematic of a PEMFC**

The PEMFC uses hydrogen and oxygen, and produces water in addition to electricity and heat. If other fuel sources than hydrogen is to be used it needs to be converted to hydrogen prior to injection to the PEMFC. For hydrocarbons this means steam reforming and water-gas-shift.

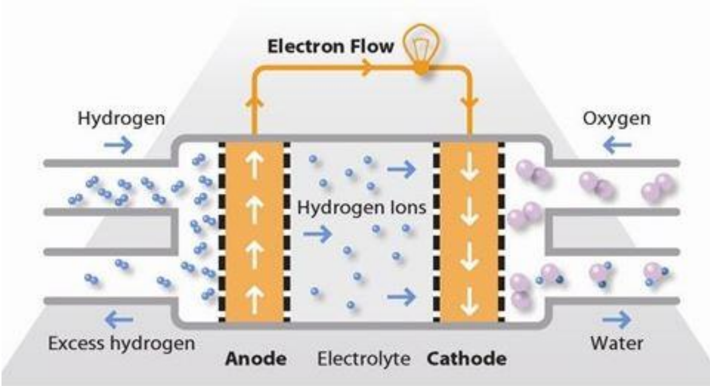


Figure 2.19 Energetic Flows in a PEMFC

In the PEMFC, the main reactions that are occurring are the following:

- Anode reaction:

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (2.22)$$

- Cathode reaction:

$$O_2 + 4H^+ + 4e^- \rightarrow 4H_2O \quad (2.23)$$

- Total reaction:

$$2H_2 + O_2 \rightarrow 2H_2O \quad (2.24)$$

Benefits and Challenges of PEMFCs

The PEMFC has high power-to-weight ratio (100- 1000W/kg), a low operation temperature that allows for flexible operation and less stringent material requirements that make it a suitable fuel cell for transportation. **The efficiency of the PEMFC system is moderate, 50 - 60% and excess heat is of such a quality that heat recovery is not feasible**. Also, the low temperature leads to a complex system for water management to obtain efficient operation of the PEMFC. The platinum catalyst leads to a higher cost, and it can be poisoned by carbon monoxide (CO) and sulphur (S). A pure hydrogen source is needed, but the PEMFC is not as sensitive to poisoning as the AFC. Hydrocarbons can be used as a fuel for PEMFC, but a separate steam reforming and subsequent water-gas-shift system is required to make hydrogen of the necessary purity. If hydrogen is used as a fuel, the PEMFC emits only water. CO_2 and low levels of NO_X are emitted if hydrocarbons are used as fuel.

Further Development of PEMFCs

There is continuous development of the PEMFC to improve operation flexibility and durability, and reduce cost. New membrane materials as Metal-Organic frameworks and reducing catalyst loading are part of this development. High temperature PEMFC (HT-PEM) and Direct Methanol PEMFC (DMFC) are subcategories of PEMFCs that are further described below.

2.6.2.1 High Temperature PEMFCs (HT-PEMFCs)

The main difference between a High temperature PEMFC (HT-PEMFC) and a PEMFC is the operating temperature. **The HT-PEMFC can operate at temperatures up to 200 ℃; by using a mineral acid electrolyte instead of a water based one**. The reaction and fuel are the same as in the PEMFC. A 12 kW HT-PEMFC has been in use in the passenger ferry MF Vagen using metal hydride as the source of hydrogen.

Picture 2.13 A HT-PEMFC Vessel, the MF Vagen

Benefits and Challenges of HT-PEMFCs

Compared with the PEMFC, the High temperature PEMFC is less sensitive to poisoning by CO and sulphur and has no need for a water management system. It is also possible to harness the excess heat from the fuel cell in a heat recovery system. A HT-PEMFC has a lower power density, and it is not possible to cold start it. **The electrical efficiency of a HT-PEM fuel cell is similar or slightly better than PEM fuel cells, 50-60 %, but there is a potential to harvest more energy from heat recovery with can increase the overall efficiency of a HT-PEM fuel cell system.**

2.6.2.2 Direct Methanol FCs(DMFCs)

As the name says, the Direct methanol fuel cell (DCFC) uses methanol directly without prior reforming to hydrogen. As the PEMFC, the DMFC has a polymer membrane electrolyte. The electrodes have a platinum-ruthenium catalyst able to directly utilize the hydrogen in methanol (CH_3OH) to generate electricity.

DMFC is generally good for delivering a small amount of electricity over a prolonged time, and power outputs of up to 5 kW is the norm. The DMFC normally operates between 50-120 ℃. Higher temperature and pressure can increase cell efficiency, but will lead to higher overall losses in the system, and the benefit is lost. The DMFC uses a weak methanol in water solution (3 %) as fuel. As methanol is the fuel, the oxidation at the anode leads to CO_2 emission.

The main reactions in the DMFC are:

- Anode reaction:

$$\mathbf{CH_2OH + 2H_2O \rightarrow 6H^+ + CO_2 + 6e^-} \quad \textbf{(2.25)}$$

- Cathode reaction:

$$\mathbf{3/2\,O_2 + 6H^+ + 6e^- \rightarrow 3H_2O} \quad \textbf{(2.26)}$$

- Total reaction:

$$\mathbf{CH_2OH + 3/2\,O_2 \rightarrow CO_2 + 2H_2O} \quad \textbf{(2.27)}$$

Benefits, Challenges & Development of DMFCs

The DMFC uses methanol directly without any need for reforming. This is a fuel with high energy density, that is easy to handle and store compared with hydrogen. Using methanol also leads to CO_2 emissions, but the DMFC has no NO_X emissions. The efficiency of a DMFC is low, around 20 %. Also, the major challenge with DMFC is methanol crossover, which is that methanol crosses over the membrane to the cathode where it reacts directly with oxygen. This leads to reduction of cell efficiency.

Improvement of membranes may reduce methanol crossover.

2.6.2 Molten Carbonate FCs (MCFCs)

The Molten Carbonate Fuel Cell is a high temperature fuel cell operating at temperatures between 600 – 700 ℃. The electrolyte is a molten carbonate salt, and there is no need for noble-metal catalyst. The anode is normally a nickel alloy and the cathode is normally nickel oxide with lithium incorporated in the structure.

The MCFC have been used in the FellowSHIP project (320 kW fuel cell using LNG on Viking Lady), in the US SSFC (625 kW fuel cell concept development) and in the MC-WAP project (150 kW fuel cell using diesel).

The high temperature makes the MCFC flexible towards the choice of fuel, both LNG, flue gases from coal and hydrogen can be used. A reforming unit is not needed, as the reforming occurs in the fuel cell itself. Using hydrocarbons leads to CO_2 emissions. As no air is present where the reforming takes place at the anode, the reforming is not a source for NO_X emissions, but the subsequent heat and energy recovery systems have the potential for some NO_X emissions.

Internal Reforming:

- Steam reforming:

$$\mathbf{CH_4 + H_2O \rightarrow CO + 3H_2} \qquad \textbf{(2.28)}$$

- Water-gas shift:

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2} \qquad \textbf{(2.29)}$$

- Total reaction from reforming:

$$\mathbf{CH_4 + 2H_2O \rightarrow CO_2 + 4H_2} \qquad \textbf{(2.30)}$$

Fuel Cell Reactions:

- Anode reaction:

$$2H_2 + 2CO_2^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^- \qquad (2.31)$$

- Cathode reaction:

$$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_2^{2-} \qquad (2.32)$$

- Total reaction for fuel cell:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (2.33)$$

As with the PAFC, the MCFC is suitable for a heat recovery system. The flue gases can be used in an after burner or a gas turbine, and more energy can be extracted in a steam turbine. **The electrical efficiency is around 50 %, but the total efficiency for a MCFC can be as high as 85 %. A flowchart for a MCFC using LNG, methanol or other hydrocarbons is given in** Figure 2.20.

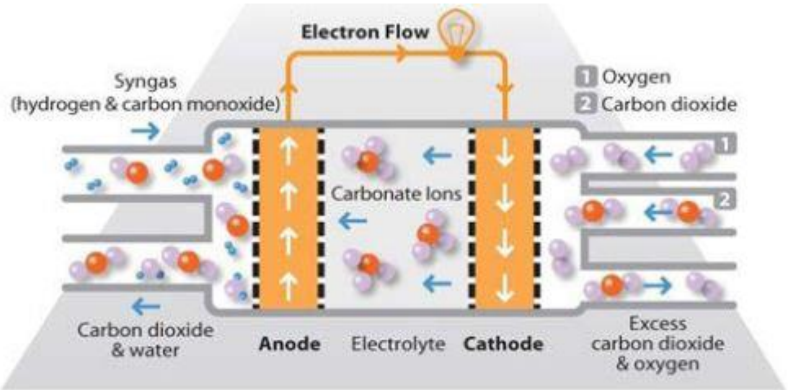


Figure 2.20 Energetic Flows in a MCFC

If hydrogen is used as the fuel, there will be no CO_2 emissions from the cell, only CO_2 in circulation to regenerate carbonate in the electrolyte.

Benefits, Challenges and Development of MCFCs

The MCFC is a highly efficient fuel cell, with low cost catalyst and electrolytes, and high flexibility towards fuels and contaminants. The high temperature makes it suitable for energy recovery systems, but also makes it vulnerable to negative cycling effects like corrosion and cracking of components. The MCFC has a slow start-up, and is less flexible towards changing power demands than low temperature fuel cells.

Combining MCFCs with batteries to allow for a more stable operation of the fuel cell may significantly reduce the thermal strain from cycling. This will also allow for more flexible operations with faster start-up and ability to cater to changing power demands

. 2.6.3 Solid Oxide FCs (SOFCs)

Solid Oxide Fuel Cells (SOFC) is another high temperature fuel cell. The SOFC operates at temperatures between 500-1000 °C. The electrolyte is a porous ceramic material, yttrium stabilized zirconia is common. As the MCFC, the SOFC uses a nickel alloy as the anode, but the cathode is a normally made of lanthanum strontium manganite, a material that has the required porosity and is compatible with the electrolyte. A schematic representation of a SOFC is given in Figure 2.21.

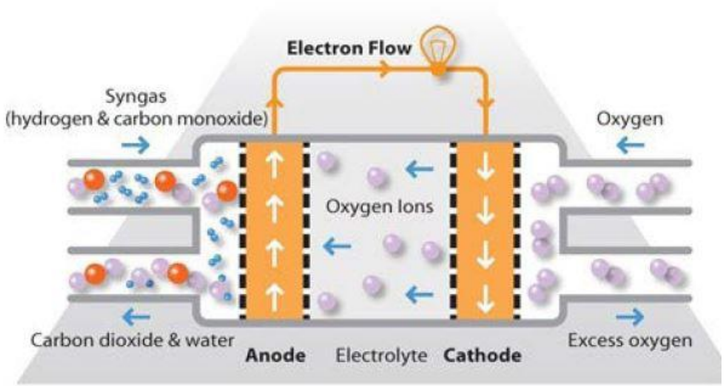


Figure 2.21 Energetic Flows in a SOFC

SOFCs are generally used in large scale power production on shore up, with capacities up to 10 MW. Several projects have been looking into SOFCs for maritime use, including the Methapu, Felicitas and SchIBZ projects.

The SOFC shows the same flexibility towards fuels as the MCFC, being able to use hydrogen, LNG, methanol and hydrocarbons as diesel. The reforming to syngas (hydrogen and carbon monoxide) occurs within the fuel cell. Unlike the MCFC the SOFC does not require CO_2 to be added at the cathode. The emission from the SOFC is CO_2, but this is eliminated if hydrogen is used as the fuel.

These are the reactions that happen in a SOFC:

Internal Reforming of LNG:

- Steam reforming:

$$\mathbf{CH_4 + H_2O \rightarrow CO + 3H_2} \quad \textbf{(2.34)}$$

- Water-gas shift:

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2} \quad \textbf{(2.35)}$$

- Total reaction from reforming:

$$\mathbf{CH_4 + 2H_2O \rightarrow CO_2 + 4H_2} \quad \textbf{(2.36)}$$

Fuel Cell Reactions:

- Anode reaction:

$$\mathbf{2H_2 + 2O_2^{2-} \rightarrow 2H_2O + 4e^-} \quad \textbf{(2.37)}$$

- Cathode reaction:

$$\mathbf{O_2 + 4e^- \rightarrow 2CO_2^{2-}} \quad \textbf{(2.38)}$$

- Total reaction for fuel cell:

$$\mathbf{2H_2 + O_2 \rightarrow 2H_2O} \quad \textbf{(2.39)}$$

The electrical efficiency of a SOFC is high, about 60 %, but can be increase to as high at 85 % or higher if a heat recovery system is applied.

Possible Topologies of SOFCs

There are two possible geometries for SOFCs; Planar and tubular. In a planer SFOC (Figure 2.22 A) each cell is a flat plate, each component of the cell laid upon each other. The tubular SOFC (Figure 2.22 B) is formed as a tube, one electrode being the inner tube, and the outer tube being the other electrode, and the electrolyte between them. Even though the tubular SOFC is more stable towards thermal cycling, the planar SOFC is considered the more favorable design due to a higher energy density and that it is easier to produce. As for the MCFC, combing SOFCs with a battery will reduce thermal strain and ensure a more flexible operation.

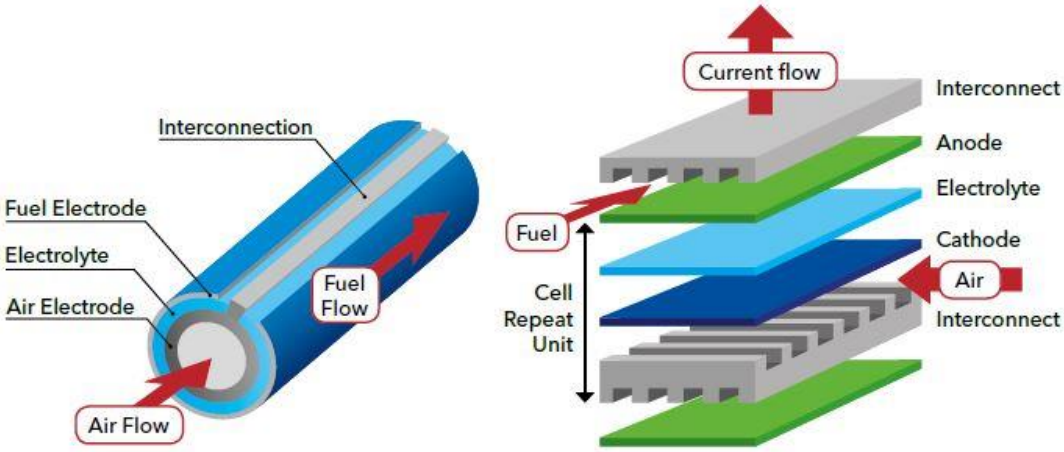


Figure 2.22 Cell structure of tubular (A) and planar (B) Solid Oxide Fuel Cell

Table 2.7 Summary of Fuel Cell Types

Technology	Relative Cost	Module Power Levels	Lifetime	Fuel	Maturity	Size	Sensitivity to fuel impurities	Emissions	Safety Aspects	Efficiency
Alkaline Fuel Cell (AFC)	Low	Up to 500 kW	Good	High Purity Hydrogen	High Experience	Small	High	No	Hydrogen	50 - 60 % (electrical)
Phosphoric Acid Fuel Cell (PAFC)	Moderate	100 - 400 kW	Moderate	LNG,Methanol, Diesel, Hydrogen	High Experience	Large	Medium	CO_2 & low levels of NO_x if carbon fuel is used	High Temperatures (up to 200 ℃) Hydrogen and CO in reforming unit	40% (electrical) 80% (with heat recovery)
Molten Carbonate Fuel Cell (MCFC)	High	Up to 500 kW	Good	LNG,Methanol, Diesel, Hydrogen	High Experience	Large	Low	CO_2 & low levels of NO_x if carbon fuel is used	High Temperatures (up to 600 - 700 ℃) Hydrogen and CO in reforming unit	60% (electrical) 85% (with heat recovery)
Solid Oxide Fuel Cell (SOFC)	High	20 - 60 kW	Good	LNG,Methanol, Diesel, Hydrogen	Moderate Experience	Medium	Low	CO_2 & low levels of NO_x if carbon fuel is used	High Temperatures (up to 650 - 800 ℃) Hydrogen and CO in FC from internal reforming	60% (electrical) 85% (with heat recovery)
Proton Exchange Membrane Fuel Cell (PEMFC)	Low	Up to 120 kW	Moderate	High Purity Hydrogen	High Experience	Small	Medium	No	Hydrogen	50 - 60 % (electrical)
Hight Temperature PEM Fuel Cell (HT-PEMFC)	Moderate	Up to 30 kW	Moderate	High Purity Hydrogen	Low Experience	Small	Low	No	Hydrogen	50 - 60 % (electrical)
Direct Methanol Fuel Cell (DMFC)	Moderate	Up to 5 kW	Low	Methanol	Under Development	Small	Low	CO_2	Methanol	20 % (electrical)

3rd CHAPTER

Fuel Cells Getting On-board

A Summary of Fuel Cell Projects in Marine Industry

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Picture 3.14 Offshore Supply Vessel, the "Viking Lady".
One of world's most environmentally friendly ships.

3.1 Introduction

The main objective of this chapter is to summarize today`s most promising fuel cell projects in marine industry and offer background information about their distinctive features and objectives. The projects vary from assessments of potential for fuel use rule development and feasibility studies as well as concept design to testing of fuel cells in various vessels.

In order to achieve that, a plethora of data was collected from relative academic bibliography and executive studies. During this quest, a total of 23 fuel cell projects in the maritime sector was identified and placed appropriately in Table 3.8 & Table 3.9. In this list the main characteristics of each project are abstracted and categorized.

Ultimately, supplemental knowledge is provided for 4 selected initiatives; FellowSHIP, e4ships, SF-Breeze & Elektra. This section acts as guide whose main purpose is to pinpoint the key points, objectives and technical details, where applicable, of each venture.

Table 3.8 Summary of Fuel Cell Projects in Marine Industry – Part A

Project	Concept	Main Partners	Active Years	Fuel Cell Type	Capacity	Fuel
1. FellowSHIP	320 kW MCFC system for auxiliary power of Offshore Supply Vessel	Eidesvik Offshore, Wärtsilä, DNV	2003-2011	**MCFC**	**320 kW**	**LNG**
2. Viking Lady METHAPU Undine	20 kW SOFC tested for the evaluation of 250 kW SOFC solution for marine APU.	Wallenius Maritime, Wärtsilä, DNV	2006-2010	**SOFC**	**20 kW**	**Methanol**
3. E4Ships - Pa-X-ell MS MARIELLA	60 kW modularized HT-PEM fuel cell system developed and tested for the decentralized auxiliary power supply onboard passenger vessel MS MARIELLA	Meyer Werft, DNVGL, Lürssen Werft, etc	Phase 1: 2009-2017 Phase 2: 2017-2022	**HTPEM**	**60 kW (each stack contributes 30 kW)**	**Methanol**
4. E4Ships - SchIBZ MS Forester	100 kW containerized SOFC system developed and tested for the auxiliary power supply of comercial ships. Scalable up to 500 kW units.	Thyssen Krupp Marine Systems, DNVGL, Leibniz University Hannover, OWI, Reederei Rörd Braren, Sunfire	Phase 1: 2009-2017 Phase 2: 2017-2022	**SOFC**	**100 kW**	**Diesel**
5. E4Ships - Toplanterne	Support of IGF Code development to include a FC chapter and set the regulatory baseline for the use of maritime FC systems	DNV GL, Meyer Werft, Thyssen Krupp Marine Systems, Lürssen Werft, Flensburger Schiffbaugesellschaft, VSM	Phase 1: 2009-2017 Phase 2: 2017-2022	-	-	-
6. RiverCell	250 kW modularized HT-PEM fuel cell system developed and to be tested as a part of a hybrid power supply for river cruice vessles	Meyer Werft, DNVGL, Neptun Werft, Viking Cruises	Phase 1: 2015-2017 Phase 2: 2017-2022	**HTPEM**	**250 kW**	**Methanol**
7.RiverCell - Elektra	Feasibility study for a fuel cell as part of a hybrid power supply for a towboat	TU Berlin, BEHALA, DNVGL	2015-2016	**HTPEM**	-	**Hydrogen**
8. ZemShip - Alsterwasser	100 kW PEMFC system developed and tested onboard of a small passenger ship in the area of Alster in Hamburg, Germany	Proton Motors, GL, Alster Touristik GmbH, Linde Group etc.	2006-2013	**PEM**	**96 kW**	**Hydrogen**
9.FCSHIP	Assess the potential for maritime use of FC and develops a Roadmap for future R&D on FC application on ships	DNV, GL, LR, RINA, EU GROWTH progam	2002-2004	**MCFC, SOFC, PEM**	-	**Various**
10. New-H-Ship	Research project on the use of hydrogen in marine applications	INE (Icelandic New Energy), GL, DNV	2004-2006	-	-	-
11.Nemo H2	Small passenger ship in the canals of Amsterdam	Rederij Lovers etc.	2012 - present	**PEM**	**60 kW**	**Hydrogen**
12. Hornblower Hybrid	Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell	Hornblower etc.	2012 - present	**PEM**	**32 kW**	**Hydrogen**
13. Hydrogenesis	Small passenger ship which operates in Bristol	Bristol Boat Trips etc.	2012 - present	**PEM**	**12 kW**	**Hydrogen**

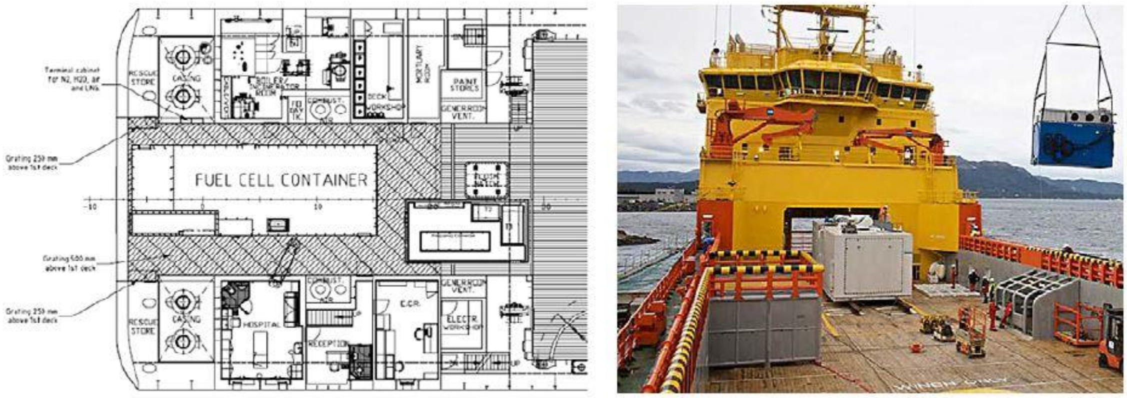
Table 3.9 Summary of Fuel Cell Projects in Marine Industry – Part B

Project	Concept	Main Partners	Active Years	Fuel Cell Type	Capacity	Fuel
14. MF Vagen	Small passenger ship in the harbour of Bergen	CMR Prototech, ARENA-Project	2010	**HTPEM**	**12 kW**	**Hydrogen**
15. Class 212A/214 Submarines	Hybrid propulsion using a fuel cell and a diesel engine	CMR Prototech, ARENA-Project, ThyssenKrupp Marine Systems, Siemens	2003 - present	**PEM**	**306 kW : 1) 30-50 kW per module , 2) 120 kW per module**	**Hydrogen**
16. US SSFC	The program addresses technology gaps to enable fuel cell power systems that will meet the electrical power needs of naval platforms and systems	U.S. Department of Defens, Office of Naval Research	2000 - 2011	**PEM , MCFC**	**500 kW (PEM) 625 kW (MCFC)**	**Diesel**
17. SF-BREEZE	Feasibility study of a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco bay area	Sandia National Lab., Red and White Fleet	2015 - present	**PEM**	**120 kW per module. Total power 2.5MW**	**Hydrogen**
18.MC-WAP	MC-WAP is aiming at the application of the molten carbonate fuel cell technology onboard large vessels, such as RoPax, RoRo and cruise ships for auxiliary power generation purposes	FINCATIERI, Cetana, OWI, TÜBITAK, RINA, NTUA, Techip KTI, etc	2005 - 2010	**MCFC**	**Concept design of 500 kW, final design of 150 kW**	**Diesel**
19.FELICITAS subproject 1	Application requirements and system design for FC in heavy duty transport systems	Lürssen, FhG IVI, AVL, HAW, Rolls-Royce, INRETS, VUZ	2005 - 2008	-	-	-
20.FELICITAS subproject 2	Mobile hybrid marine version of the Rolls- Royce Fuel Cell SOFC system	Rolls-Royce, Uni Genoa, Lürssen, HAW, Uni Eindhoven	2005 - 2008	**SOFC**	**250 kW (60 kW sub system)**	**LNG Other fuels also evaluated**
21.FELICITAS subproject 3	PEFC-Cluster - improving PEFC reliability and power level by clustering	NuCellSys, FhG IVI, CCM	2005 - 2008	**PEM**	**Cluster system (80 kW basis component)**	**Hydrocarbon fuels & Hydrogen**
22.FELICITAS subproject 4	Power management – concerns general technical problems of FC-based propulsion	FhG IVI, Lürssen, NTUA, NuCellSys, CCM, Uni Belfort, AVL, CDL	2005 - 2008	**PEM**	-	-
23.Cobalt 233 Zet	Sports boat employing hybrid propulsion system using batteries for peak power	Zebotec, Brunnert-Grimm	2007 - present	**PEM**	**50 kW**	**Hydrogen**

3.2 Fellowship – Viking Lady

FellowSHIP (Fuel Cells for Low Emission Ships) is a research and development project. Its mission is to fully integrate fuel cells on board ships and off-shore platforms in order to make them commercially viable for industry. The FellowSHIP project is funded exclusively by the Research Council of Norway. It also involves industrial partners: Eidesvik Offshore, provided the ship; Wärtsilä, the energy, and DNV, the classification rules.

The project included a thorough development and testing regime, with complete development and testing of the 330 kW prototype fuel cell power pack on land with all subsystems before lifting aboard. Thereafter followed the testing and qualification program onboard the newly delivered offshore supply vessel Viking Lady. The vessel is all electric, powered by LNG by use of dual fuel engines. This made it an attractive test platform since the “infrastructure” of fuel and robust electrical plant was in place.



Picture 3.15 Fuel Cell Container on Viking Lady

In this project, a 330 kW fuel cell was successfully installed on board the offshore supply vessel Viking Lady. The project used a Molten Carbonate Fuel Cell (MCFC) , which operates at 650 ºC and was developed by MTU in Germany and modified to operate in a marine environment. Viking Lady is the first vessel to use high-temperature fuel cell technology.

Hydrogen Gas is the most favorable fuel for the cell of the gas electric propulsion system, but the technology has been developed to also work with methanol, LNG, biofuels, and; no additional fuel system was needed to support the MCFC. Its smooth operation was demonstrated for more than 7000 h.

Electricity for propulsion is supplied by four Wartsila 6R32DF engines with an output of 2010 kW each. Its four main generators are Alconza NIR 6391 A-10LWs, each producing 1950kW of power. The ship also has two Rolls Royce AZP100FP propeller systems.

In the current installation, as illustrated in Figure 3.23, the MCFC delivers power to a direct current (DC) link that is connected to the ship's alternating current (AC) bus through power converters. Therefore, the ship's electrical propulsion system consumes from the fuel cell the same amount of energy provided by the main generators.

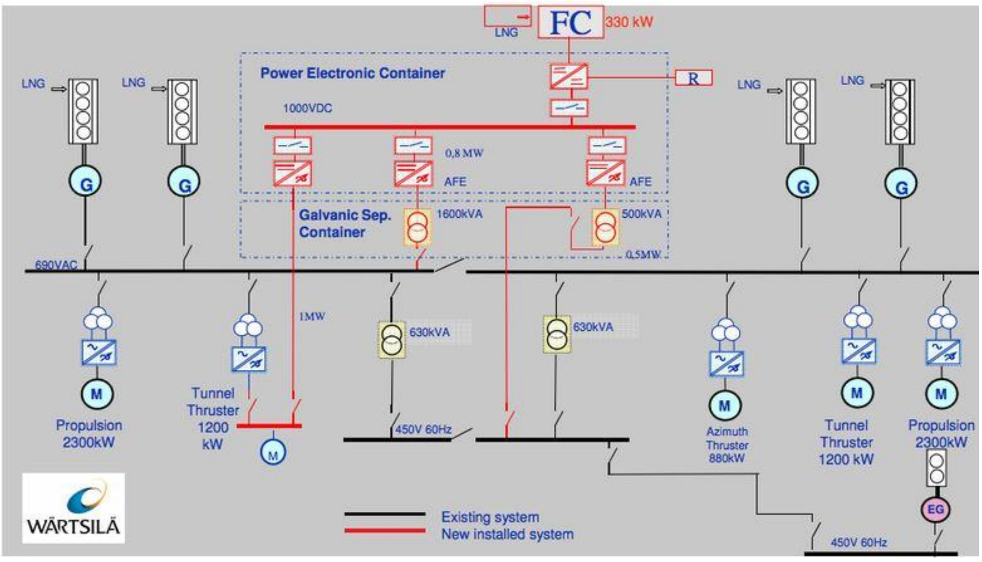


Figure 3.23 Fuel Cell integration in "Viking Lady's" electric propulsion system

The Fuel Cell delivers a direct current voltage varying between 380VDC – 520VDC depending of its load condition and age. Due to material limitations requiring slow load changes, the electrical system had to be designed to keep stable conditions for the Fuel Cell.

The fuel cell stack is located in a large, purpose-built container $(13\ \text{m} \times 5\ \text{m} \times 4.4\ \text{m})$. Project-specific electrical components (transformers, converters and DC bus), designed to protect the fuel cell from potentially harmful disturbances on the power grid, are situated in a standard 20-ft container. The total weight of the containers is 110 tons, but DNV representatives feel that both weight and volume could be significantly reduced with fully integrated systems in the future.

Viking Lady began operations on the North Sea in April 2009, and, in September of the same year, had the 330 kW MCFC power pack installed. The FellowSHIP fuel cell is considered as supplementary power.

Rules were developed based on existing fuel cell standards that were adapted for a ship environment. The DNV rules "Fuel cell installations" was issued in July 2008, and Viking Lady with the FellowSHIP installation was the first vessel to obtain a certificate with the " FC-Safety" notation. The prime role of DNV in the project was to assure that the installation was compatible with marine safety requirements. The approval process had focus on gas safety and the electrical interface to the vessels existing power system.

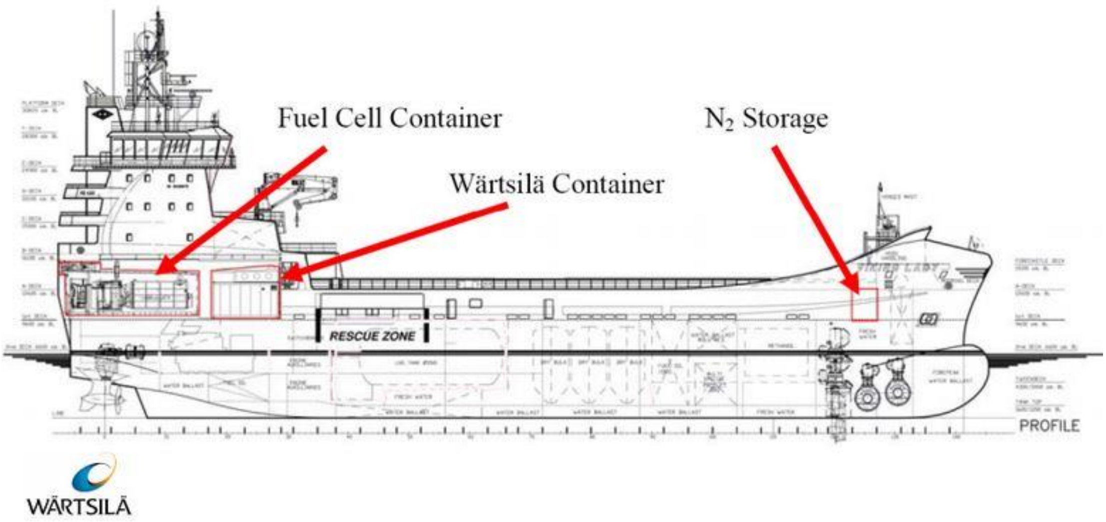


Figure 3.24 Layout of "Viking Lady's " fuel cell elements on board

Being a pilot installation the project has revealed a number of areas for further development. For example, future installations will have a different solution when it comes to nitrogen purging, and pure hydrogen for start-up sequence will be likely not be necessary. No major showstoppers have been revealed, but the required investment cost is considered high. The project partners brought the vessel Viking Lady to Copenhagen during the UN Climate Change Conference "COP 15", putting focus on the LNG fueled vessels and fuel cell technology as two promising technologies to reduce global and local pollution from shipping.

3.3 E4ships Projects

The e4ships project is a cooperative venture funded by the German government that brings together leading German shipyards, shipping companies, fuel cell manufacturers and classification societies in the framework of the National Innovation Programme Hydrogen and Fuel Cell Technology (NIP).

The project partners share an interest in the use of fuel cell technology to ensure a climate-friendly energy supply, primarily for use with auxiliary power units and on board ship supply systems. To accomplish each main objective, the projects employs PEMFC (Proton Exchange Membrane Fuel Cell) and high temperature fuel cells are to be employed

The superordinate module, TOPLATERNE, addresses issues relating to climate change mitigation impacts, economic efficiency, technical safety standards, and the market introduction strategy, also for fuels not yet conventionally used such as sulphur-free diesel or methanol.

The two subordinate projects, SchIBZ and Pa-X-ell, are involved in testing the practical use of fuel cells in the maritime sector. The results of the two demonstration projects have also been used to help produce worldwide rules and standards for the licensing and installation of fuel cells on ships.

Picture 3.16 Cruise ferry MS Mariella – operated by Viking Line between Helsinki and Stockholm

The two subordinate projects, SchIBZ and Pa-X-ell, are involved in testing the practical use of fuel cells in the maritime sector. The results of the two demonstration projects have also been used to help produce worldwide rules and standards for the licensing and installation of fuel cells on ships.

As well as the practical testing of the fuel cells themselves, proposals were elaborated for common regulations governing the use of low-emission fuels like sulphur-free diesel, natural gas or methanol on ships and their provision in ports, so that this innovative technology can be used in future around the world.

In the e4ships joint project, the two major shipyards MEYER WERFT and Thyssenkrupp Marine Systems are developing technically different fuel cell systems with their partners, using different fuels - methanol in one case and diesel in the other. In both cases the result is an almost complete reduction of emissions of soot, sulphur and nitrogen oxides as well as a significant decrease in emissions of climate-damaging carbon dioxide.

E4ships has set itself the goal of substantially reducing harmful emissions through the use of fuel cells on seagoing ships. The first step is to achieve clean on board energy supply in the form of electricity, heat and cooling where appropriate. If ships obtain their energy from fuel cells when in port in future, a considerable improvement in air quality will be achieved.

3.3.1 PA-X-ELL Project

The Pa-X-ell project under the leadership of MEYER WERFT, has been testing the use of high temperature PEM fuel cells in a number of different applications. The goal is to achieve long-term decentralized energy generation on passenger ships.

The fuel cell systems developed in the Pa-X-ell project are liquid-cooled HT PEM fuel cells (in the courtesy of Serenergy) on a modular basis, which use a mix of methanol and water as a fuel (LNG can also be used). Liquid cooling means that exhaust gases can be used in thermal processes, such as an absorption refrigeration system.

A fuel cell module currently has a maximum electric output of 5 kW and contains all components necessary for operation. Alongside the cell stack itself, the reformer, afterburner, in-process heat exchanger, the DC/DC converter and the controls are all located in the module housing. Six such modules can be integrated in a 19” control cabinet modified with an exhaust shaft as well as fuel and cooling water piping, providing an electrical output of 30 kW. The fuel cell module has been tested under different climatic conditions, to establish the limits of its usability. Results indicate that the systems can be used in the air temperatures and air humidity typical of the maritime environment.

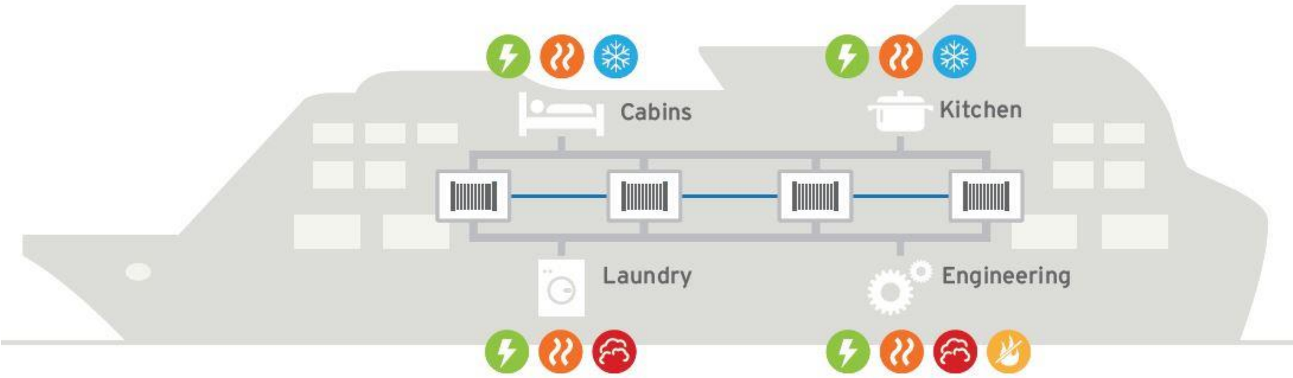
Picture 3.17 Composition of a fuel cell with the inside of a module, the module housing and the fuel cell cabinet [Courtesy of Serenergy]

The fuel cells used offer a high level of efficiency across a very large output range. Especially in the partial-load range, they achieve significantly higher efficiency levels than conventional diesel units. As well as developing the fuel cell systems, the project has run simulations of fuel cell integration in existing on board grids. Both stationary and transient processes were examined, in order to identify the influences of fuel cells on the overall system.

The fuel cell system was installed on the MS Mariella ferry which operates between Stockholm and Helsinki. Here a 60 kW unit was designed and installed as a prefabricated unit on the sun deck of the ferry. In addition, a methanol tank was installed. It is filled by a tanker truck onshore.

This system is also meant for long-term operation, in order to gain experience in the operation of fuel cells on ships. The challenge here is primarily to deal with the constant vibrations and ship movement caused by the ships' engines and sea swell.

The long-term goal of the project partners is to deploy fuel cells in decentralized networks on board passenger ships. Decentralization increases security, as the breakdown of a single unit has no serious effects on the overall system. Each individual fi re zone on a ship can be supplied with power generated by fuel cells. Aside from the positive safety aspect of energy supply of the hotel area, reduced energy flows will also increase the efficiency of the overall system.



Picture 3.18 The Principles of a decentralized network with fuel cells supplying electric power

A further important aspect in the introduction of this new technology is the economic perspective. The fuel cell systems developed in Pa-X-ell are technically fairly mature, but the costs in relation to installed output, and the output per module are not yet competitive for large-scale applications. Here continued intensive development work is still needed, embracing module production and higher energy density.

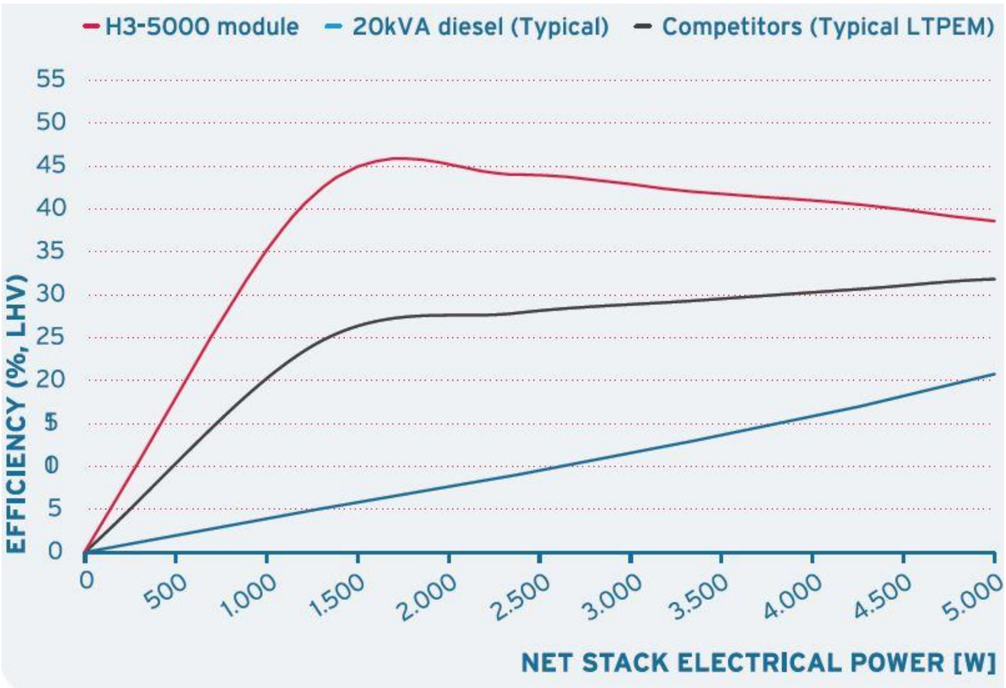


Figure 3.25 Typical level of efficiency of the Serenergy fuel cell and competing products

3.3.2 SCHIBZ Project

The research project SchIBZ [SchiffsIntegration BrennstoffZelle] was initiated to improve the electricity supply on passenger ships and other special vessels. It is aimed at developing a maritime FC-APU (Auxiliary Power Unit) for diesel fuel.

The SchIBZ programme differs from other pilot projects on ships in that it uses a fuel that is commonly known and easily available, with the highest possible energy content. “The use of pure hydrogen is not viable at the present time, because there is no acceptable process available to store the hydrogen within a reasonable volume,” explains Keno Leites, Project Manager of Blohm + Voss Naval GmbH, the leading company. Therefore, the fuel cell system is powered by either diesel or LNG.

All the membrane solutions are viable, according to a preliminary study, which compares the systems available in the market.

Nevertheless, costs are “unacceptably high” with the PEM (Polymer Electrolyte Membrane), especially when the system is compared with the SOFC. That is why they have decided to use a configuration with the SOFC (in the courtesy of Sunfire Co.), where the diesel reformer simultaneously acts as a backup sulphur trap.

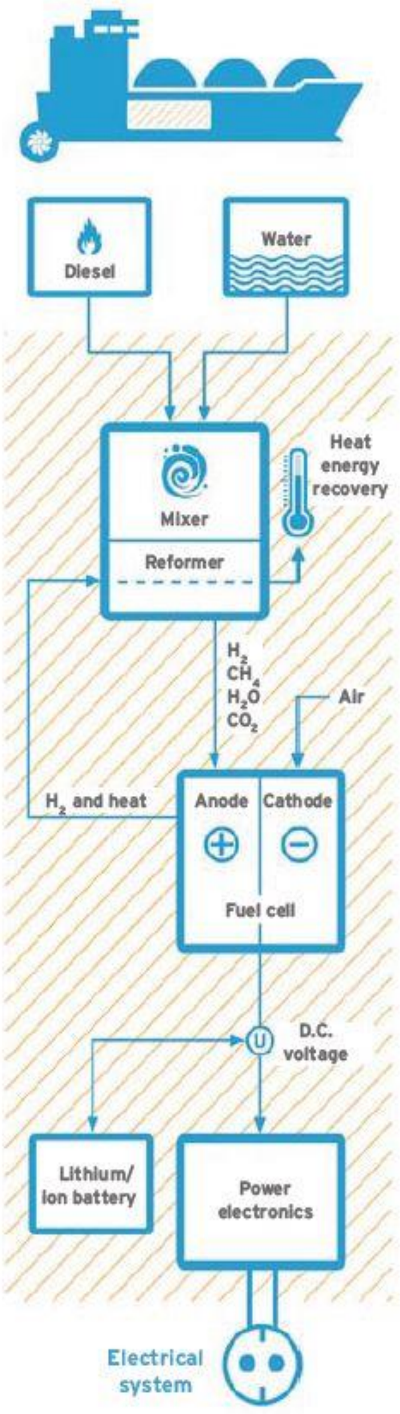


Figure 3.26 Hybrid Synergy of an electrical FC system [e4ships, 2019]

The work on the fuel cell system comprises all stages from the draft and the design of the system and the fuel gas generation to the fuel cell and its power electronics. It also includes the specification of installation requirements, room ventilation and safety concepts. An additional auxiliary unit is an energy buffer, which balances any discrepancies between the consumer grid and fuel cells. A hybrid solution with lithium-ion cells and a super condenser was developed with M&P GmbH, Dresden. It was designed specifically for the subsequent test environments in line with the conditions of the consumer grid. Further fields of work included the development of a system control unit and operational strategies as well as producing a demonstration unit.

What is special about the system is that it uses diesel fuel with a sulphur content of 15 ppm as a fuel for the SOFC. With a relatively simple, cost-effective fuel gas process developed by the Oel-Waerme-Institut, an electrical efficiency level of over 50 % can be achieved. If exhaust heat is used a total degree of use of 90 % can be achieved. The fuel cells and the residual gas burner system work at temperatures of 750 °C, where no thermal nitrogen oxide (NOx) is produced, so that the aggregate exhibits minimal NOx emissions despite the use of diesel without exhaust gas treatment. The emission of sulphur oxide (SOx) and methane (CH_4) is completely inhibited.

For the economic assessment, an innovative fuel cell system for the generation of electric energy was compared with a conventional on board diesel engine (including electric generator), under current operating conditions. Life Cycle Analysis utilized as the main tool used for the economic evaluation of the project. Life cycle analysis is a methodology for determining the overall costs and environmental impacts of a product and for comparing it with other innovative solutions where necessary.

A typical demand profile for electricity generation, manufacture and maintenance costs of the electricity generation systems to be compared, fuel costs as well as the required replacement of fuel cell stacks after about 4 years in operation (see also net present value graph below) served as the input values. In addition to the environmental impacts during the operation of the two electricity- generating systems, the energy required to produce the fuels was calculated, along with the resulting CO_2 emissions.

Results indicate that fuel cells can be operated at a profit in future, if manufacturing costs can be reduced, further efficiency gains realized, and longer lifetimes of fuel cell stacks achieved. This will require intensive technical developments, but the partners believe that the targets can be achieved in the next decade. In addition, fuel cell technology must be placed on an equal political footing in terms of environmental impacts as the legally permissible emissions levels for current diesel generators are still higher.

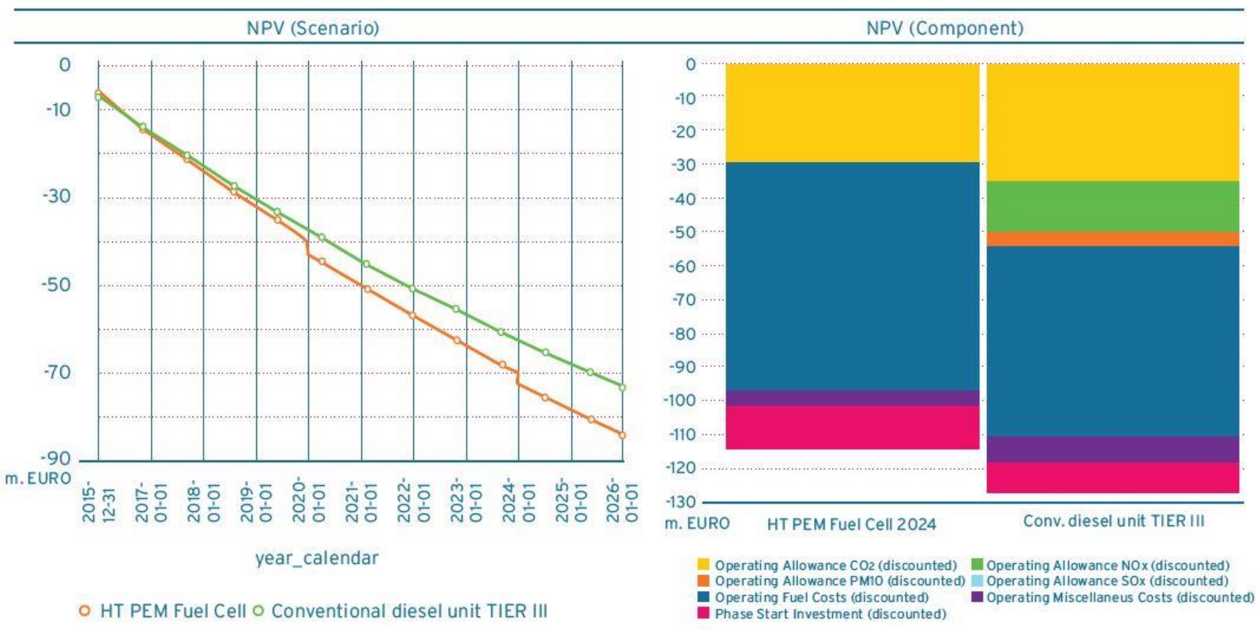


Figure 3.27 **Economics of SCHIBZ Project [e4ships, 2019]**

3.4 NEMO H_2: First FC-Powered Canal Boat

By early 2006, 5 companies (Alewijnse Marine Systems, shipping company Lovers, Linde Gas, Marine Service North and Integral) concurred to set up a project aimed at the development, construction and exploitation of a hydrogen boat, Nemo H2 (Picture 3.19). The hydrogen boat was intended for transport of passengers in the city center of Amsterdam. Finally, world's first fuel cell powered canal boat "Nemo H_2" was launched in Amsterdam on December 2009.

Picture 3.19 NEMO H2, the first fuel cell powered canal boat

Some interesting features of Nemo H2 fuel cell boat are:

- It is an Innovative, durable, carbon neutral & zero-emission canal boat.
- Operates with no combustion!

The ship is propelled by electricity generated by the fuel cell by mixing hydrogen and oxygen. Also part of the project was the realization of a hydrogen filling station at the waterside. The hydrogen station is powered by Noordzee Wind for the electrolysis of water and has a production of 60 m^3 of hydrogen per hour which would be sufficient for two cruise boats.

NEMO's H_2, boat specifications:

- **Passengers:** It is a boat for 87 passengers + 2 crew members.
- **Dimensions:** It is 21.95 m, has a wide of 4.25 m, a depth of 1 meter and a freeboard of 65 cm above the water.
- **Propulsion:** An 11 kW electric bow thruster and a 75 kW electric azimuth thruster
- **Power System:** A PEM Fuel Cell with a power of 60 – 70 kW and an integrated battery of 30 – 50 kW
- **Hydrogen Storage:** It has 6 hydrogen storage tanks with a pressure of 35 MPa for 24 kg of hydrogen.
- **Autonomy:** The ship has a 9-hour range at a cruising speed of 9 knots.
- **Certificates:** The canal boat meets all European Regulation for barges

The Fuel Cell installation including fuel cell system, batteries and hydrogen storage were successfully approved and integrated in the ship. The risk assessment, approval, onshore and onboard testing showed that a safe operation of the vessel is possible

3.5 SF-Breeze

SF-BREEZE (San Francisco Bay Renewable Energy Electric vessel with Zero Emissions) is a collaboration project between Sandia National Laboratories, The Red and White Fleet, the American Bureau of Shipping, the U.S. Coast Guard and naval architect Elliott Bay Design Group.

The project started in 2015 and is a feasibility study to examine the technical, regulatory and economic aspects of building and operating a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco bay area. The project aims to design, build and operate a 150 passenger high-speed hydrogen fuel cell passenger ferry using (Picture 3.20) a PEM fuel cells and liquid hydrogen as fuel.

Picture 3.20 Illustration design of SF-BREEZE [Sandia National Laboratories, 2015]

Hydrogen-powered ferries do exist, but most are smaller, slower vessels used for tours on lakes and rivers. The SF-BREEZE study set out to discover whether it is technically feasible to build a large, fast vessel; it could meet maritime regulations; and it could be economically competitive with modes of transportation already available in the San Francisco Bay area.

The group drew up conceptual specifications: a 150-passenger commuter ferry that would travel four 50-mile round-trip routes each day at a top speed of 35 knots (roughly 39 miles per hour) about 60 percent of the time. The ferry could refuel midday, between the morning and afternoon commutes.

“This kind of boat has never been built before,” says mechanical engineer Curt Leffers, the project manager for Elliott Bay Design Group. “Hydrogen fuel cells are heavier than diesel engines for a given power output, so achieving the right power-to-weight ratio for the vessel was tricky.”

The need for speed drove the design to a slightly longer catamaran. The engineers were able to save weight by consolidating the support equipment for the fuel cells.

To achieve the necessary safety standoffs from the fuel cells, the designers placed fuel cells on the main deck of the vessel in a separate compartment. Leffers explains that this provides physical separation between the fuel cells and passengers.

SF-BREEZE, boat specifications and main goals

- **Passenger capacity:** 150 (the maximum allowed by Subchapter T regulations)
- **Top Speed:** 35 knots
- **Total installed power:** 4.92 MW (4.4 MW for propulsion at top speed, 120 kW for auxiliary power, and the remainder for margin) consisting of (41) 120 kW PEM fuel cell racks, each rack containing four 30 kW PEM fuel cell stacks.
- **Fuel:** 1,200 kg (~4,500 gallons) of LH_2 (Liquid Hydrogen) contained in a single Type C (pressurized vessel) storage tank on the top deck, enough for two 50 nm round trips before refueling, with 200-400 kg margin.
- **Electrical architecture:** DC power from the fuel cells converted to AC power for the motors. Either one or two motors per shaft.
- **Propulsion:** Waterjet or Voith linear jet
- **Amenities:** Standard passenger cabin with restroom and snack bar
- **GHG emissions:** Zero greenhouse gas and criteria pollutants during operation
- **Maneuverability:** Superior response time during power changes (such as during maneuvering)
- **Passenger-friendly:** Less noise and vibration on-board
- **Waste Policy:** Elimination of diesel fuel spills, diesel odor, and exhaust odor

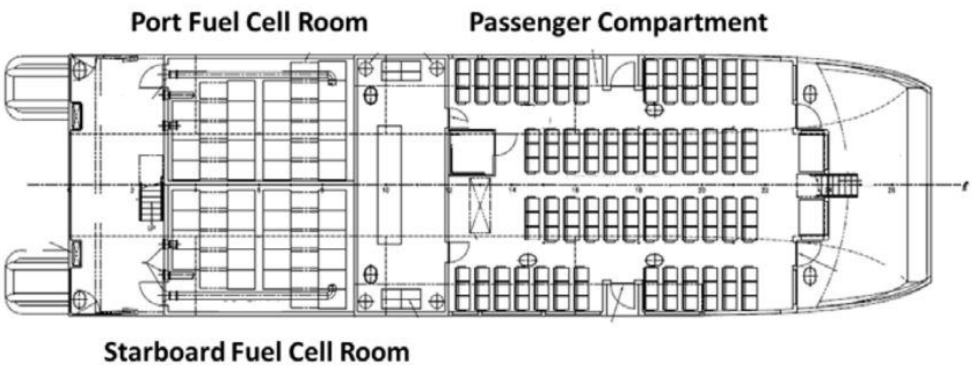


Figure 3.28 **Cutaway view of the Main Deck of the SF-BREEZE. The PEM fuel cells are distributed into a Starboard Fuel Cell**

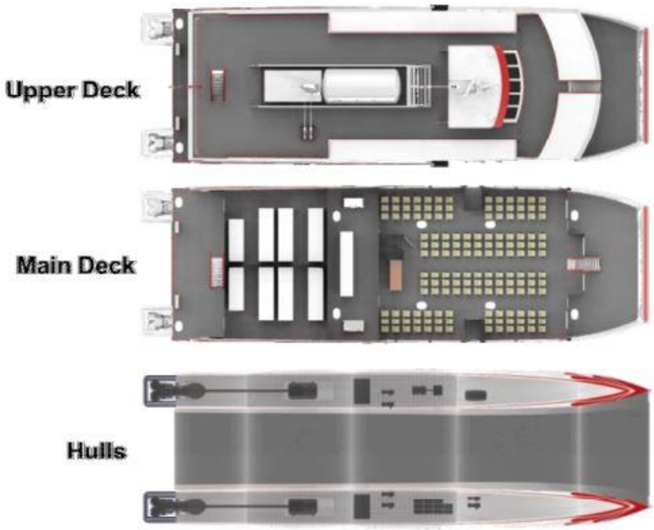


Figure 3.29 **The three decks of SF – BREEZE**

A feasibility study, held in 2016, stands for San Francisco Bay Renewable Energy Electric Vessel with Zero Emissions. Funded by the Department of Transportation's Maritime Administration and led by Sandia, the feasibility study brought together the American Bureau of Shipping (ABS), the US Coast Guard, naval architect Elliott Bay Design Group, the Port of San Francisco, and dozens of other contributors.

A high speed passenger ferry was chosen as the subject hydrogen fuel cell vessel for this feasibility study partly because of its clear commercial application and familiarity to the project originator, Red and White Fleet. To the project team, just as important in this choice was the fact that a high speed passenger ferry would stretch the limits of feasibility in ways that low speed and/or cargo vessels could not. The team felt that if feasibility of a zero emission hydrogen vessel was demonstrated with a high speed craft, the conclusion would apply to a wider range of other commercial vessels.

This study concludes that a zero-emission high-speed, 150-passenger vessel and its associated hydrogen station are both technically feasible, with no technical or regulatory show-stoppers identified, and that the vessel will be acceptable from a regulatory perspective once a more detailed “ready-to-build” design is generated.

These conclusions were reached after careful consideration of vessel design with a novel fuel and powerplant, implementation of liquid hydrogen as a fuel including on-board safety and bunkering logistics, existing and developing regulations, and development of actual candidate bunkering sites. There is no reason to believe these conclusions would be different for slower vessels or vessels with larger passenger capacity, although this would need to be verified.

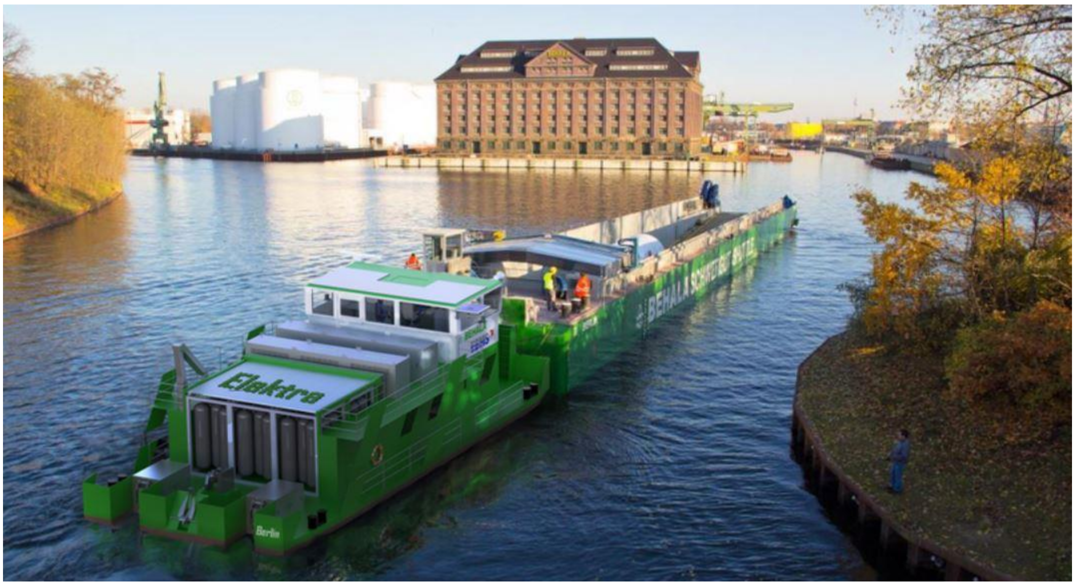
However, the economics of the SF-BREEZE high speed ferry are challenging in the near term given 1.5-2 times increase in capital cost and the roughly 3-10 times higher operating cost if it were to be built and operated today. The situation improves if the expected reductions in hydrogen technology (fuel cells, tanks, etc.) costs occur. As mentioned in various places, the high capital and operating cost differential is due primarily to the high cost of fuel cell technology today. This problem is exacerbated by the lower transportation efficiency of the SF-BREEZE on a per-passenger basis, which in turn is due to the higher weight of the vessel.

3.6 Elektra

The Technische Universität Berlin is developing an electric pusher boat, with batteries and fuels cells as the source of energy. Project's main leader is the engineer Gerd Holbach who is a Professor at Berlin's technical university. **Elektra uses a hybrid drive system, a combination of rechargeable batteries and fuel cells. Hydrogen would be the main fuel of the FC system.**

The pusher boat is being developed in close collaboration with the users and sponsors, the logistical service providers BeHaLa and Imperial. The project is due to be completed in December of 2024.

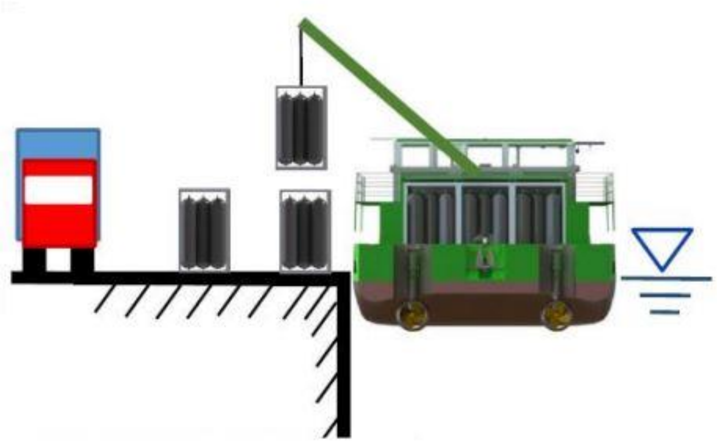
The drivetrain is geared to the sizes and user profiles of cargo ships in the Berlin-Brandenburg region. At 19 meters long, it can take a barge through all the locks of Hamburg or the Baltic Sea ports without having to detach, and its 8.20-meter width is needed for the 1,400-ton gas turbines from the Siemens factory in Berlin.



Picture 3.21 Elektra: a hybrid ship using FCS and rechargeable batteries

The ship is equipped with two electric motors of 200 kW each. With fully charged batteries (twice 1,250 kWh), it has a range of 65 km at 8 km/h.

The vessel can manage longer journeys to the seaports of Hamburg and Stettin, a day trip of 130 km at a speed of 8.5 km/h, using its hydrogen fuel cells that are connected in parallel for a total capacity of 192 kW. The ship has a reservoir of 740 kg hydrogen on board, stored under 500 bar pressure in six tanks. Further, on the wheelhouse roof, there are solar panels with a peak capacity of 2.5 kW for the on-board power supply, which also has a 230 kWh battery.



Picture 3.22 **Elektra's proposed bunkering system**

Due to the limited space on the ship for the drive system – it also needs to provide room for three crew members on journeys lasting several days between the seaports and Berlin – it has a maximum speed of 10 km/h, necessary for special manoeuvres. The ship is therefore not permitted to navigate the Rhine, as a peak speed of 13 km/h is prescribed there.

Thanks to a financial injection of 4.7 million euros from the German transport ministry and from involved partners, the concept is to go into production. Holbach is currently looking for suppliers. He estimates that construction of the prototype will commence in the autumn of 2019, w ith the launch scheduled a year later. Realisation also depends on developments in Germany's hydrogen infrastructure, which is currently being developed.

With its shore power and hydrogen, the ELEKTRA sails under zero emission. If both are generated sustainably, then the passage of this ship is completely zero emission. And that's precisely what the partners of this project are aiming for. **The ELEKTRA anticipates the desire to make all Berlin's transport zero emission by 2050.**

4th CHAPTER

Regulations for Fuel Cells in Shipping

A Summary of Standards & Guidelines for FCs & Hydrogen

Picture 4.23 **IMO is United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.**

4.1 Introduction

Chapter 4 gives an overview of current applicable standards, regulations and guidelines for bunkering of fuel, on-board storage and distribution and on-board use of fuel cell installations in shipping. Regulatory information has been reviewed both on a national and international level.

Low flashpoint fuels (methanol, ethanol, low flashpoint diesel and bio diesel) including hydrogen have huge potential to contribute to future sustainable low-carbon economy. There is large expectation and ambition towards wider application of such fuels including hydrogen made from carbon free resources. Especially, the automobile industry, has made gigantic steps for the introduction of hydrogen fueled-power vehicles in the market. Toyota, which is one of the leading manufacturers in the world, has already put into production the Hydrogen-Powered car called "Mirai" due to enormous efforts and long-term determination. "Mirai" is truly a visionary car. From the advanced fuel cell stack at its heart and with 0% emissions that car revolutionizes the automobile industry while it dictates the morality of the Toyota which envisages an era of peace and respect between the transport industry and our planet. **After all, the evolution is real only when the impacts of our products and technology benefits both the human race and their surroundings, environment and outer atmosphere**. As a matter of fact, it is anticipated that future hydrogen trade will be encouraged by wider utilization and higher demand. To achieve this, new solutions will be needed both for supply side and demand side. It will be needed to scale up the distribution/transportation which bridges between supply and demand. As preparation for the full-fledged commercialization of fuel cell vehicles, huge effort has been put on the coordination of Regulation, Codes and Standards for fuel cell vehicles and their infrastructures

However, there are no existing regulations or rules that completely cover hydrogen bunkering, storage facilities or fuel cell systems safe operability but there are related regulations and guidance that, when combined with technical knowledge of hydrogen properties and systems, can be used to help define a regulatory approach for LH_2 bunkering and guarantee a secure fuel cell operation. Considering the current rate of environmental regulations coming into force, it should be safe to say the industry is amid a turning point. - **Relevant work is currently ongoing at international level, one example being rules for fuel cell installations currently in development in IMO.**

4.2 Standards/Regulations & Guidelines for FCs in Shipping

The overview provides a snapshot of the regulatory environment for fuel cell installations aboard ships. **Chapter 4** will identify and assess current Regulations, Codes & Standards, including Guidelines, related to fuel cells and associated fuels. While it is of high importance to analyze every possible fuel used in fuel cells (LNG/CNG, methanol, ethanol, low flashpoint diesel and bio diesel), this section focuses on the operability of hydrogen fuel cell systems as they compose the most promising and opportune technology in transport industry.

4.2.1 Current Status

As mentioned in **Chapter 3**, there have been a plethora of completed projects using fuel cell powering systems. Those initiatives (led, in the majority of the cases, by companies to increase their social status, popularity and competition) have shed light upon many blurry aspects of fuel cells while they have showcased their advantages and challenges. Nevertheless, the international organizations, as well as the states**,** find the venture of developing specific rules for hydrogen and fuel cells vessels pretty demanding. **Efforts have** been made to overcome those barriers but **at this point no certified legislation has been developed.** These law gaps bring a high level of uncertainty, discourages the scientific community and as a result undermines the future of fuel cell technology. However, observing the absence of vital and solid guidelines for the application of fuel cells on ships, while witnessing the continuing interest in the fuel cell powered systems**, classification societies have taken action and decided to conduct relevant research on the pick and support safe design, operation and maintenance of fuel cell power systems onboard ships.**

4.2.2 European Framework

The EU policy aiming at reducing emissions from shipping and introducing alternative fuels have led to introduction of important European legislation. The most important ones are outlined in this subsection.

After 1st January 2015, the EU Member States are required to ensure that ships in the Baltic, the North Sea and the English Channel use fuels **with Sulphur content not exceeding 0.10%**. In other European sea areas, the limit is 0.5% by 2020. Operations with higher sulphur contents are still possible, but only if appropriate exhaust cleaning systems are in place. Previously, the maximum sulphur content of marine fuels was limited to 3.5%. The Directive on Sulphur Content in Marine Fuels (2012/33/EU) allows the use of LNG as an alternative fuel for compliance with more stringent emission standards.

A Baltic and North Sea NO_X Environmental Control Area was adopted by Marine Environment Protection Committee (MEPC), MEPC 71on July of 2017, and will become effective on the 1st of January in 2021. If so, this will apply to ships constructed on or after Jan.1 2021. The requirements will be similar to the North American / U.S. Caribbean NECA.

For CO_2, amendments to MARPOL were adopted at MEPC 70 in 2016, the new regulation requiring global reporting of fuel consumption data. Guidelines are still under development. All vessels above 5000 GT need to report fuel consumption. This regulation put into force in the 1st of January in 2019.

Simultaneously, the European Commission in 2015 launched a separate and rather similar initiative, the MRV regulation[1]. The MRV (Monitoring, Reporting and Verification) regulation aims to quantify and reduce CO_2 emissions from shipping and will create a new kind of benchmarking system in Europe. Ships above 5000 GT (all flags) must annually report CO_2 emission on voyages to, from and between EU ports

4.2.3 International Rules – IMO

Shipping is an international industry, and international environmental, security and safety standards for shipping are developed by the International Maritime Organization (IMO). IMO is a United Nation specialized agency.

The Directive on Sulphur Content in Marine Fuels (1999/32/EC) has been amended to include provisions of Annex VI of IMO's Marine Pollution Convention, MARPOL 73/78. However, the European Commission called for further action by the International Maritime Organization (IMO) to reduce emissions. Thus, an amended Annex VI was adopted in October 2008. MARPOL Annex VI lowers the maximum permissible sulphur content of marine fuels inside and outside of SECAs. These limits are now EU law outlined in Directive 2012/33/EU.

Maritime applications of fuel cell systems must satisfy:

- **A.** requirements for on-board energy generation systems and
- **B.** fuel-specific requirements regarding the arrangement and design of the fuel handling components, the piping, materials and the storage.

In current regulations, these aspects are handled separately. In the present section, the relevant international regulations of the IMO for both aspects mentioned above are presented.

At international level IMO is the responsible body for drafting, discussing, approving, publishing and maintaining the main regulatory instruments that will be important for fuel cell installations in ships. The IMO structure is presented in Figure 4.30 below providing an overview of the structure for this organization. Further to the main structure presented, the IGF (International Code of Safety for Ships Using Gases) and IGC (International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk) codes are included close to the Sub-Committee on Carriage of Cargo and Containers – the one responsible for the work on the IGF Code. The IGF Code will, at international level, provide the necessary regulatory certainty for the adoption of low flashpoint marine fuels, by ships designed and built in compliance with the code.

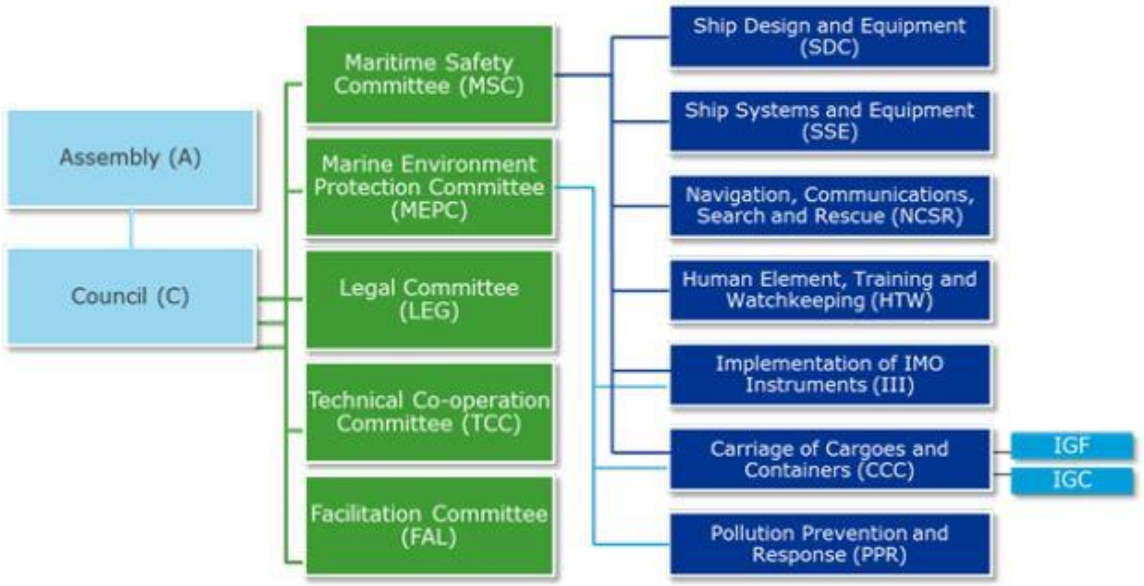


Figure 4.30 IMO's Modular Structure [EMSA, 2015]

4.2.3.1 SOLAS

The International Convention for the Safety of Life at Sea (SOLAS) defines as an international agreed minimum requirement for the construction, equipment and operation of ships. Flag States must ensure that these minimum requirements are met. IMO has developed requirements for vehicle carriers carrying motor vehicles with compressed hydrogen or natural gas in their tanks for their own propulsion as cargo (SOLAS II-2 Reg. 20.1). This is the part relevant to fuel cells. The IMO sub-committee on Fire Protection (FP) agreed to introduce new requirements for electrical equipment and wiring, ventilation and gas detection. Entry into force was on 1 January 2016.

When it comes to a suggested alternative design and arrangements for machinery, electrical installations and low – flashpoint fuel storage and distribution systems, the Regulation 55 (and MSC.1/Circ.1455) must be followed. In this document, a methodology is proposed for the evaluation of a suggested alternative design. Although the process is deconstructed in detailed guidelines, the conduction of this task is really meticulous.

4.2.3.2 IGF Code

Based on the experience with the approval and operation of gas-powered ships, the Norwegian administration initiated **the development of an international code for gas-powered ships in 2004**. A lot of effort was needed in order to establish a globally approved code through a multitude of Resolutions. Finally, The IGF Code development resulted in adoption by the MSC committee in June 2015, meaning that the code was formally approved. The IGF Code entered into force on 1 January 2017.

The IGF Code is mandatory for all gases and other low flashpoint fuels. However, it only contains detail requirements for natural gas (LNG or CNG) as fuel. Internal combustion engines, boilers and gas turbines are included as consumers. For other gases and low flashpoint fuels, the IGF Code Part A requires the alternative design method in accordance with SOLAS Regulation II-1/55 to be used demonstrating an equivalent level of safety.

It should be noted that the fuel cell regulations under development in IMO will cover the fuel cell installation, but not the fuel storage and fuel supply system. If the fuel cell is using other gases or low flashpoint fuels than natural gas (covered by Part A-1 of the Code), the alternative design approach must be used in accordance with Part A of the Code for the fuel storage and fuel supply system until specific provisions for these aspects are developed for each of the low-flashpoint fuels in question.

Major Outcomes of the 5th Session of the IMO Sub-Committee on Carriage of Cargoes and Containers (CCC5)

The above mentioned session took place from 10 to 14 in the last September (2018). Some of each major outcome, when it comes to fuel cells and the use of hydrogen fuel are summarized in item 3 (amendments to the IGF code and development of guidelines for low-flashpoint fuels).

Its main components are:

A. CCC5 re-established the Correspondence Group (CG) to continue the work on the draft amendments to the IGF Code regarding fuel cells and the development of the draft technical provisions for the safety of ships using methyl/ethyl alcohol as fuel.

B. CCC 5 agreed to develop the safety provisions for fuel cells as interim guidelines, instead of developing a new part E of the IGF Code for fuel cells, as formerly envisaged (task should be completed by 2024).

C. Unfortunately, hydrogen specific requirements are not yet on the agenda in IMO/CCC

As there is a great interest in the scientific community and marine industries about fuel cell technology, the development and legislation of safety provisions for fuel cell systems from IMO is of a great necessity while is highly expected.

4.2.3.3 IMDG Code

The IMDG (International Maritime Dangerous Goods Code) **Code covers hydrogen and other dangerous goods as packed cargo**. Transport of such goods in the ship’s own cargo tanks is not included. The IMDG code gives requirements for compressed hydrogen and refrigerated liquid hydrogen which are comparable to those for compressed natural gas and refrigerated liquid natural gas. As packed cargo, compressed and liquid hydrogen cannot be transported by cargo or passenger ships which carry more than 25 passengers or 1 passenger per 3m of overall length. In any case, liquid hydrogen cannot be stowed in under deck. Compressed and liquid natural gas have the same limitation in the IMDG code as packed cargo.

However, as fuel, IGF code enables to store fuel natural gas on-board passenger ships carrying more than 25 passengers. **Due to its properties, it should be anticipated that hydrogen will be considered at least as strict as natural gas**. Initial restriction regarding storage quantities and location can be anticipated (**e.g. storage on top deck**)

Picture 4.24 A Ship Bunkering

4.2.4 Classification Rules Applicable for Fuel Cells

This section considers the relevant Class Rules issued - or under development - by the largest relevant classification societies. A detailed description of the rules and how the rules apply are given in the Appendix, with the example of DNV GL.

In response to the observed lack of consistent and traceable standards for the application of fuel cells on ships, while acknowledging the increasing interest in alternative powering systems, Classification Societies have decided to research the topic and create guidelines to support safe design, manufacturing, operation and maintenance of fuel cell power systems onboard ships

4.2.4.1 Status

Presently the guidelines have preliminary status and are subject to internal and external review. Internal comments have been received and feedback analysis is in progress. At the same time the preliminary version of the guidelines is used for application to real projects, which provides additional opportunities for refinement and completion. The guidelines are primarily based on the “Interim Guidelines for Natural Gas-Fueled Engine Installations in Ships”, as prepared by the IMO’s Sub-Committee on Bulk Liquids and Gases (BLG), which was replaced by the International Code of safety for Gas-fueled Ships (IGF Code)

4.2.4.2 Perspective

The objective of the guidelines is to provide criteria for the arrangement and installation of machinery for propulsion and auxiliary purposes, using fuel cell installations, which have an equivalent level of integrity in terms of safety, reliability and dependability as can be achieved with (new and) comparable conventional oil fueled main and auxiliary machinery.

The guidelines apply to fuel cell systems on ships using a gas as fuel and oxygen from ambient air as oxidant. The use onboard of both gas (in particular hydrogen) and hydrocarbon based fuel is subject to special examination to take into account the specificities of hybrid powering systems (e.g. safety issues associated with the possible interactions between the different fuel systems).

The guidelines are primarily intended for application to new ships, but can be used for retrofitting fuel cell systems on existing ships as well (extent of application of the guidelines to be decided on a case-by-case basis). The guidelines are to be applied in addition to the relevant provisions of the SOLAS Convention, as applicable.

There is no limitation on the type or power of the applied fuel cell power system. There is also no limitation on the type of gas used, although the guidelines mainly focus on natural gas and hydrogen as fuels. The gas may be stored in both gaseous and liquid state, while gas reforming is covered as well. Other types of processes, such as metal hydride storage of hydrogen and storage and use of pure oxygen as oxidant are not explicitly covered and are therefore subject to special examination.

4.2.4.3 Overview of Classification Rules

Table 4.10 and Table 4.11 give an overview of applicable Classification Rules for Fuel Cell installations and their characteristics.

Table 4.10 Overview of applicable class rules for fuel cell installations and their status

Short Name	Association	Title of Document	Status
ABS	American Bureu of Shipping	Fuel cell Powered Ships Guide	In development
BV	Bureau Veritas	Guidelines for Fuel cell Systems On-board Commercial ships	Realeased in April 2009
DNV GL	DNV GL	NV GL rules for classification of ships Part 6 - Chapter 2 - Section 3: Fuel cell Installation - FC	Released in January of 2016
	Det Norske Veritas	DNV Rules for Classification Part 6 - Chapter 23: Fuel cell Installations	Released in July of 2008 (expired)
	Germanischer Lloyd	GL Klassifikationsvorschriften VI-Teil 3-Kapitel 11: Richtlinien für den Einsatz von Brennstoffzellen-System an Bord von Wasserfahrzeugen	Released in 2002 (expired)
KR	Korean Register of Shipping	Guidance for Fuel cell Systems on Board of Ships GC - 12CE	Released in July of 2014
LR	Lloyds Register	LR Technical Papers Development of requirements for Fuel cells in the marine environment – Performance and prescription	Released in 2006

Table 4.11 Key features of applicable Classification Rules regarding to Fuel Cell installations

Description	ABS	BV	DNV GL	LR	KR
Own prescriptive rules	Directive under development. Since 2009	Directive published in 2009	Directive published in 2016	-	Direcrive published in 2014
Alternative authorization procedure	-	-	-	Risk-based process	-
Based on MSC.285(86) (LNG interim guidelines)	-	Yes	Yes	No	Yes
Regulated fuels	-	Natural gas, Hydrogen	All fuels with flashpoint ≤60 °C	No; Risk-based process	All fuels with flashpoint ≤60 °C
Class approval	-	No	FC(Power) FC(Safety)	No	“FC-PWR” “FC”
Risk analysis required	Yes; No specific method	Yes; No specific method	Yes; FMEA	Yes; No specific method	Yes; FMEA
Complementary material requirements	-	Yes; Hydrogen (gaseous, liquefied)	Reference to general guidelines of DNV GL.	No	Reference to IEC 62282-3 and Rules for the Classification of Steel Ships (KR)

4.2.5 Standards for Fuel Cell Applications

The International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) developed rules and standards to cover safety and test requirements of fuel cells primarily for road vehicles and small stationary power systems. The first larger number commercial developments of fuel cells are as power sources for stationary applications for the heat and power supply with up to 1.4MW electrical output. Based on these developments the IEC reviewed and expanded their technical specifications to fuel cell technologies in all applications including but not limited to stationary power, transportation, portable power and micro power applications.

The following standard series are recognized to be relevant for maritime applications and have been widely adopted in Germany, EU, Korea, Canada, South Africa and China, as additions to the national rules:

- **IEC 62282 – Fuel Cell Technologies**
- **ISO 16110 – Hydrogen Generators**

IEC 62282 – Fuel Cell Technologies

[1] **IEC 62282 – 1:2012 "Terminology"**

IEC 62282-1:2012 "Terminology" The first part of the standard series provides uniform terminology in the forms of diagrams, definitions and equations related to fuel cell technologies in all applications.

[2] **IEC 62282 – 2:2012 "Fuel Cell Modules"**

This part provides the minimum requirements for safety and performance of fuel cell modules with or without an enclosure which can be operated at significant pressurization levels or close to ambient pressure. It applies to fuel cell modules with any kind of electrolyte chemistry.

[3] IEC 62282 – 3 – 100:2012 "Stationary fuel cell power systems - Safety"

This standard is applicable to stationary fuel cell power systems intended for indoor and outdoor commercial, industrial and residential use in non-hazardous areas, with or without the ability to recover useful heat. It applies to all kind of fuels like natural gas and other methane rich gases, fuels from oil refining, liquids and hydrogen rich gaseous. Although this part does not cover propulsion fuel cell power systems, it is applicable to marine auxiliary power systems.

[4] IEC 62282 – 3 – 200:2012 "Stationary fuel cell power systems – Performance test methods"

This part covers operational and environmental aspects of the stationary fuel cell power systems performance for systems with an electrical output of over 10 kW (systems with less than 10kW are dealt with IEC 62282-3-201).

[5] IEC 62282 – 3 – 300:2012 "Stationary fuel cell power systems Installations"

This part provides minimum safety requirements for the installation of indoor and outdoor stationary fuel cell power systems in compliance with IEC 62282-3-100.

[6] IEC 62282 – 7– 1:2010 "Single cell test methods for Polymer Electrolyte Fuel Cell (PEMFC)"

This Technical Specification describes standard single-cell test methods for polymer electrolyte fuel cells (PEFCs). It provides consistent and repeatable methods to test the performance of single cells and cell components, including membrane-electrode assemblies (MEAs) and flow plates. This Technical Specification is also available for fuel suppliers to determine the maximum allowable impurities in fuels.

[7] IEC 62282 – 7 – 2:2014 "Single cell and stack performance tests for Solid Oxide Fuel Cells (SOFC)"

This standard describes test methods for a single cell and stack that is to be employed in power generation systems using solid oxide fuel cells (SOFCs), but is not applicable to small button cells that are designed for SOFC material testing and provide no practical means of fuel utilization measurement. It is to be used for data exchanges in commercial transactions between cell manufacturers and system developers.

[8] ISO 14687 – 3:2014 "Proton Exchange Membrane (PEM) fuel cell applications for stationary appliances"

The purpose of this part is to establish an international standard of quality characteristics of hydrogen fuel for stationary fuel cells

[9] ISO 16110 – 1:2007 "Hydrogen generators using fuel processing technologies – safety"

Part 1 of this standard applies to packaged, self-contained or factory matched hydrogen generation systems with a capacity of less than $400\ \mathrm{m}^3/\mathrm{h}$ at $0\ ℃$ and $101{,}325\ kPa$, intended for indoor and outdoor commercial, industrial, light industrial and residential use. It applies to hydrogen generators using one or a combination of different fuels like natural gas and other methane-rich gases, fuels derived from oil refining, fossil fuel sources (e.g. methanol) and gaseous mixtures containing hydrogen gas. Hydrogen generators are referred to as devices that convert a fuel to a hydrogen-rich stream of composition and conditions suitable for the type of device using the hydrogen. This device can be a fuel cell power system, or a hydrogen compression, storage and delivery system. It aims to cover all significant hazards, hazardous situations and events relevant to hydrogen generators, with the exception of those associated with environmental compatibility.

These guidelines contain information on the individual components of a fuel cell as well as on the structure of a fuel cell system. Even if the primary applications are road vehicles and stationary power supplier, these guidelines may be consulted to orient fuel cell design for use on ships. In particular, the regulation of different fuels, simplifies adaption to the environmentally conditions on a ship.

The IEC is currently working on the extension of 62282-3-400, to regulate small stationary fuel cell power system with combined heat and power output and on 62282-8, to regulate Energy storage systems using fuel cell modules in reverse mode

4.2.6 Hydrogen Fuel

When mentioning fuel cells, the fuel that immediately may come to mind will be hydrogen. This is indeed the fuel used by fuel cells in the core of its electrochemical working principle. It is however also the case that the hydrogen (or any form of H_2 rich gas, usually called "syngas") can be obtained through reforming of a different fuel source, used for practical energy storage purposes. In any case hydrogen will be present in the close vicinity of the fuel cell. More specifically, hydrogen will be present through all the process lines between the reforming unit and the fuel cell. **For storage, bunkering, distribution and handling, the applicable requirements are therefore those that apply for the fuel used before reforming.**

Notwithstanding any potential reservations regarding hydrogen as fuel for shipping, hydrogen has been used throughout the world as an industrial gas for a long time. Therefore, regulations, standards and codes covering industrial use are in place. Areas as land transport and local pipelines are also reasonable well covered. Hydrogen as fuel is a newer application, but the regulatory scheme for hydrogen refueling stations and fuel cell vehicles are becoming established.

The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) covers all road transport of dangerous goods as cargo. Just as for maritime, transport of own fuel is not included in ADR, but in other codes (EC directives). ADR can be considered as the land transport parallel to the maritime code for transport of maritime dangerous goods as cargo (IMDG Code), and the structure of the IMDG Code and the ADR are consistent. Even though the IMDG Code and ADR cover hydrogen as cargo, but not as fuel, the codes can provide valuable input for developing requirements for hydrogen as a fuel in shipping. ADR includes provisions for both gas and liquid fuels and includes e.g. classification of dangerous goods according to the danger the different substances present, requirements for packing and tank provisions and provisions concerning the conditions of carriage, loading, unloading and handling.

Maritime transport using packages is covered by IMDG Code. A good starting point is ISO technical committee 197 Hydrogen technologies, offering standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen[4]. The ISO TC 197 also includes a H2 bunkering procedure for airports.

4.2.7 Hydrogen Storage

The main standards for each storage condition of hydrogen are the following:

4.2.7.1 Compressed Gas Storage

[1] ISOTR 15916 "Basis considerations for the safety of hydrogen systems"

ISOTR15916 gives a very useful overview of safety relevant properties and related considerations for hydrogen. Annex C gives a good and very relevant overview of low temperature effects of hydrogen on materials, and the document also suggest suitable material selection criteria including how to consider hydrogen embrittlement.

[2] ISO 15399 "Gaseous Hydrogen – Cylinders and tubes for stationary storage"

This standard covers cylinders and tubes intended for the stationary storage of gaseous hydrogen of up to a volume of 10 000 l and a pressure of 110 MPa, of seamless metallic or composite construction.

European standards covering pressure vessels used for pressures exceeding 0.5 bar are harmonized with PED. EN 1252-1:1998 on storage tank materials, EN 1797:2001 on gas/material compatibility, and EN 13648 part 1, 2, and 3 on safety devices for protection against excessive pressure are some of the standards related to hydrogen storage.

[3] ISO 26142:2010 "Hydrogen Detection Apparatus – Stationary Applications"

This standard defines the performance requirements and test methods of hydrogen detection apparatus that measure and monitor hydrogen concentrations in stationary applications. The standard cover hydrogen detection apparatus used to achieve the single and/or multilevel safety operations, such as nitrogen purging or ventilation and/or system shut-off corresponding to the hydrogen concentration. The requirements applicable to the overall safety system and the installation requirements are excluded. This standard sets out only the requirements applicable to a product standard for hydrogen detection apparatus, such as precision, response time, stability, measuring range, and selectivity and poisoning. This standard is intended to be used for certification purposes.

4.2.7.2 Liquid Hydrogen Storage

The IGC and IGF codes cover storage of liquefied gas on-board ships. The defined **C-tank rules** for storage of liquefied gas will in principle cover hydrogen cooled to liquefied form. Additional considerations will however be required due to the properties of hydrogen including the low storage temperatures.

ISO/TC 220 is a standard for Cryogenic vessels developed for land based application. Set of standards in the field of insulated vessels (vacuum or non-vacuum) for the storage and the transport of refrigerated liquefied gases of class 2 of "Recommendations on the Transport of Dangerous Goods - Model regulations - of the United Nations", in particular concerning the design of the vessels and their safety accessories, gas / materials compatibility, insulation performance, the operational requirements of the equipment and accessories.

4.2.7.3 Hydrogen Piping Network

The standard **ISO 15649:2001** on piping for petroleum and natural gas industries is used as a guideline also for hydrogen technologies. This standard is applicable to piping within facilities and for packaged equipment, with exclusion of transportation pipelines and associated plant.

Picture 4.25 Hydrogen Storage is a delicate issue that requires carefulness and cautious strategies

4.2.7 Gas Fuels

Existing pressure vessel rules is expected to form the regulatory basis and cover most needs for the physical storage vessels for pressured gas fuels to be used in fuel cells on-board ships. Road transport of compressed hydrogen is regulated by the UN Model Regulation, the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) and the European Transportable Pressure Equipment Directive (1999/36/EC – "TPED"). The Seveso III Directive (Directive 2012/18/EU) is applicable in case of storage of more than 5 tons of hydrogen.

The UNECE Inland Transport Committee (ITC) provides an international legal framework and technical regulations for development of international road, rail, inland water and dangerous goods transport. In Europe, also, the EIGA IGC Doc 06/02 is relevant (European Industrial Gases Association), in addition to any local regulation. The codes covering own fuels include limitations regarding allowed quantities that can be stored in vehicle. For pipeline transport, EIGA (IGC Doc 121/04) will apply in Europe, in addition to any local regulation.

4.2.7.1 Stationary Gas Fuel Applications

This sub-chapter lists some of the most relevant European Directives and applicable standards for hydrogen fuel cell systems and components**. This particular list was developed for an onshore building project, but it will also be applicable for most stationary hydrogen applications as well as many transport applications with hydrogen involving the referred system components.**

Table 4.12 gives a summary of relevant applicable regulations. These regulations are also considered applicable for maritime hydrogen projects.

Table 4.12 Overview of European Directives applicable for Gas Fuels

Relevant Regulations	SYSTEM					
	Electrolyser Fuel	Fuel cell micro CHP	H2 storage, piping	H2 burner, boiler	Energy management control system	Safety system
ATEX Directive (94/9/EC)	x	x	x			
Pressure Equipment Directive (97/23/EC)	x	x	x			
Gas Appliance Directive (2009/142/EC)		x		x		
Electromagnetic compatibility Directive (2004/108/EC	x	x		x	x	x
Low Voltage Directive (2006/95/EC)	x	x		x	x	x
Hot Water Boiler Directive (92/42/EEC)				x		

4.2.7.1 Electrolyzers

The most relevant standards are enlisted and briefly described in the following.

[1] **ISO 22734 – 1:2008 "Hydrogen generators using water electrolysis process Part 1: Industrial and commercial applications"**

This standard is applicable to hydrogen generators intended for indoor and outdoor commercial and industrial use (non-residential use).

[2] **ISO 22734 – 2:2011 "Hydrogen generators using water electrolysis process Part 2: Residential applications"**

This standard is applicable to hydrogen generators intended for indoor and outdoor residential use.

4.2.7.1 Fuel Cell-based Micro Cogeneration Systems

The most relevant standards are enlisted and briefly described in the following.

[1] IEC 62282 "Fuel Cell Technologies"

This is a series of standards divided into 7 parts, covering stationary, portable, and micro fuel cell power systems.

[2] EN 50465 "Gas appliances"

Fuel cell gas heating appliances - Fuel cell gas heating appliance of nominal heat input inferior or equal to 70 kW.

[3] ISO/DIS 14687 – 3 "Hydrogen Fuel – Product specification – Part 3 Proton Exchange Membrane (PEM) fuel cell applications for stationary appliances"

This standard specifies the quality characteristics of hydrogen fuel in order to assure uniformity of the hydrogen product for utilization in stationary proton exchange membrane (PEM) fuel cell power systems.

Picture 4.26 **Due to their nature, Fuel Cell Modules are very sensitive and their safe operation requires specialized stuff**

5th CHAPTER

Hydrogen and FCs in Shipping

The Emergence of Hydrogen Economy and its Maritime Potential

« The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of the planter – for the future. His duty is to lay the foundation for those who are to come, and point the way. »

Nikola Tesla (1856–1943)

« Every time we invent something, we make it easier to invent something else. »

Erik Brynjolfsson, Director of the Initiative on the Digital Economy

Picture 5.27 Alternative Fuels and Technologies are the spearheads of a viable social evolution [DNV GL, 2019]

5.1 Introduction

The main purpose of this chapter is to provide a generic view on the potential of hydrogen to fuel modern shipping transportation. What is the beneficial nature of hydrogen and how HFCs promise a feasible synergy for the propulsion of the future ships? What is the current status of hydrogen distribution network in European countries and what are the challenges of its integration as a possible fuel? What are the alternative promising marine fuels? Is it likely for hydrogen's supply chain to cover shipping sector's needs and what is the economic impact of this endeavor? Is there any chance for hydrogen-powered vessels, with the current technology infrastructure and overall knowledge, to deliver economic prosperity for the investors? Is fuel cell on ships a feasible scenario and what are the benefits and risks of this endeavor? **Chapter 5** is targeted to find answers to abovementioned questions and lay the foundation for the calculative part of this diploma thesis.

5.2 Hydrogen and Its Supply Chain

5.2.1 Breeding Ground

As analytically mentioned in previous chapters, serious environmental problems such as global warming and air pollution would be caused by the result of processing, transporting and burning conventional petroleum-based ship fuels. Furthermore, a hydrogen-fueled powertrain system has several potential cost benefits; to mention one, hydrogen's production and market are characterized by a more stable price certainty (insulated from fossil fuel price volatility). Furthermore, as previously mentioned, numerous international authorities (IMO, European Union, etc.) and states (Norway) have already endorsed their ambition to marginalize conventional fuel oils in their greater effort to secure a more sustainable future development on the shipping industry.

What is more, it is a well-known fact that when hydrogen is used as fuel, it essentially generates water vapor hydrogen and commits no pollution. Therefore, hydrogen is superior to its competitive fossil fuel in terms of environmentally-friendliness.

These reasons, as well as the unparalleled characteristics of hydrogen as a fuel source of energy, are the main driving force that has actuated the scientific community and private organizations to invest money and energy to bring the idea of HFC into existence in the marine sector. Meanwhile, other cleaner fuel such as LNG or biodiesel are considered and attempted to be used as marine fuel as well as hydrogen

In an effort to cover the full spectrum of HFC potential in marine industry, this chapter will identify advantages and disadvantages of hydrogen as fuel source for shipping, stress its superiority, compared to other fuel sources, and mention its concurrent bottlenecks that stand in hydrogen's expansion way.

5.2.2 The Nature of Hydrogen & its European Status

Hydrogen is an abundant element that is found in many forms on Earth. In its molecular form of H_2 (two protons and two electrons), it is not readily found but rather needs to be extracted or "reformed" from hydrocarbon fuels, both fossil and biological, or extracted from water using a "water splitting" process called electrolysis. Hydrogen is the smallest and lightest of all gas modules and has characteristics of invisible, tasteless, colorless, non-polluting and renewable form of energy. Hydrogen has an environmental perspective that it emits no carbon dioxide due to the fact that it contains no carbon.

There are many means of hydrogen production, from established ones such as steam methane reforming, where half of the produced hydrogen comes from natural gas or biogas and half comes from steam used in the reaction to grid-powered electrolysis that uses electricity to split water molecules in hydrogen and oxygen. Various other hydrogen production methods are becoming commercially viable, including gasification or pyrolysis processes of various types of feedstocks (e.g., biogas, biosolids, fossil fuel production residues, etc.) and biological production through fermentation processes. Further from commercialization but under active study are more recently developed electrochemical, photo-electrochemical, and thermochemical processes, with potential to produce renewable hydrogen to meet growing demand for hydrogen use at larger scale in the future.

Hydrogen is a widely produced and used industrial commodity for fertilizer production, oil refining, food production, and metallurgy, used at a level of tens of millions of tons per year around the world. Moreover, hydrogen could be easily used as an energy carrier due to its storability, portability and flexibility.

In order to take advantage of these characteristics, some societies and industries have shifted into "Hydrogen Society", as hydrogen is considered a universal fuel that could provide power to automobiles, aircraft, spacecraft, power plants and appliance. When it comes to international organizations, IEA (International Energy Agency) is considered the spearhead for the promotion, development and commercialization of H_2 amongst its 29 member countries (Greece included) and beyond.

Hydrogen Europe[3] is a pillar for the establishment of hydrogen-fueled power in Europe's territory.

[3] **Hydrogen Europe** is the European Hydrogen and Fuel Cell Association. It currently represents more than 100 industry companies, more than 68 research organizations as well as 13 National Associations. The

However, there are also some countries that have taken major steps into the incorporation of hydrogen-powered systems in their power sources arsenal:

[1] Scotland

The remote island of Eday is home to an experimental energy initiative backed by the European Marine Energy Centre. In 2017, the project successfully used tidal power to produce hydrogen. The project was recently awarded €12 million in funding to develop a hydrogen power system for the car and passenger ferries that connect the Orkney archipelago.

[2] Germany

The world's first hydrogen-powered trains are operating in northern Germany on a 100km stretch of track. Although costlier than existing diesel locomotives, the new zero-emissions engines are kinder to the environment. Equipped with fuel cells that produce electricity, the trains emit only water and steam instead of harmful carbon dioxide. The engines can run for 1,000 km on a tank of hydrogen and store excess energy produced by the fuel cell on board in ion-lithium batteries.

Picture 5.28 Island of Eday [REUTERS, 2018]

association partners with the European Commission in the innovation programme Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

Picture 5.29 **World`s first hydrogen-powered fuel cell train operating in northern Germany [REUTERS, 2018]**

[3] England

Unlike battery electric vehicles (BEVs), ferries, cars, trucks and ships powered by hydrogen can be refueled as quickly as a conventional petrol or diesel vehicle. Fast refueling is an important consideration for London's Metropolitan Police Service, which has added 11 Toyota Mirai cars fitted with hydrogen fuel cells to its fleet of response vehicles. The zero-emissions police cars can access five gas filling stations throughout London and this number is set to increase. The new vehicles have a 480km range and rapid acceleration, although top speeds are limited to around 170km per hour.

[4] Belgium, France, Netherlands

A pipeline network would be the best option for the comprehensive and large-scale use of hydrogen as an energy source. However, pipelines require high levels of initial investment, which may pay off, but only with correspondingly large volumes of hydrogen. Nevertheless, one possibility for developing pipeline networks for hydrogen distribution is local or regional networks, known as micro-networks. These could subsequently be combined into trans-regional networks.

Worldwide there are already (2016) more than 4,500 km of hydrogen pipelines in total, the vast majority of which are operated by hydrogen producers [HyARC 2017]. The longest pipelines are operated in the USA, in the states of Louisiana and Texas, followed by Belgium France, Netherlands, and Germany. The following chart depicts the total length of H_2 pipeline network in world`s leading countries in H_2 transport section.

Figure 5.31 Leading Countries in Hydrogen's Inland Pipeline Transport Network [HyARC, 2017]

[5] Spain

Spain's Valencia Port will be the first in Europe to use hydrogen (H_2) for its cargo operations thanks to a $4.6m European pilot programme that aims to reduce port activities' environmental impact. The project will start with the use of a reach stacker and of a terminal tractor, used to manipulate containers, both powered by H_2 batteries. The pilot project, denominated H_2Ports, also incorporates the installation of a new mobile station to supply H_2.

The project will test and validate hydrogen technologies for port machinery in order to achieve solutions that produce zero local emissions, without affecting the performance and safety of port operations. H_2PORTS will allow these new prototypes to be demonstrated at the Grimaldi and MSC terminals in the Port of Valencia, which will become the first European port to incorporate hydrogen energy to reduce the environmental impact of its operations.

The plan was made possible after authorities of the Valencia Port signed the accord with Fuel Cells and Hydrogen Joint Undertaking to promote the use of H_2. Valencia, located on Spain's southeastern Mediterranean Sea coast, has been known in recent years for its futuristic structures. The port moves over five million containers annually. It is one of the two main ports of Spain in traffic and moved cargo.

Picture 5.30 **Port of Valencia**

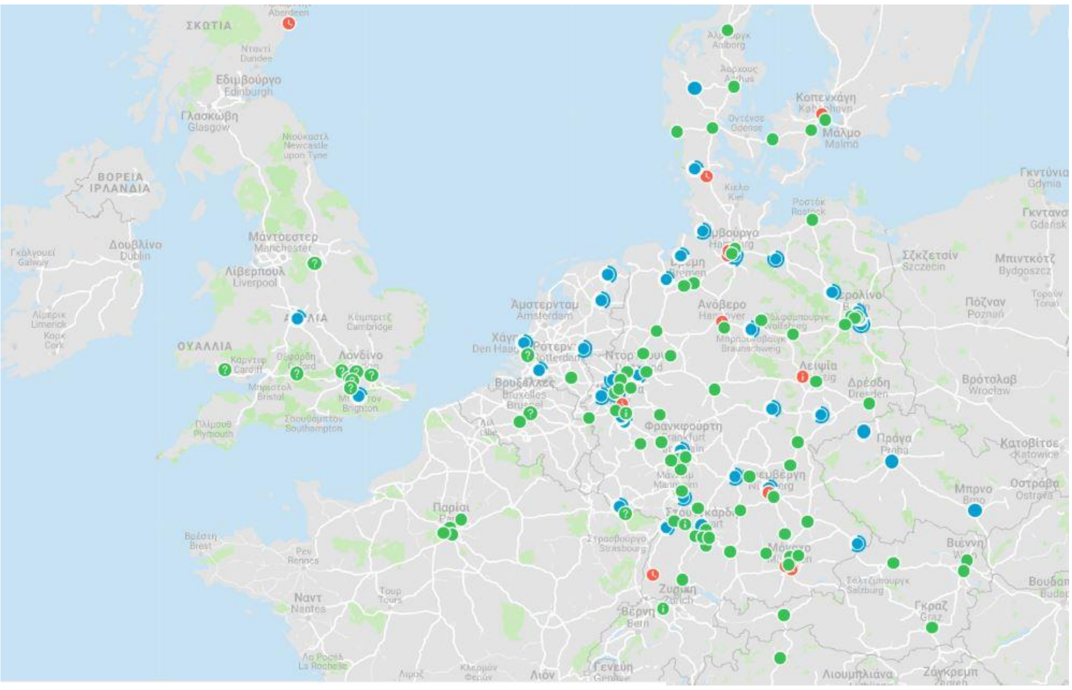
Taken the above into account, it is a worldwide belief that as a zero-carbon emission fuel, H_2 is able to revolutionize the industry and transportation section and it is expected to be widely utilized in the near future. In this context, many European countries have already scheduled (or already developed) hydrogen gas pipeline network to fuel their ports (ships bunkering) and place interconnections between their refueling stations and places of high energy demands (cities, etc.)

Picture 5.31 AirLiquide integrated pipeline network in the Benelux countries. Red lines represent H2 pipeline network. [AirLiquide, 2016]

The existing hydrogen pipeline network is limited and based on natural gas technology. Western Europe owns the longest pipeline network: about 1500 km that covers part of France and the Benelux countries. The operating pressures are normally between 10 and 20 bars, with diameters between 25 and 30 cm.

At Picture 5.32 there is a schematic representation of the refueling stations – targeted for vehicles refueling operations – in the European Continent. Blue circles mark the H_2 fuel stations that are in progress whilst green and red signify those which are currently operating.

Note that these are the only H_2 refueling stations in Europe. It is a great misfortune that there is no operating or short-term scheduled H_2 station in the vicinity of the Mediterranean Sea (Greece included). Currently, there are more than 34 operating stations in Europe and optimists declare that by the end of 2025 more than 200 stations will have been integrated in the European network of H_2 refueling stations.



Picture 5.32 European map of H2 refueling stations [European Union, 2018]

[6] Australia

On 20th of July Kawasaki Heavy Industries announced its agreement with Australian government for the creation of a pilot Hydrogen export terminal in Victoria State. Amongst its main goals is to put hydrogen into vehicles, homes and power stations, with the Tokyo Olympics as a showcase in 2020. To be more specific, it refers to a 500 million pilot project that encompasses all the necessary arrangements for the establishment of the necessary facilities for the liquefaction and shipping of hydrogen. This facility will convert hydrogen gas into liquefied hydrogen, which will be stored and then loaded onto the world's first specialized marine carrier for transport to Japan. The Project will involve the production of hydrogen from Latrobe Valley brown coal whilst it will create a new innovative technical foundation for the development of an exciting hydrogen export industry for Australia.

The construction work includes building and mechanical installation including a liquefaction facility and a storage container to be completed by June 2020, to be followed by commissioning, with the target operating period being from 2020 to 2021. Kawasaki will use its know-how and experiences gained in past liquefied hydrogen and industrial plants to deliver the Project safely and on time. Kawasaki and Hydrogen Engineering Australia (HEA) Pty Ltd. will continue to work with the local community to share information about the Project and respond to community feedback [REUTERS, 19th July of 2019].

5.2.3 Hydrogen Roadmap & the Vision of EU

This section describes an ambitious scenario for hydrogen deployment in the EU to achieve the 2-degree target[4]. This scenario is based on the perspective of the global Hydrogen Council, input from Hydrogen Europe (representing the European hydrogen and fuel cells industry), and, more specifically, data from 17 member companies active in hydrogen and fuel cell technologies.

All the necessary information and statistics, which is employed for the development of this chapter, is derived from the executive summary of the European Union titled “Hydrogen RoadMap Europe, 2019”.

Across sectors, we see the potential for generating approximately **2,250 terawatt hours** (TWh) of hydrogen in Europe in 2050, representing roughly **a quarter of the EU’s total energy demand.** This amount would fuel about 42 million large cars, 1.7 million trucks, approximately a quarter of a million buses, and more than 5,500 trains. It would heat more than the equivalent of 52 million households (about 465 TWh) and provide as much as 10% of building power demand. In industry, approximately 160 TWh of hydrogen would produce high-grade heat and another 140 TWh would replace coal in steelmaking processes in the form of direct reduced iron (DRI). 120 TWh of hydrogen combined with captured carbon or carbon from biomass would also produce synthetic feedstock for 40 Mt of chemicals in 2050.

Achieving this vision puts the EU on a path to reducing about **560 Mt of CO_2 emissions by 2050** – as much as half of the required abatements needed to achieve the 2-degree scenario. The EU needs to reduce its CO_2 emissions from 3,500 Mt today to 770 Mt in 2050. Deploying available technologies and existing energy and climate-related commitments from European countries would close approximately 60% of the gap. The use of hydrogen in power sectors could help to reduce half of the remaining 1,100 Mt and achieve the 2-degree scenario. In addition, it could enable deep decarbonization of the power sector and hence indirectly reduce carbon emissions.

Besides reducing carbon emissions, the deployment of hydrogen and fuel cell technologies would remove local emissions. In transportation, NO_X emissions could be reduced by 0.5 Mt per year in 2050. Rivers, lakes, and ports would be less polluted, steel

[4] As part of the Paris agreement, EU member states have committed to achieving the 2-degree scenario and making efforts towards achieving at least a 1.5-degree scenario.

and other industrial plants would avoid dust and tar exhaust, and noise from diesel trains and trucks would drop significantly.

The projected deployment of hydrogen would create an estimated EUR 130 billion industry for the fuel and associated equipment for EU companies by 2030, reaching EUR 820 billion by 2050. It would create a local market for EU industry to use as a springboard **for competing globally in the new hydrogen economy**. The export potential in 2030 should reach an estimated EUR 70 billion, with net exports of EUR 50 billion. Altogether, the EU hydrogen industry could provide employment for about 1.0 million highly skilled workers by 2030, reaching 5.4 million by 2050.

Realizing this ambition will require a significant step-up of activities along the whole value chain. The ramp-up should start now as **hydrogen and fuel cell technologies are technically ready for most segments** and the EU industry must scale up to reduce costs and gain a leading position in the global energy transition economy. Towards 2030, deployment should focus on priority segments such as the blending of hydrogen into the natural gas grid and use in commercial transportation fleets, larger passenger vehicles, heavy transport (trucks, trains, ships), material handling, and the decarbonization of existing hydrogen production.

To achieve the desired outcome, the following **concrete milestones** are proposed:

- In **transport**, by 2030 fuel cell electric vehicles (FCEVs) could account for 1 in 22 passenger vehicles and 1 in 12 of light commercial vehicles (LCVs) sold, leading to a fleet of 3.7 million fuel cell passenger vehicles and 500,000 fuel cell LCVs. In addition, about 45,000 fuel cell trucks and buses could be on the road by 2030. Fuel cell trains could also replace roughly 570 diesel trains by 2030.
- For **buildings**, hydrogen could replace an estimated 7% of natural gas (by volume) by 2030, and 32% by 2040, equivalent to roughly 30 TWh in 2030 and 120 TWh in 2040. In 2030 this amount would be equivalent to Germany, UK, the Netherlands, France and Denmark blending up to 7.5% of hydrogen (by volume) into the grid and five mid-sized cities (~300.000 inhabitants) switching to pure hydrogen networks. It would cover the heating demand of about 2.5 million and more than 11.0 million households in 2030 and 2040, respectively, in addition to commercial buildings. In parallel, the deployment of more than 2.5 million fuel cell CHPs by 2040 would increase energy efficiency and take about 15 TWh of power off the grid.

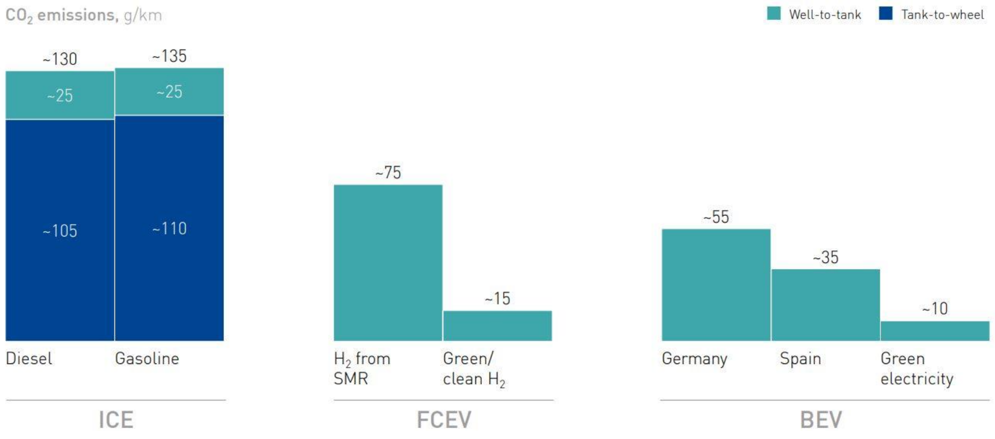


Figure 5.32 **Comparison of Well-to-Wheel emissions across different powertrains [Hydrogen Roadmap Europe Executive Summary, 2019]**

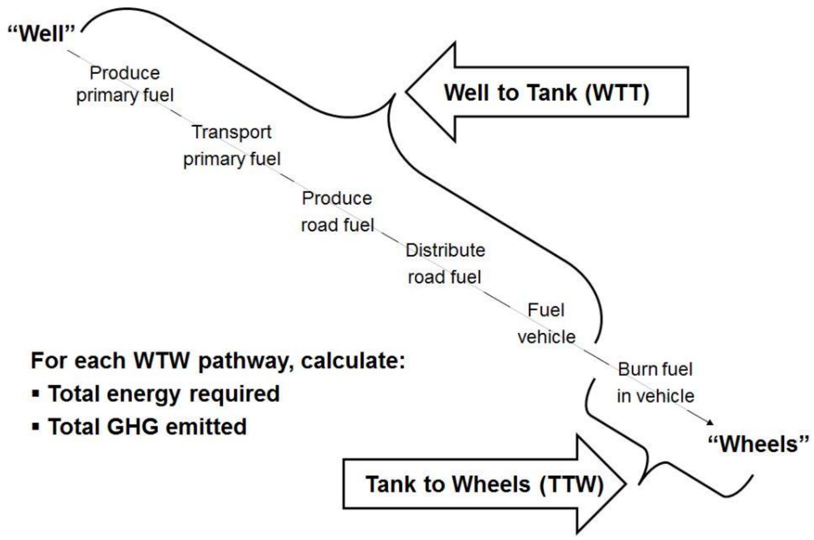


Figure 5.33 **Graphic representation of Well-to-Wheels Analysis [EU Science Hub, 2019]**

Assumption: Compact car (C-segment[5]) as reference vehicle (4.1 l/100 km diesel; 4.8 l/100 km gasoline; 35.6 kWh battery), 120,000 km lifetime average grid emissions in 2016; 10 kg CO2/kg H_2 from SMR; 0.76 kg H_2/100 km; 13 kWh/100 km; manufacturing emissions are not considered.

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[5] **The C-segment** is the third smallest of the European segments for passenger cars, and is described as "medium cars". It is equivalent to the Euro NCAP "small family car" size class, and the compact car category in the United States and Great Britain.

The European segments are not based on size or weight criteria. In practice, C-segment cars have been described as having a length of approximately 4.5 metres (15 ft). In 2011, the C-segment had a European market share of 23% - Source Wikipedia.

- In **industry**, a transition to one-third ultra-lowcarbon hydrogen production by 2030 could be achieved in all applications, including refineries and ammonia production. In addition, applications with large abatement potential, such as DRI steelmaking, must undergo large-scale feasibility testing.
- In the **power system,** the at-scale conversion of "surplus" renewables into hydrogen, large-scale demonstrations of power generation from hydrogen, and renewable-hydrogen generation plants could also take place by 2030.
- In Europe's Gas Network, by developing the necessary distribution infrastructure; there are two feasible methods to establish H_2 pathways to decarbonization. The first, should utilize the **existing natural gas pipelines**, by blending gaseous H_2 **up to a concentration of ~ 5 - 15%** - modifications to existing pipeline monitoring and maintenance practices are necessary to ensure safety. The second, refers the **retrofitting or replacement** of existing steel pipelines to **noncorrosive and non-permeable materials** (e.g., polyethylene, fiber-reinforced polymer pipelines) and leakage control is required for the transportation of pure gaseous H_2

Realizing these ambitious milestones will require **a coordinated approach by policymakers, industry, and investors.**

Figure 5.34 Long-term Benefits of Hydrogen for the EU [Hydrogen Roadmap Europe Executive Summary, 2019]

5.2.4 H2 Supply Perspective

5.2.4.1 Production

Hydrogen in molecular form can be produced from many different sources and in many different ways. Most commonly clustered into three groups: [1] production of hydrogen as the **byproduct from** processes in **the chemical industry,** [2] **reforming** of natural gas or biogas and [3] **water electrolysis**.

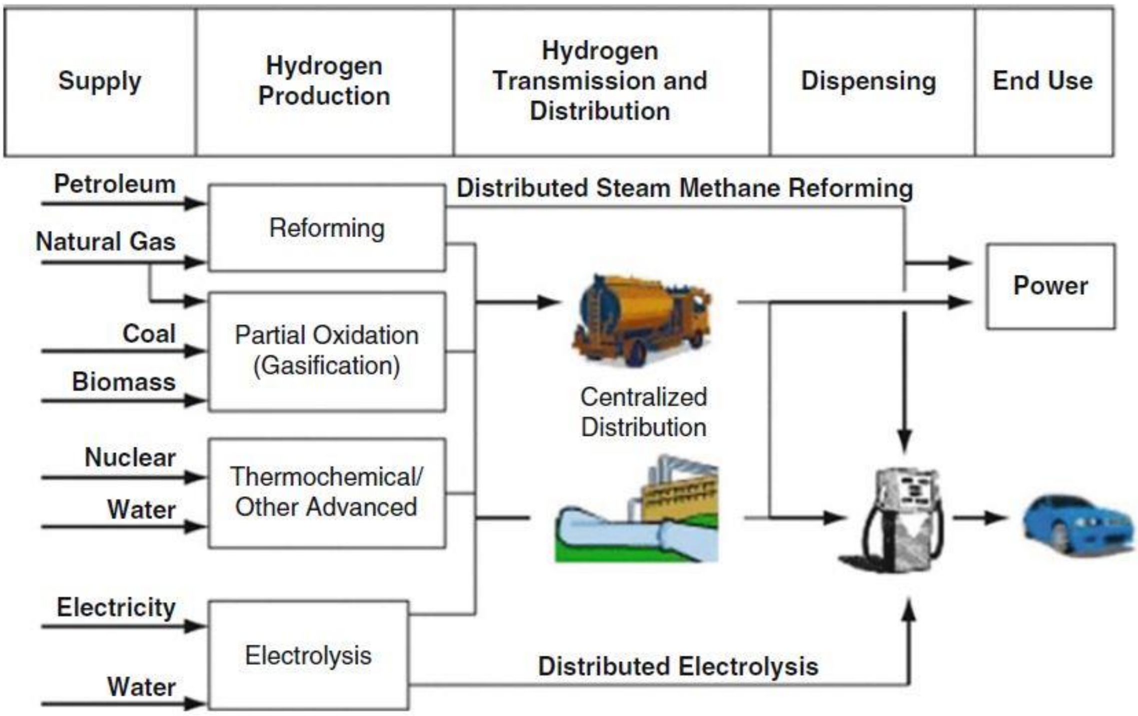

Figure 5.35 **Hydrogen Production Pathways [US Energy Information Administration (EIA), 2018]**

Currently, the most common method to produce large volumes of hydrogen is natural gas reforming into H_2 and CO or CO_2 in a **Steam Methane Reformer** (SMR). The remaining CO_2 steam can be very pure and is therefore well suited for **Carbon Capture and Storage** (CCS). SMR is currently the cheapest available hydrogen production method and will in any case be an integral part of the transition to a hydrogen economy. **Auto-Thermal Reforming** (ATR) is another process for producing hydrogen from hydrocarbon feedstock, such as natural gas. ATR produces syngas, composed of hydrogen and carbon monoxide, by partially oxidizing a hydrocarbon feed with oxygen and steam and subsequent catalytic reforming. The syngas can be used as feedstock for hydrogen by separation into pure hydrogen, carbon monoxide, and carbon dioxide.

In case of tight emission targets, SMR and ATR need to be equipped with CCS to remain viable. As renewable power prices come down, water electrolysis can become more cost-efficient in the future because it does not rely on feedstock other than water.

Water electrolysis produces high-purity hydrogen by using electricity to split water. Alkaline electrolysis is the more established technology today, while proton exchange membrane (PEM) water electrolysis has higher potential for further improvements. If electrolysis from renewable energy sources is used, it is a carbon-free hydrogen production method and both central and decentral hydrogen production is possible. That makes water electrolysis in combination with wind or solar power a well-suited technology to drive decarbonization of the energy system. In locations where CCS is technically not feasible, biomethane reforming, water electrolysis, and longer-term biomass gasification will be the only ultra-low-carbon hydrogen production methods. Ideally, **a mix of ultra-low-carbon sources will produce hydrogen** in the future

5.2.4.1.1 Centralization Degree

To classify the degree of centralization of the HSC, two categories will be used either **centralized or decentralized (on-site) units**. A centralized production option would be analogous to current gasoline supply chains, where the economies of scale are capitalized upon within an industrial context and large quantities are produced at a central site and then distributed [Hugo et al., 2005; Murthy Konda et al., 2011]. Centralized plants not only promise higher hydrogen production efficiency but also some difficulties are associated in high-volume hydrogen to be transported.

Decentralized production consists in small regional plants or even local filling stations that could generate hydrogen. **While hydrogen generation efficiency for decentralized is lower than those for centralized plants, losses in hydrogen transport can make such a scheme more efficient** [Kim et al., 2008; Haeseldonckx and D'haeseleer, 2011]. There is a tendency in the literature to argue that decentralized production plants could overcome many of the infrastructural barriers facing a transition to hydrogen [Ball and Wietschel, 2008]. **Most studies consider the decentralized route as the key to by-passing the infrastructural problem** [Haeseldonckx and D'haeseleer, 2011]. A decentralized approach often results in higher costs as efficiencies are generally lower and because on-site production facilities are often dimensioned to cover peak demand (especially when no storage is foreseen or possible). However, a further increase of demand will require larger pipelines, which thus implies new investment costs.

5.2.4.1.2 Steam Methane Reforming

Most of hydrogen (95%) stems from steam reforming of natural gas also known as SMR [Koroneos et al., 2004]. SMR is used in the chemical and petrochemical industries; **it is currently the cheapest production method and has the lowest CO_2 emissions of all fossil production routes** [Ball and Wietschel, 2008].

The main steps during the production of hydrogen from natural gas are [Hajjaji, 2011] (a) production of the synthesis gas, (b) conversion of carbon monoxide to hydrogen (water shift gas), and (c) purification. The first stage (see Figure 5.36) is a catalyzed endothermic reaction between methane (natural gas) with water vapor at high temperature (steam reforming) to produce synthetic gas, which mainly consists of carbon monoxide and hydrogen along with some water, carbon dioxide, and methane. During steam reforming, hydrocarbons are catalytically split in the presence of steam at temperatures of 800 – 900℃. Then, carbon monoxide is converted to carbon dioxide following the exothermic shift reaction. In the purification stage, pressure swing adsorption is the prevailing process in which the reactive gas mixture, containing methane and hot steam, is fed to the tube side of a catalytic furnace reactor.

Ultimately, the hydrogen-rich gas is sent to purification system which usually consists of four or five adsorbers filled with different adsorbents. The purification process is based on pressure swing adsorption by which the impurities are separated to obtain high-purity hydrogen with purities up to 99.999 vol-%. The purge gas from depressurization and purging during the regeneration step is used as fuel gas in the reforming section.

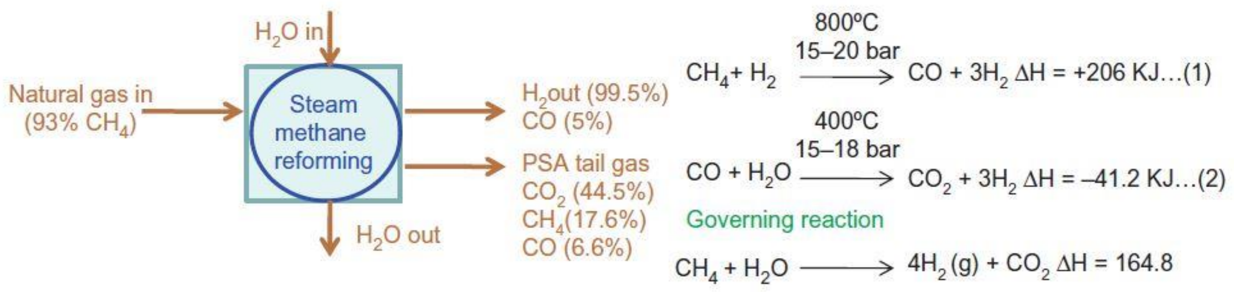

Figure 5.36 SMR block diagram and governing reaction [A.Scipioni, 2017]

The reformation of a given carbohydrate with a general type of C_nH_m, conforms with the following chemical reactions:

$$C_nH_m + nH_2O \rightarrow nCO + \left(\frac{m}{2} + n\right) H_2 \quad \textbf{(5.1)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \textbf{(5.2)}$$

Since the reaction is endothermic, the combustion of methane with air in the furnace side of the reactor provides the required reaction heat. The exhausted beds are regenerated via hydrogen washing, so even if a high purity product obtained, about 25% of hydrogen is lost.

SMR produces a hydrogen-rich gas that is typically on the order of 70 – 75% hydrogen on a dry basis, along with smaller amounts of methane (2 – 6%), carbon monoxide (7 – 10%), and carbon dioxide (6–14%) [Hirschenhofer JH, Stauffer BD, et al., 2000]. The efficiency of the SMR process using natural gas as a feedstock is typically about 74 – 80 % on an LHV basis [US Department of Energy, 2011]. SMR can accept only vapor feeds so either gas or light liquid hydrocarbons that can be easily vaporized are used. One advantage of this technology is that it is well proven, simple, and does not require O_2 like the ATR and POX (Partial Oxidation Method).

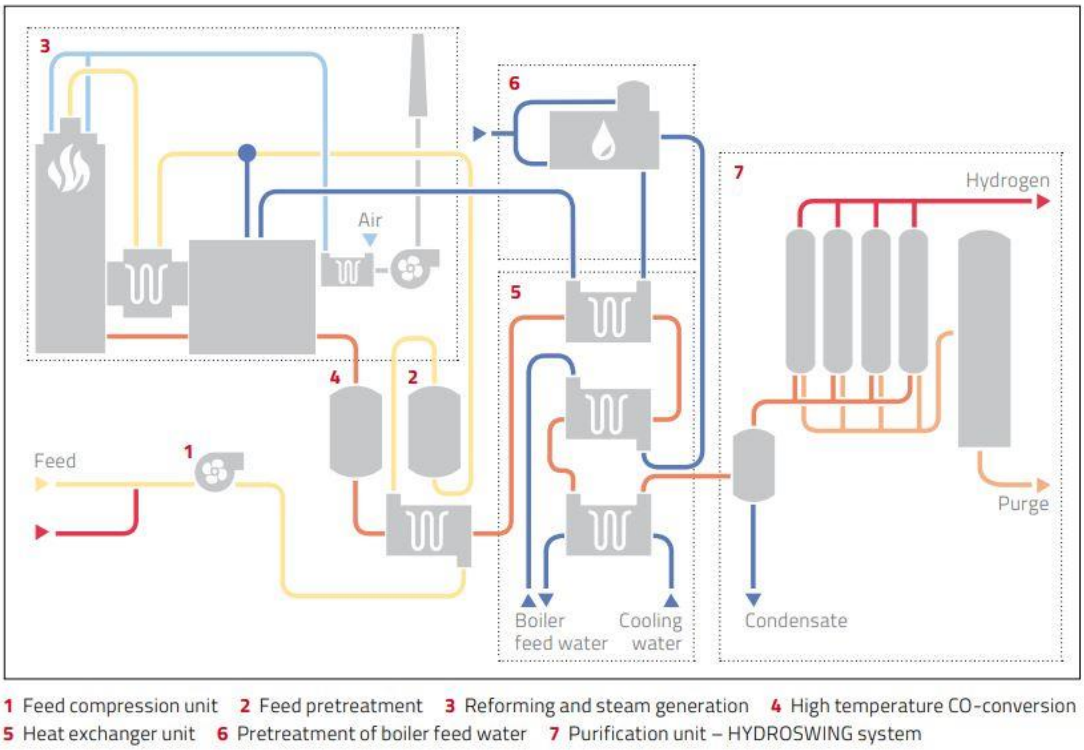

Figure 5.37 **Typical Arrangement of SMR Plant [Mahler AGS, 2019]**

5.2.4.1.2.1 Market Analysis of SMR Technology

Steam Methane Reforming (SMR) technology for hydrogen production is currently available in the market for both small and large scale production. Steam reforming of natural gas, LPG or naphtha (feedstocks) with subsequent purifications is the most economic and thus most common process for hydrogen production and serves 95% of the world's hydrogen demand. Conventional steam reforming plants operate **at pressures between 200 and 600 psi** (14 – 42 bar) with **outlet temperatures in the range of 815 to 925 °C.**

With more than 4.500 plants built worldwide since 1950, Mahler AGS is a highly respected manufacturer of on-site gas plants for hydrogen generation, oxygen generation and nitrogen generation.

At their webpage [Mahler AGS, 2019] some of the **plant data** characteristics are being projected, such as:

- Feedstock: Natural Gas, LPG, Naphtha
- Hydrogen Capacity: 200 to 10.000 Nm^3/h
- Hydrogen Product Pressure: 10 – 30 bar (abs)
- Hydrogen purity: Up to 99,999 vol.-%
- Life expectancy: 25 years – service every 3 years

Typical consumption data for 1.000 Nm^3/h of hydrogen:

- Natural gas: 430 Nm^3/h
- Demineralized water: 900 kg/h
- Cooling Water: 38 m^3/h
- Electric Power: 38 kW

A significant drawback of SMR is that it does not composites an all-green solution for the production of hydrogen due to the GHG emissions through its operation. Therefore, when seeing it from an environmental point of view it cannot serve for complete decarbonization purposes of a propulsion system. Though, with the current technological development, centralized NG SMR offers the most feasible and environmental-friendly policy for the production of H_2 (for example water electrolysis demands a great portion of electric power which in order requires a proportionate quantity of carbohydrates – when no renewable sources such as wind or hydro energy is used for the production of electric current -).

5.2.4.1.3 Water Electrolysis

Water electrolyzers can be divided into two categories, alkaline and proton exchange membrane (PEM) electrolyzers. According to Ball and Wietschel (2008), **electrolysis processes are more expensive than SMR and only applied if high-purity hydrogen is required.**

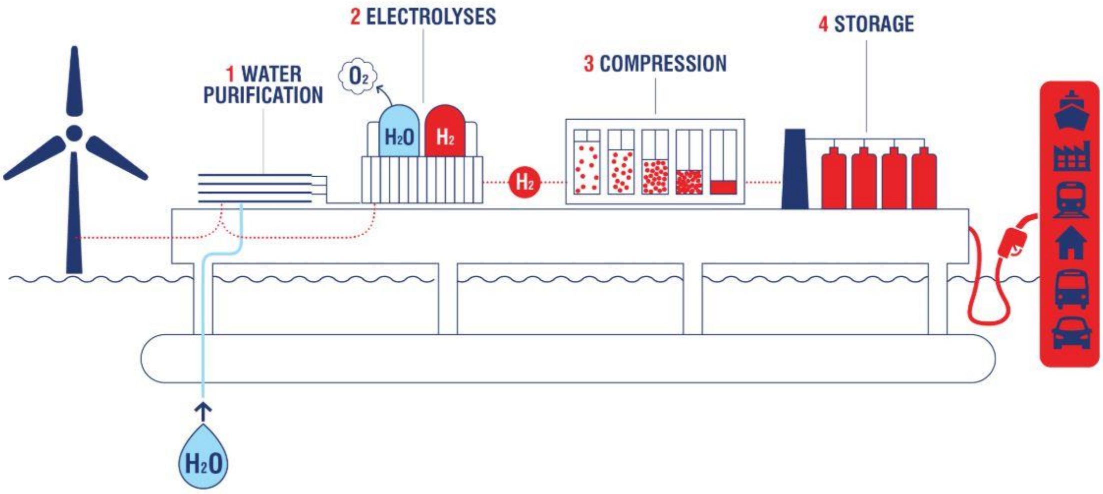

Figure 5.38 Schematic presentation of Water Electrolysis using Wind energy conversion [Hydroville, 2019]

The work of Bartels et al. (2010) reports that H_2 production from electrolysis may become economically competitive because fossil fuel feedstock costs also increase, and technological advancements decrease the cost of alternative energy types. Significant cost reductions are also expected for many materials, and catalysts and cell components used in PEM electrolyzers could benefit from large-scale production of PEM fuel cell of similar concept and design. As long as electricity comes from a clean source, electrolysis is a clean process. **But producing hydrogen via electrolysis and then using hydrogen to produce electricity again is associated with considerable losses** (Hake et al., 2006). At present, research and development work is focused mainly on the realization of long-lasting materials to extend both the lifetime and the performance of electrolysis stacks. Reduction in system complexity also remains a major challenge.

A key feature for this hydrogen production method is that, currently, water electrolysis only contributes for a 4% share [Md Mamoon Rashid, Mohammed K. Al Mesfer, 2015] of the annual global hydrogen production. At present, research and development work is focused mainly on the realization of long-lasting materials to extend both the lifetime and the performance of electrolysis stacks. Reduction in system complexity also remains a major challenge.

Taken all these into account, realizing that there is no commercial availability at large scale for this method (at this moment its technology status limits it into laboratories – liquid and corrosive dynamics, acidic environments [PEM], low durability due to high heat [High Temperature Electrolysis]) **it is concluded that there is no feasible scenario in which it seems reasonable move to generate hydrogen through electrolysis exploiting electrical sources consuming many MWe while the examined ship proposes an electrical propulsion powertrain (which utilizes electric energy for the propulsion of the ship).**

5.2.4.2 Hydrogen T&D

Conceptually, transportation is divided into two parts: Transmission and Distribution. Transmission refers to H_2 transportation from a plant to other regions without-plant units and distribution refers to H_2 transportation to the refueling stations from a plant or regional conditioning center in any region.

There are **various methods for transporting hydrogen**, but **choosing the best one depends** on different parameters such as the distance of the demand center from the production site [Ball and Wietschel, 2008], the amount of transferred hydrogen, and the existing infrastructure such as natural gas pipeline, road, and rail. Note also that the choice of transportation mode is correlated with the architecture of the distribution network. Indeed, a supply chain including liquid hydrogen requires trucks, while a supply chain not including condensers or compressors requires pipelines.

Due to the aforementioned low volumetric energy density of H_2, transportation costs can be significant. Therefore, as transport is so expensive, hydrogen should be produced close to the user centers.

The costs could be considerably reduced if the natural gas pipeline could be adapted to hydrogen. As hydrogen can diffuse quickly through most materials and seals and can cause severe degradation of steels, mainly due to the embrittlement, the use of existing natural gas pipelines could be problematic and has to be investigated on a case-by-case basis. Coating or lining the pipelines internally, or adding minor amounts of oxygen, could solve the problems in using existing long-distance transmission pipelines made from steel. In addition, valves, manifolds, and in particular compressors would need to be modified, as they are optimized to work under a certain range of conditions, such as gas composition. Another possibility could be to blend hydrogen with natural gas up to a certain extent and either separate the two at the delivery point or use the mixture, e.g., in stationary combustion applications**. As mentioned before, this is one the policies that EU wants to establish in order for the commercialization of H_2.**

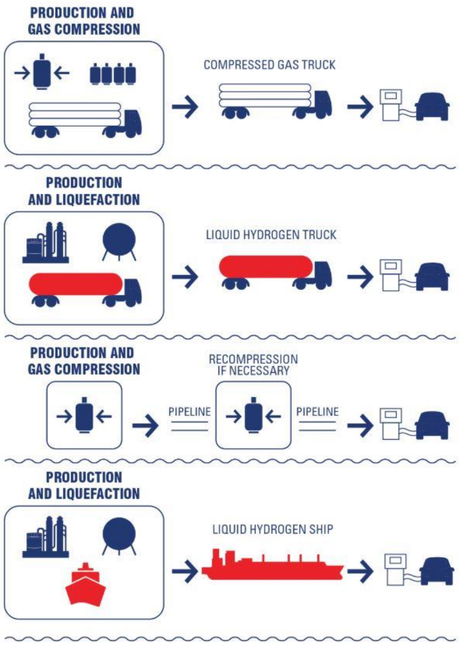

Figure 5.39 Delivery Paths of Hydrogen [Hydroville, 2019]

5.2.4.2.1 Pipelines

Pipelines have been used to transport hydrogen for more than 50 years [Ball and Wietschel, 2008]. The longest hydrogen pipeline in the world to supply chemical and petrochemical industries (about 1050 km in France, Germany, and the Benelux countries) is operated by Air Liquide [Central Electricity Authority, 2013]. The United States has more than 720 km of hydrogen pipelines concentrated along the Gulf Coast and Great Lakes, the estimation of the capital cost of hydrogen transmission pipelines range from 200,000 to 1000,000 US$/km [Dagdougui, 2011b].

From a production unit, the gas is transported through a transmission line medium pressure (100 bars). This means that less space is required to store the same amount of hydrogen. In addition, as hydrogen is stored throughout the entire pipeline network, there are no large concentrations of hydrogen at the same location, improving the overall safety. The exact amount of hydrogen that can be stored depends on the maximum and minimum pressure, the hydrogen flow, and the length and diameter of the pipeline.

5.2.4.2.2 Tube Trailers

From a conditioning center, compressed hydrogen can be transported at around 200 - 250 bar by tube trailers. With the appearance of decentralized, regional production, tube trailers use is a solution for the transition phase toward the use of pipelines [European Commission, 2008]. Commercial tube trailers are well established. Generally, transporting CH2 over the road in high-pressure tube trailers is expensive and used primarily for short distances; it becomes cost prohibitive when transporting farther than about 321 km from the point of production [Dagdougui, 2011]. Compressed gas truck delivery is not considered as a long-term delivery solution because their low hydrogen capacity would necessitate too many deliveries.

5.2.4.2.3 Tanker Trucks

From the liquefaction unit, LH_2 can be transported by tanker trucks (cryogenic liquid hydrogen tankers). This transportation mode is the most economical pathway for medium market penetration (Dagdougui, 2011b). They could transport relatively large amounts of hydrogen and reach markets located throughout large geographic areas. Forty ton trucks can carry 3500 kg of LH_2 so that the transport of liquid hydrogen is limited by volume, not by weight (Bossel, 2006).

Table 5.13 Quantitative overview of hydrogen T&D technologies

Delivery Pathway	Capacity	Transport Distance	Energy Loss	Fixed Costs	Variable Costs	Deployment Phase
Gaseous Tube Trailers	Low	Low	Low	Low	High	Near term
Liquefied Truck Trailers	Medium	High	High	Medium	Medium	Medium to long term
Hydrogen Pipelines	High	High	Low	High	Low	Medium to long term

5.2.4.3 Carbon Footprint of Hydrogen Production and Transport & Distribution

The carbon footprint for different hydrogen pathways for the European Union is shown in Figure 5.40. Depending on the production and T&D pathway, today's carbon footprint for hydrogen can be significant. Decentralized hydrogen production (at the refueling station) using today's EU grid electricity mix, and including compression to 88 MPa (880 bar), results in a carbon footprint which is almost three times higher than that for gasoline or natural gas. Conversely, when produced from renewable power, biomass or fossil fuels with CCS, the carbon content of hydrogen can be reduced to below 20 gCO_2eq/MJ. Still, in combination with the higher efficiency of FCEVs, the use of hydrogen from natural gas SMR without CCS results in lower per kilometer emissions than the use of gasoline in comparably sized conventional cars.

Hydrogen T&D and retailing ("Conditioning and Distribution") have a substantial carbon emission contribution, which is mainly due to the energy-intense compression of the hydrogen gas to 88 MPa, but also due to hydrogen T&D using trucks (with hydrogen either in gaseous or liquefied form) or pipelines. Furthermore, the comparison suggests that the liquefaction of hydrogen for T&D purposes leads to around 25% to 30% higher carbon emission compared to gaseous truck or pipeline transport.

In the future, the carbon footprint of low-carbon hydrogen could be reduced further if low-carbon electricity was used for compression.

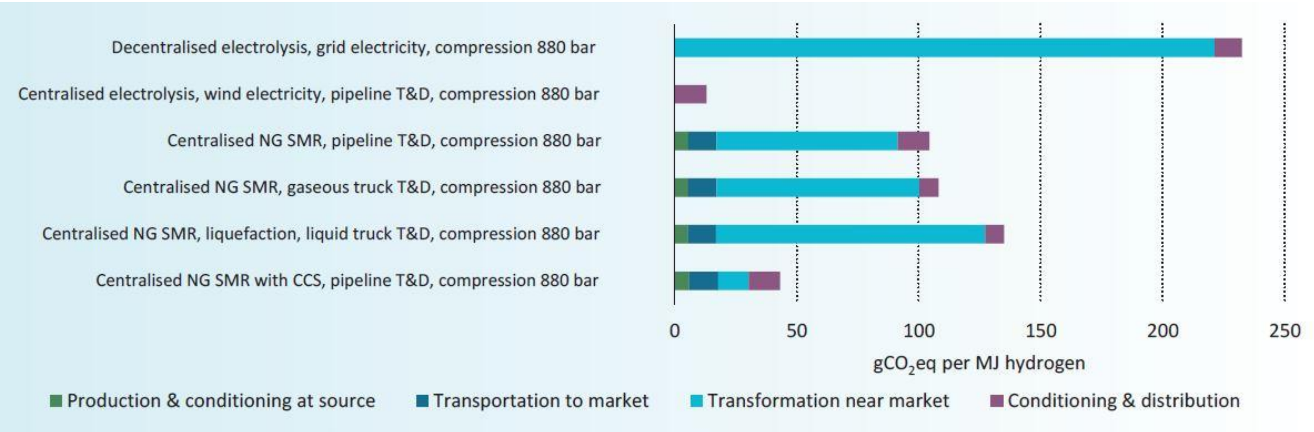

Figure 5.40 Today's carbon footprint for various hydrogen pathways in the European Union adapted from [Joint Research Center, 2013]

5.2.4.4 Hydrogen Conditioning and Storage

5.2.4.4.1 Introduction

Hydrogen storage is a key enabling technology for the development of a hydrogen and fuel cell based economy. Hydrogen has the highest energy density per unit mass of any fuel; however, its low volumetric density at ambient temperature and pressures correspondingly results in a rather low energy density per unit volume. This poses a potential problem in terms of storing large amounts of hydrogen. The traditional means of storage such as pressure tanks and cryogenic tanks have improved dramatically, and a number of new storage technologies are currently under development. The least complex method of storing pure hydrogen is as a compressed gas in a high-pressure cylinder. The lack of storage implies that enough production capacity needs to be installed in order to cover the peak demand for hydrogen.

The physical limits for the storage density of compressed and liquid hydrogen have more or less been reached, while there is still potential in the development of solid materials for hydrogen storage, such as systems involving metal hydrides. Designing tanks both compact, lightweight, safe, and cheap is crucial since this is the possibility of making hydrogen storage particularly attractive compared to electricity.

Hydrogen conditioning for storage requires the removal of residual oxygen, hydrogen drying, and compression to the final storage pressure level. There is little technical information available on the efficiency of the individual steps of hydrogen conditioning. The compression of hydrogen to the chosen storage pressure is one of the major factors Furthermore, when it comes to safety facets, storing as well as utilizing hydrogen reserve requires particular caution as H_2 is extremely flammable, leaks with ease from valves and small pores, and to a specific ratio with oxygen forms an explosive mixture. Hydrogen's flame is almost invisible to human eye, what someone can see is only the deflection of its light.

5.2.4.4.2 Storing Properties

Hydrogen can be physically stored as either a compressed gas, a cryogenic liquid, or with materials-based storage, using metal-hydrides, organic molecules, etc. Storage as a gas (1 atm. density of 0.08375 kg/m3 at NTP[6]) typically requires high-pressure tanks (350–700 bar). Storage of hydrogen as a liquid (density of 70.85 kg/m^3) requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure (approximately at sea level) is -252.8 ºC. Approximately, 800 liters of gaseous H_2 at normal temperature and pressure (20 ºC and 1 atm.) can be contained in 1 liter of liquid H_2. However, around 11 % of the energy content is used to reach a pressure of 350 bar, 13 % to reach 750 bar, 25% to reach liquid state. Metal hydride storage is more energy efficient than LH_2 storage using only 15% of the LHV of the stored gas[7].

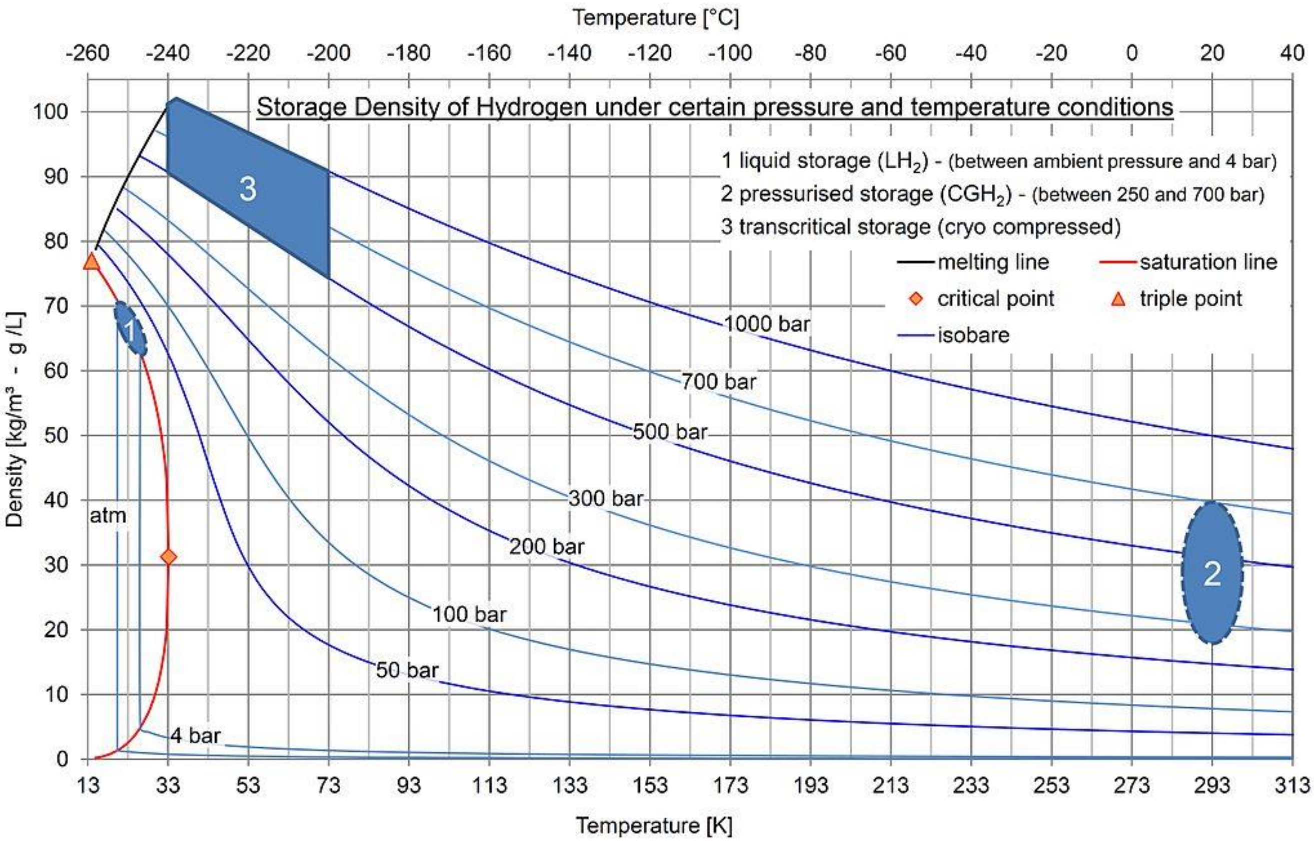

Figure 5.41 Net Storage Density of Hydrogen [Wikipedia, 2019]

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[6] NTP is commonly used as a standard condition for testing and documentation of fan capacities: NTP - Normal Temperature and Pressure - is defined as air at 20℃ (293.15 K, 68℉) and 1 atm.

[7] J.O. Jensen, Q. Li, N.J. Bjerrum, The Energy efficiency of different hydrogen storage techniques, in: Jenny Palm (Ed.), Energy Efficiency.

5.2.4.4.3 Overview of Storage Techniques

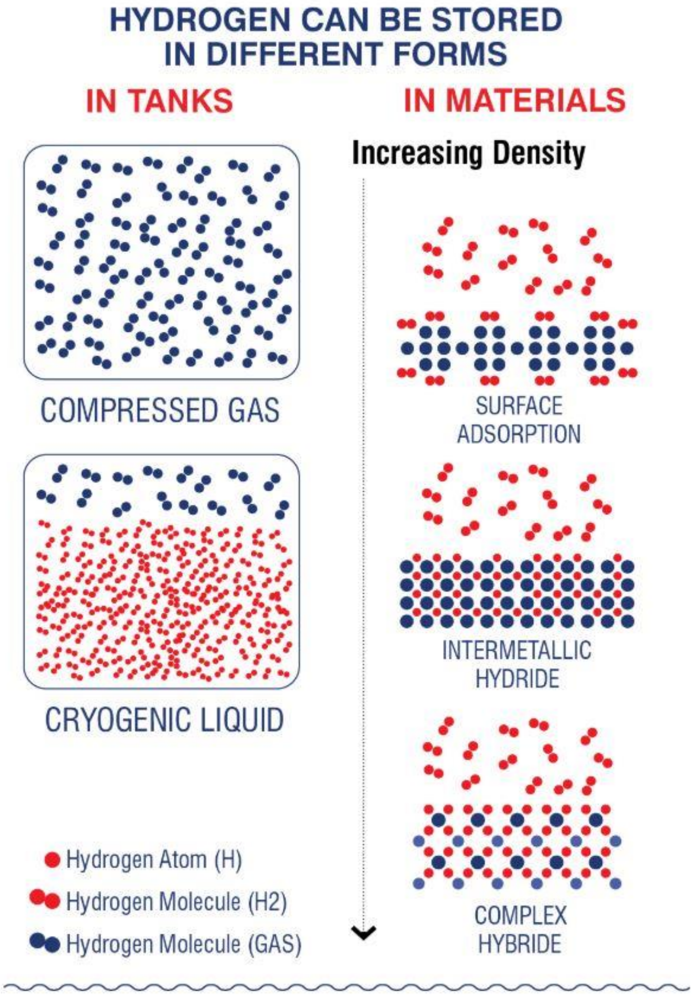

Figure 5.42 Hydrogen Storage Techniques [Hydroville, 2019]

Hydrogen is a volatile gas at ambient conditions, and the storage challenge is to fight the kinetic energy of the hydrogen molecules.

Basically there are three ways to go:

1. The gas can be confined at high pressure by external physical forces.
2. The energy of the molecules can be withdrawn by cooling and ultimately the gas condenses into a liquid.
3. The molecules can be bound to a surface or inside a solid material. This way hydrogen is more or less immobilized and like in the case of liquid hydrogen, most of its kinetic energy is removed.

Therefore, hydrogen can be stored in tanks as compressed gas or cryogenic liquid, but also in materials. There are three ways to store hydrogen in materials: surface adsorption (the hydrogen is attached to the surface of a material as hydrogen molecules); intermetallic hydride (hydrogen molecules dissociate into hydrogen atoms that are incorporated into the solid lattice framework); complex hydride (hydrogen can be strongly bound within molecular structures, as chemical compounds containing hydrogen atoms).

Compressed hydrogen is kept in a dense state by external physical forces only. This is what happens in a pressure vessel. It takes mechanical energy to compress the gas, but the release is free of charge.

Liquid hydrogen is kept together by weak chemical forces (van der Waals) at very low temperature but at ambient pressure. Heat must be supplied to release hydrogen through boiling, but due to the low boiling point of 20 K, the heat can in principle be taken from the surroundings or any waste heat. Liquefaction of hydrogen by pressurization alone is not possible since the critical point is as low as 33 K (and 13 bar)

Hydrogen can bind to matter in many ways. It can be via adsorption on a large surface with some affinity for hydrogen molecules. In order to obtain a reasonable storage capacity this is always done in combination with either cooling (to reduce the energy of the hydrogen molecules), pressurization or both. The binding forces are the weak van der Waals forces like in liquid hydrogen, but the interaction is stronger due to the substrate. Release is comparable to a combination of compressed and liquid hydrogen. Absorption of hydrogen takes place in specialized solid materials into which hydrogen can diffuse and bind by metallic, ionic or covalent bonds. These forces are much stronger than the van der Waals forces and consequently, it takes more energy to release hydrogen afterwards. Examples are interstitial metal hydrides and complex hydrides.

One way to arrange the storage techniques is shown in Figure 5.43, where they are ordered in a line ranging from pure physical storage to a gradually more chemical technique. **A tendency that goes with this is that the more chemical the technique, the less easily available is the hydrogen. This less easy availability of hydrogen is seen as higher energy demands for hydrogen release and/or higher release temperatures.**

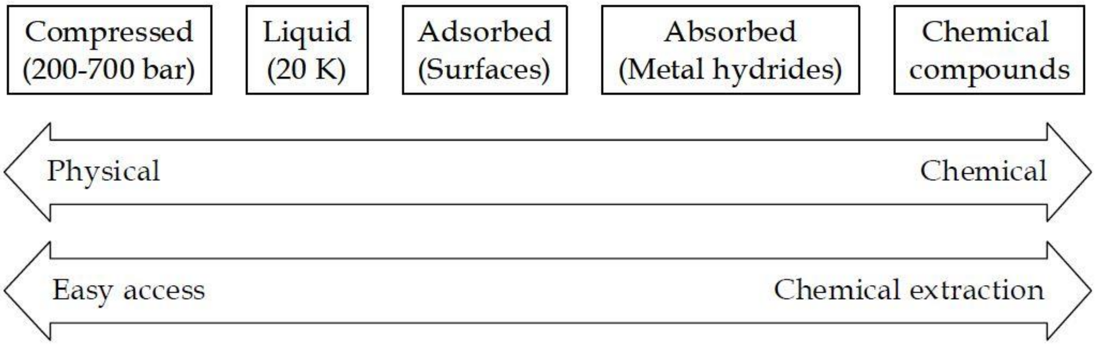

Figure 5.43 The sequence of hydrogen storage techniques from physical to increasingly chemical [Jens Oluf Jensen, Qingfeng Li and Niels J. Bjerrum, 2014]

5.2.4.4.4 Main Characteristics and Energy Requirements of each Alternative

When analyzing an energy system, the major pillars of comparison between alternatives are primarily the feasibility, the energy analog and the economic analysis of each option. Although hydrogen storage does in principle not depend on the application, onboard storage is assumed since here we have the most demanding situation that may justify sophisticated and possibly expensive techniques.

Firstly, the primary intention of this section is to compare the different alternatives of the storage and release of hydrogen fuel.

A true comparison would involve a detailed analysis of whole systems. Such analyses are truly relevant but also complicated with numerous assumptions on which the outcome will strongly depend. Instead, transparency is aimed at with the hope that the conclusions are less questionable, although they do not tell the whole story. Thus, at this preliminary study, the comparative measures will be linked with storage densities, costs and efficiencies (possible losses due to evaporation etc.). For the scope of this paper, the lower heating value (LHV) of the fuel is used instead of the higher heating value (HHV). The reason that lies behind this assumption is connected with the security of the calculated results (grounded on the safe side of the calculations). Realizing the worst case of a scenario is – in many applications – more significant than knowing a convenient one.

When energy is needed for the release, typically heat, it can in some cases be supplied by otherwise wasted heat from an engine or a fuel cell, but it depends on the temperature of that heat whether it is possible. Alternatively, the heat for release can be supplied by part of the hydrogen via a burner. In the latter case the available hydrogen for the main purpose (e.g. propulsion) will be reduced comparatively and the effective storage capacity is thus lower than predicted from the amount of hydrogen stored.

5.2.4.4.4.1 Compressed Hydrogen

Despite many attempts to develop advanced techniques for compact, practical and safe hydrogen storage, pressurization is still the dominating technique. This is a fact for onboard hydrogen as well as for hydrogen storage in general. The standard pressure for steel cylinders is 200 bar, but high pressure fiber composite tanks rated for up to 7-800 bar have been developed.

One strong advantage of compressed hydrogen is that it is easily available at a pressure high enough for **fast transport through tubes**. Even though the pressure vessel will cool during release, the pressure will in most cases still be way above ambient pressure. Therefore, **no energy is needed for the release**. In principle, part of the compression energy can even be reclaimed via an expander, but as it adds to complexity and cost it can be argued whether or not it is feasible.

The work of compression in real systems is estimated by Bossel et al [Bossel et al., 2003] and Weindorf et al [Weindorf et al.,2003]. According to these studies, compression to 700 spending 13 % (Weindorf) of LHV. Compression to a final pressure of 800 bar costs 15.5 % of LHV.

5.2.4.4.4.1.1 Maritime Background

A high-pressure gas cylinder based hydrogen storage system is used on board small inland passenger ships such as the FCS Alsterwasser and the Hydrogenesis. Tanks are usually made of aluminium alloys and austenitic steel since they are resistant to hydrogen interaction at the material surface but tend to be heavy [Hirscher, 2010]. More advanced tanks are built from composite materials which can withstand higher pressures with similar volume but lighter construction.

Typical pressures for compressed hydrogen are 350 bar and 700 bar which give a density of 23.3 kg/m^3 and 39.3 kg/m^3 respectively. The greater the pressure, the more energy is required for compression, and a wider consideration of the viability of hydrogen fuelling should incorporate this aspect. 350 bar storage systems are the most common option; they are typically packages of long, small diameter tanks, frequently in modules compatible with ISO container dimensions designed for road transport [FIBA Canning, 2008]. **However, this initial study will consider the total energetic cost as 11% and 13% of hydrogen's LHV for a compression of 350 and 700 bar respectively.**

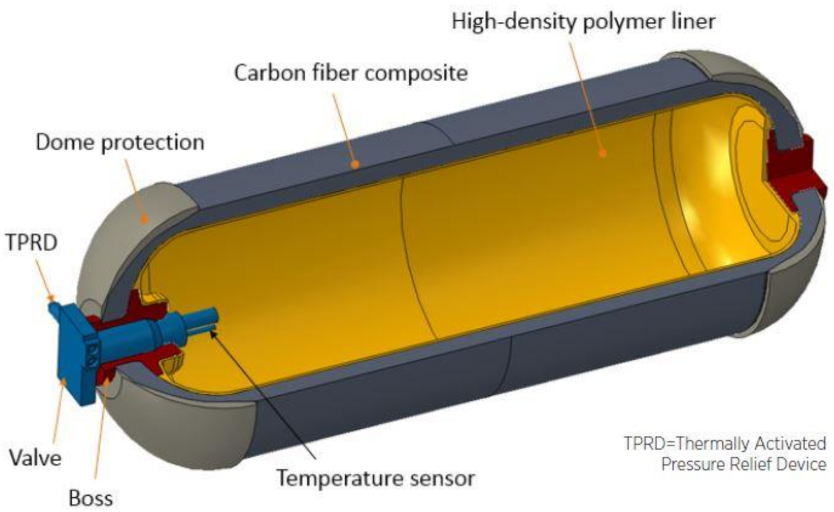

Figure 5.44 A schematic of a Composite overwrapped pressure vessel designed for compressed hydrogen storage onboard FCEVs [U.S. Department of Energy, 2018]

For the case of 700 bar or above the tanks tend to be smaller in volume in order to withstand the higher pressures. This means that a large amount of these tanks need to be used on board in order to cover the ship's fuel demand. Issues such as the cost of high pressure tanks are being improved over time due to interest from the automotive industry and future tanks may generally be of higher pressure but this work will start with the conservative 350 bar tanks. The gravimetric energy density (i.e. mass of the stored hydrogen fuel by mass of the storage system) fluctuates between 3.5% and 5.5% depending on the tank's pressure, construction and material used [Hirscher, 2010]. In this work the gravimetric energy density is assumed to be 5% of the Lower Heating Value (LHV).

5.2.4.4.4.2 Liquefied Hydrogen

Liquid hydrogen has the advantages that it is quite dense and that fueling is fast and in principle as easy as for gasoline. The main drawbacks are that liquefaction is very energy intensive and that hydrogen continuously evaporates due to influx of heat. The latter can be reduced to a few percent per day or less by advanced thermal insulation, but it will always have to be dealt with. Liquid hydrogen tanks are high cost items and at present liquid hydrogen are only available in selected countries.

Liquid hydrogen (LH_2) has many benefits for the hydrogen infrastructure: its high density allows minimum costs for distribution (e.g. \$167/kg H_2 for a liquid trailer vs. \$783/kg H_2 for a gaseous trailer) and stationary storage, its high payload and short transfer times ease delivery logistics, its low temperature provides very low potential burst energy, and LH_2

pumps can efficiently achieve large throughputs at the refueling stations with a small footprint (low electricity consumption and compact designs).

However, using LH_2 has a few challenges: liquefying H_2 is expensive (more than 3 times the energy of compression to 700 bar [Reddi et al. 2016], setback distances are more stringent for LH_2, and boil-off losses along the LH_2 pathway may occur. The practical energy demand for liquefaction is significantly larger and depends on the size of the plant. **Today, the energy demand in a modern plant is on the order of 25 % of LHV.**

5.2.4.4.4.2.1 Boil-off Losses along the LH2 Pathway

Losses along the LH_2 pathway are intrinsic to the utilization of a cryogenic fluid. They occur when the molecule is transferred between 2 vessels (liquefaction plant to trailer, trailer to station storage, station storage to pump or compressor, then fuel cell electric vehicles etc.) and when the fluid is warmed up due to heat transfer with the environment. Those losses can be estimated with good accuracy using thermodynamic models based on conservation of mass and energy. When it comes to refueling stations (or storage tanks on ships), is expected that the only remaining boil-off losses for a refueling station would come from the LH_2 pump (utilization and idling), pump vessel cool down/warm up, and environment heat transfer. Based on experimental data measured at LLNL (Lawrence Livermore National Laboratory) on the Linde 875 bar LH_2 cryo-pump and results from the model, and extrapolating for refueling stations of various sizes, it can be shown that boil-off losses can vary from 15% of delivered LH_2 for a 100 kg/day, 5% at 400 kg/day, and down to less than 2% for stations above 1,800 kg/day. Less boil-off is to be expected for LH_2 pumps dispensing at 350 bar, so that less than 0.7% can be expected above 1,800 kg/day station capacities [G. Petitpas, 2010].

5.2.4.4.4.2.2 Maritime Background

Liquid hydrogen storage systems can reach a volumetric density of about 75 kg/m^3 – approximately double that of high-pressure gas cylinders – and gravimetric density (kg H_2/kg tank) of about 10%. In this work the volumetric density for liquid hydrogen is assumed to be 70,85 kg/m^3 which is the density used in some of the liquid hydrogen fueled cars. Liquid hydrogen can be stored in cryogenic tanks at -253˚C, ambient pressure and in open systems. Rohde & Nikolajsen [2013] created a concept for a zero-emission ferry powered by liquid hydrogen. The hydrogen was stored in IMO type C tanks on deck capable of holding 140 m^3.

This paper will also examine IMO type C tanks (which are commonly speculated as an effective LNG storage option) **for the storage of liquid hydrogen.**

5.2.4.4.4.3 LNG Boil - Off

LNG is carried in tanks that have a thick layer of insulation outside. But nothing is perfect, and a small thermal current exist between cargo and environment. This causes to LNG to boil; this vapor is the renowned boil-off phenomenon.

The boil-off can be measured in units of vapor per units of time. It can be measured in kg/h, kg/day or the measure can be relative % vaporized of all mass per unit of time.

For a cargo capacity of 228,000 m^3, a maximum specific gravity for LNG of 470 kg/m^3
and a boil-off rate of 0.14% [EMSA, 2019], results to a boil-off flow of 6250 kg/h. In reality, the boil-off rate will be somewhat less, perhaps in the region of about 5500 to 5800 kg/h depending on the LNG cargo composition.

5.2.4.4.4.3.1 IMO Type C LNG Tanks

This type of tanks has only recently hit the market. They usually have cylindrical or spherical shape, with design pressure between 2,7 bar and 4 bar. The tanks are constructed with use of high quality materials suitable for cryogenic applications such as 9%Ni-steel, stainless steel 304L, Aluminum. These materials keep their qualities in low temperatures. The tanks are designed and built according to the conventional pressure vessel codes and, as a result, can be subjected to accurate stress analyses. Moreover, in the design phase much attention is paid to eliminating possible stresses in the tank material. For these reasons, type C cargo tanks do not require a second shell. The cargo tanks are typically insulated with polystyrene or polyurethane panels attached to the tank wall. A typical bilobe IMO type C tank is shown in **Picture 5.33**.

Picture 5.33 IMO Type C tank [IMO, 2018]

The size of these tanks is limited to 30,000m^3 and above with bilobe cargo tanks by classification societies, so its profitable to use them as fuel storage or on small LNG carriers.

However, using IMO type C tanks for storage of fuel has disadvantages too. The tanks have cylindrical shape that utilizes worse the ship's hull and need more isolation space for safety reasons. This combined with the fact that the LNG has lower density, translates in 3-4 more volume required for fuel storage. That means that significant part of transported cargo is lost.

5.2.4.4.4.3 Reversible Metal Interstitial Hydrides

The term "reversible hydride" refers to hydrides' capability to be charged as well as discharged by direct solid/gas reactions (or liquid/gas). Reversible should not be understood in a thermodynamic sense in this context, it only means "capable of reversing".

Hydrogen stored in interstitial metal hydrides is bound into interstitial positions in a host metal alloy in a more or less metallic way. This bond is stronger than the van der Waals forces mentioned before and a significant amount of heat is required to release hydrogen

The general equation is:

$$\mathbf{M + H_2 \leftrightarrow MH_2} \qquad \textbf{(5.3)}$$

Interstitial hydrides are the most studied metal hydride systems for hydrogen storage. Examples are plentiful such as $LaNi_5H_6$, $TiFeH_2$, and $LaNi_5$-based alloys for nickel metal hydride batteries. They are considered very safe and easy to operate, and their main drawback apart from the price in some cases is the fact that the hydrogen storage capacity (with a few exceptions) is below 2 wt. %. One convenient characteristic is that the alloys can be tailored to a moderate equilibrium pressure of a few bars at ambient temperature. The heat of desorption is then around 30 kJ/molH_2 or 12.4 % of LHV (near room temperature for 1 bar).

During charging, this heat is liberated. In small canisters, the heat can be exchanged with the surroundings, but in larger systems like in a vehicle, active cooling by water Is necessary. The energy balance of such a cooling system depends highly on the charging rate aimed at. Consequently, only the sorption energy is considered.

When hydrogen is liberated, the hydride cools and the plateau pressure must still be above ambient pressure to avoid subsequent compression of the released hydrogen. This implies that the plateau pressure will be correspondingly higher when the hydride is heating up during charging and the charging pressure must match that. A 20-50 bar charging pressure can be suggested. Based on the discussion above, compression to 20 bar is set to 4-5 % of LHV (or 3 % with isothermal compression).

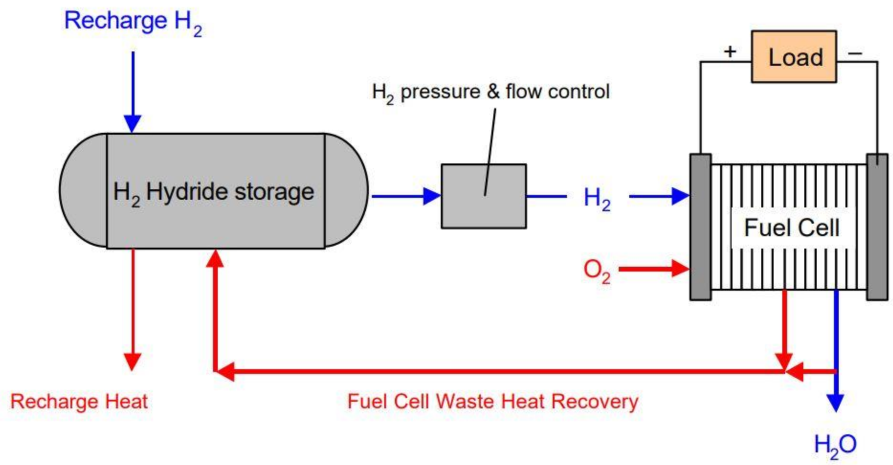

Figure 5.45 **Example of a typical vehicular hydrogen fuel cell system. [Trygve Riis and Gary Sandrock, 2005]**

The amount of heat for desorption is the same as for absorption. It can be taken from the excess heat of the fuel cell or combustion engine provided that the temperature is high enough. The interstitial hydride can be designed for that.

Metal hydrides could be used to store hydrogen on board ships. They have been successfully used in the Type 212 submarines of the German Navy. Metal hydrides tubes were installed from the stern all along to the stem of the submarines in the interior space of the double-skin sided submarines. For those applications where the need for hydrogen supply is small and the space availability is higher, metal hydrides can find a breeding ground for their development. However, they have not been applied and tested to commercial vessels yet. The metallic hydride systems working at ambient temperature and atmospheric pressure have a volumetric density of about 50 kg/m^3, and a low gravimetric hydrogen density limited to less than 2% of the total mass [Zuttel, 2010]. These solid-state storage systems also have additional requirements for heating systems to extract the hydrogen, and may not be compatible with fast-filling techniques. These aspects are beyond the scope of this paper, however. **While this kind of hydrogen storage system is promising for specific applications in the future, it is insufficiently developed, its efficiency has not been tested for commercial purposes and so is not considered in this work.**

5.2.4.5 Overall Comparison of Hydrogen's Storage Systems

Table 5.14, summarizes the main characteristics of the abovementioned storage systems.

Table 5.14 Hydrogen and LNG Storage Options and their

Phase		Gaseous		Liquid	Solid	LNG Storage (c)
Efficiency indices	**Units**	Compressed H_2 at 350 bar with electricity	Compressed H2 at 700 bar with electricity	Liquid H_2 at 1 atm Type C Tanks	Metal Hydride	
Fuel's Properties	Density and Temperature (b)	23,3 kg/m³, 280 - 300 K	39,3 kg/m³, 293 K	70,85 kg/m³, 20 K	50 kg/m³, 300 K	470 kg/m³ , 100 K
System's gravimetric density	kg H_2/kg Storage System	0,035	0,05	0,142	0,055	-
System's volumetric density	kg H_2/L Storage System	0,014	0,016	0,0425	0,040	-
Capital and Installation Cost	\$/m³	9320	17685	6000	27500	4000
System's Purchase Cost	\$/kg Fuel stored	400	450	84,69	550	8,5
	\$/MJ	3,328	3,743	1,040	4,575	0,175
	\$/kWh	11,979	13,476	3,743	16,471	0,629
Storage and Conditioning Practical Efficiency	% H_2 LHV	89	87	75, Overall system requires 150 kW (a)	85	Overall system requires 100 kW (a)

(a) DNV GL, "Alternative Fuels Guidance Paper", 2019

(b) DNV GL, "Hydrogen as Maritime Fuel", 2018

(c) European Marine Safety Agency, "Guidance on LNG Bunkering to Port Authorities", 2018

Note

For the purposes of this preliminary analysis, boil-off gas phenomena of LH_2 and LNG are not taken into consideration due to their very small impact on overall system evaluation. The provides justification is that in our case study (see 6th Chapter), our reference ship, Blue Star Paros, services short daily round trips and its inactive time is particular small. Therefore, Fuel Oil Storage Systems operate regularly without important time-consuming transitions or cut-offs. As an impact, the pressure amidst storage tank increases with small rates and the amount of physically boiled-off gas is within negligible limits.

5.2.3.5.1 Storage System Selection

The argumentation behind the conclusive selection of a storage system refers to the total efficiency of its technique. Efficiency is a term with multidimensional meaning, from supply chain aspect, infrastructure availability to verified tests of assessment for each alternative and of course economic analysis of its components (CapEx and OpEx analysis). To conduct such a comparison someone needs a big collection of data and records. However, at this preliminary study three aspects of the total subject will be considered; 1) background history - records of each alternative, 2) its economic assessment and 3) applicability of its technique on vessels. To aid in evaluation, Table 5.14 (in which data is a gathering from authorized Marine Organizations) work as collection of today's potential of each alternative.

As it is obvious from Table 5.14, **LH_2 storage prevails in all aspects**. It is economic attractive, its storage efficiency and potential has already been tested in various of projects (for example LH_2 on-board tanks would be very similar to existing ISO LH_2 tanks that has been in use for years to transport LH_2 as cargo around the world), and **provides the best gravimetric and volumetric specification** - which is vital for storage configurations and ergonomics -.

Apart from the benefits of light weight and small volume**, there are many other attendant benefits of choosing LH_2**, as the storage method of hydrogen. **These benefits include:**

1. LH_2 storage does not require high pressures. While the high-pressure composite tanks are very safe, and the composite tank manufacturers deserve a lot of credit for making such a reliable product, there exist perceptions about the safety of having such high pressures (5,000 - 10,000 psi) near people. These concerns have been largely addressed by the light-duty vehicle manufacturers, who will be using 5,000 - 10,000 psi storage of small quantities (~ 5 kg) on the first fuel cell vehicles. However, for the larger (~400 kg) quantities for the Blue Star Paros (Case Study), it's advisable to avoid high pressures if possible.

2. LH_2 storage has been used for decades for space applications (both the Apollo Saturn V and Space Shuttle launch vehicles used very large quantities of LH_2), and has also been transported on the roads in tankers for decades with an excellent safety record. The properties of LH_2 are well understood, and LH_2 storage and transport are mature technologies.

3. With LH_2 stored on the vessel, it can in principle be fueled directly from a LH_2 tanker brought to the waterfront by the gas supplier. In principle, this would not require a "hydrogen station," providing more flexibility for refueling in the early years of deployment.

4. LH_2 is very similar in its physical and combustion properties to Liquid Natural Gas (LNG). Since LNG ships are already being designed by naval architects, and approved by the international and domestic shipping authorities, **LH_2 is a natural extension of LNG maritime technology**. This provides the benefit that naval architects, having LNG design experience, can readily design hydrogen fuel cell vessels once the minor difference between LNG and LH_2 are described, and they have acquired fuel cell expertise. In addition, the domestic maritime authorities [DNV GL, American Bureau of Shipping] and international regulatory bodies [EMSA] are already writing the codes and standards for safe use of LNG on vessels. Theses codes provide a basis for consideration to allow for the safe use of LH_2 on hydrogen fuel vessels based on similarity with LNG.

From previous analysis it is obvious that LH_2 storage is the most effective and economic prosperous solution for today FC technologies.

5.2.4 Well-To-Tank Greenhouse Gas Emissions from Supply Chain

Hydrogen is a promising energy carrier in the clean energy systems currently being developed. Its implementation is thought to be the next big thing in transportation industry; its integration in concurrent supply chains is believed to be established in the next 30 years (a time window with progressive goals and targets between 2030 – 2050 has been developed and proposed by EU). However, its effectiveness in mitigating greenhouse gas (GHG) emissions requires conducting a lifecycle analysis of the process by which hydrogen is produced and supplied. The stages of the supply chains include hydrogen being produced overseas (since, at the moment, there are no hydrogen generation stations in the vicinity of Piraeus Port), converted into a transportable hydrogen carrier (liquid hydrogen or utilizing metal hydrides), imported to Piraeus by sea, distributed to hydrogen filling stations, restored from the hydrogen carrier and filled into fuel cell vehicles. For comparison, an analysis is also carried out with hydrogen produced by steam reforming of natural gas.

The analysis results indicate that some routes – methods of hydrogen supply chains using liquid hydrogen exhibited significantly lower WtT GHG emissions than those of a supply chain of hydrogen produced by reforming of natural gas. Furthermore, it suggests that the production of hydrogen, its liquefaction and the compression of hydrogen at the filling station are the GHG-intensive stages in the target supply chains.

Foreground data related to the hydrogen supply chains are collected by literature surveys and the Japanese life cycle inventory database is used as the background data [Ozawa, Inoue et al, 2017 & DNV GL, 2019]. The total results for each pathway are projected in Table 5.15. From what it can be seen from the Figure 5.46, it is quite obvious that the GHG emission factor is highly sensitive to the production method and T & D route of the H_2 supply. Liquid hydrogen storage with the same production method and T & D route has less impact on the environment, in terms of CO_2eq emissions, than the compressed one (350 – 700 bar) while with the current technological status, water electrolysis is the most energy-consuming method. However, when the electricity is derived from renewable sources such as the harnessing of wind or solar energy, the GHG emission factors are radically decreased. These results have been debated on researcher's community forums and it is a common belief that the future of hydrogen production belongs to on-site electrolysis from renewable sources.

Table 5.15 **H_2 Supply Perspective and its Environmental Effects**

H_2, LNG and LSFO Supply Perspective - Well-To-Tank Emissions for each Production, T&D and Storage Scenario				
PathWay Code	**Technology**	**T & D**	**Storage Conditions**	**WtT GHG emission Factor ($gCO_2eq/MJ-H_2(LHV)$)**
1	Central Reforming using NG	4000 km Pipeline network	Cryogenic Liquid	102
2	Central Reforming using NG	4000 km Road using Trucks		118
3	Electricity from Solar Photovoltaic cells	On site		150
4	Electricity from Wind Energy	On site		130
5	Reforming and Liquefaction at Source	On Site		130
6	NG, Central Electrolysis	4000 km Pipeline network	Compressed	205
7	Electricity from Solar Photovoltaic cells	On site		160
8	Electricity from Wind Energy	On site		140
9	On-site electrolysis using Elec EU-mix	On Site		236
10	LNG, CCGT On-site electrolysis	On Site		220
11	Centralized NG SMR	4000 km Pipeline network		105
12	Centralized NG SMR	4000 km Pipeline using Trucks		112
13	LNG, On-Site	On Site		126
14	LNG	From Qatar used in Europe	**Fossil Fuels**	19,6
15	LSFO	From Qatar used in Europe		14

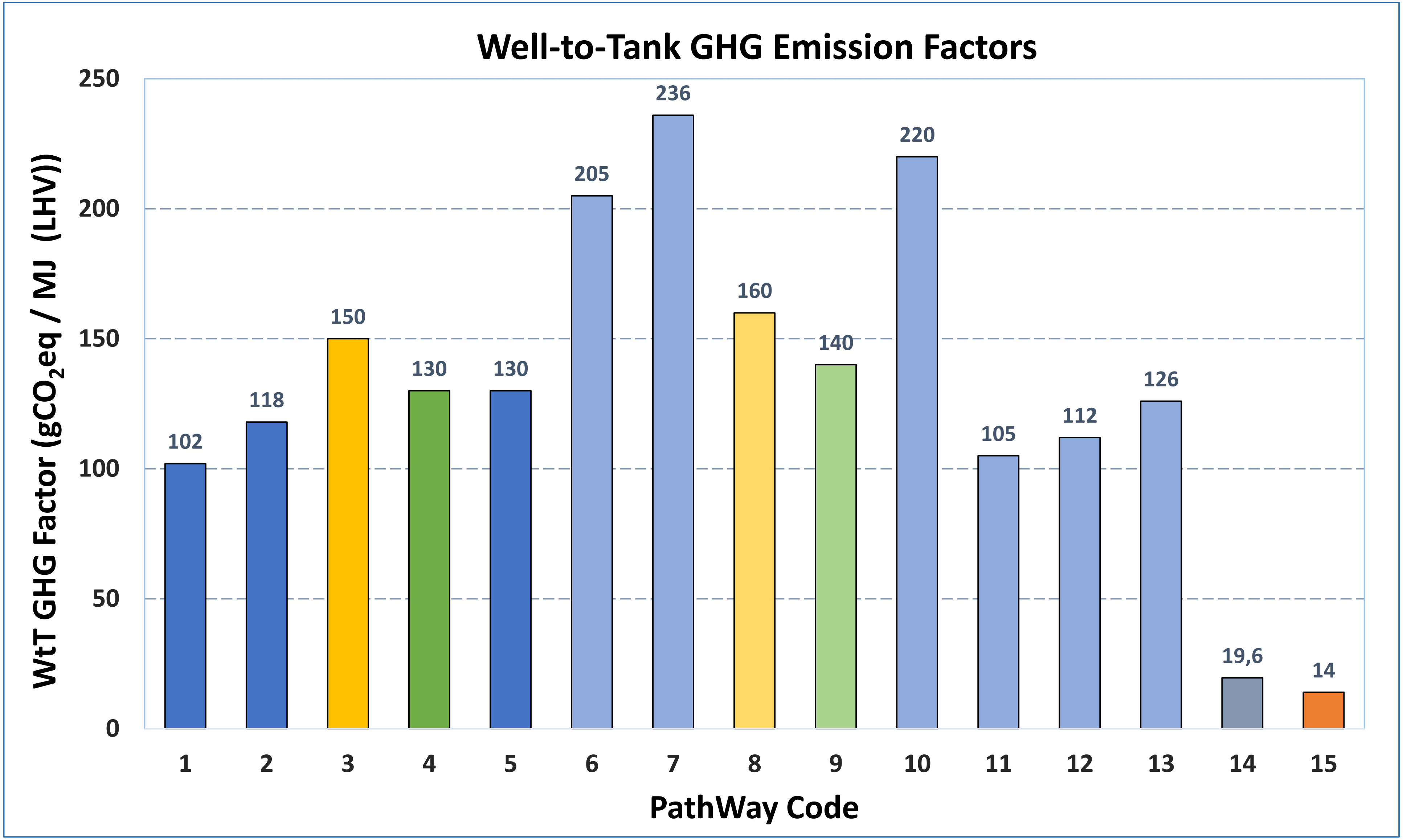

Figure 5.46 H_2 Supply Perspective and its Well-to-Tank GHG Emission Factor

5.3 Marine Fuels

This section works as a guide in an effort to infuse the reader with the necessary background information about the most commonly used fuels in the marine industry. As mentioned before, at this diploma thesis three are the fuels that will be examined:

A. Low Sulfur Fuel Oil (LSFO) which has a maximum sulfur content of 1%, and is the primary fuel of the current installation unit (Auxiliary Engines – Diesel Generators) on Blue Star Paros (the ship that is examined through case studies for the effectiveness of a Fuel Cell project plan for the displacement of the D/Gs).

B. Hydrogen (H_2) which is a pure zero-emission fuel and can be acquired and stored with great variety of methods. For example, it can be delivered directly from a production unit or be generated on-site using fuel reformers (in order to overcome storage insufficiencies) which purify fuels by extracting from them the pure hydrogen and disposing the unnecessary impure byproducts. As mentioned before, there is a variety of different methods of storage that affect directly hydrogen's properties and efficiency to be utilized as an energy carrier. Amongst the well-known storage techniques, compression, liquefaction and chemical reactions with metal hydrides are the most commonly used in the industry.

C. Liquefied Natural Gas (LNG), that is natural gas which has been cooled to a liquid state, at about -260 °F (or -162 °C), for shipping and storage. The volume of natural gas in its liquid state is about 600 times smaller than its volume in its gaseous state. This process, which was developed in the 19th century, makes it possible to transport natural gas to places pipelines do not reach and to use natural gas a transportation fuel. Its main advantages include lower emissions of greenhouse gases during combustion, competitiveness in global prices (LNG, when it comes to prices, is not as volatile as diesel oil or its distillates) and high energy content. But nothing is perfect and LNG is not an exception. Its main drawbacks refer to high storage cost (a great amount of energy is required in order to keep the natural gas liquefied at -162 °C), safety matters and the lack of authorized regulations for both international organizations, continentals as wholes and countries as units. Bunkering issues and partial or total absence of LNG infrastructure at ports are only some of the most common bottlenecks in the way of its expansion and consolidation as opportune marine fuel. Many of these hurdles also emerge during the supply, transmission and storage of hydrogen and specifically LH_2.

Taking that into account, for the sake of completeness, the following table presents a brief description of the main representatives of marine fuels in shipping industry.

Table 5.16 Main Marine Fuels & their Characteristics

Fuel Name	Feedstock & Production Technology	Production Technology	Lower Heating Value (LHV) (MJ/kg)[8]	Indicative Price - Port of Piraeus (2019)[9]	Comments
Hydrogen **(H_2)**	Onsite production with Reformer or Distribution from Production Sites	Onsite : SMR - Steam methane reforming with CCS or Electrolysis	120.21	5 – 9 $/kg	A global transition to H_2 is oriented between 2030 & 2050 It has no carbon emissions in the point of operation
Liquefied Natural Gas **(LNG)**	Natural Gas	Extraction and liquefaction	48.62	415 $/ton	It has lower GHG emissions than oil derived fuels, is competitive in prices, and is already used in part of the global fleet
Marine Gas Oil **(MGO)**	Based on the Lighter Distillates	• The ISO 8217 DMA quality label has a maximum permissible value of 1.5%. • Low sulfur marine gasoil (LS-MGO) has a sulfur content of less than 0.1%.	45.61	620 $/ton	Has a low viscosity and can easily be pumped into the engine at temperatures of around 20°C
Heavy Fuel Oil **(HFO)** Intermediate Fuel Oil **(IFO)** IFO–380 IFO–180	Residual Oil Marine diesel with higher proportions of heavy fuel oil	Trans Esterification or Gasification • HSFO has a maximum Sulfur Content of 3.5% as permitted under ISO 8217. • ULSFO can have a max of 0.1% Sulfur Content • IFO 180 & IFO 380 can have a max of 3.5 % Sulfur Content They are also sold in a low-sulfur variant, which has a sulfur content of less than 1% [ECAs] – LSFO.	42.7	Crude Oil Brent 438 $/ton IFO 380 450 $/ton IFO 180 460 $/ton LS380 480 $/ton ULSFO 575 $/ton	ULSFO is a necessity for ships from 1/1/2020 and thereafter in EU due to IMO's agreement. Currently, most of ships run on IFO 180 or IFO 380. When approaching a EU Port or during operations at it, it is obligatory to use ULSFO (2015 -)

[8] LHV as mentioned in IMO's Resolution MEPC.281(70)

[9] Average Prices at Piraeus Port in 2019 according to Ship&Bunker.com.
Hydrogen Prices are based on a certified report developed by Fuel Cells and Hydrogen 2 Joint Undertaking [2019] on behalf of European Commission. The range of value in sale prices depicts the legal level of competition between hydrogen suppliers within European Union.

5.3.1 Hydrogen as a Marine Fuel

5.3.1.1 General Information

The maritime industry is at a crossroads. It has reached a point in its history where it has to pick the right path to meet its decarbonization targets. Specifically, the International Maritime Organization's (IMO) climate strategy has set out to reduce the total greenhouse gas emissions by at least 50% by 2050. Nevertheless, the shipping world is yet to carve out the strategy on how to fulfill this ambition

To propel marine industry into the future, a large burden has fallen on the engineers and the role of technology in coming up with ingenious solutions to decrease emissions, redesign ships and help the industry reinvent itself. In this transient, for the marine transportation sector, period a great quandary arises. **Could hydrogen be the zero-emissions fuel the shipping industry strives for or its commerciality and usability is unrealistic for the time being?**

Hydrogen as marine fuel faces some significant obstacles such as lack of reliability or high cost. However, compared to some other proposed alternative fuels, such as LNG, methanol and biodiesel, hydrogen has some advantages as marine fuel. **What follows is a summary of the main superior points of hydrogen over other conventional fuels.**

To begin with, hydrogen is superior to other alternative fuels in the environmental perspective. DNV GL investigates that [DNV GL, 2018 Report] CO_2 emission of LNG from the tank to the propeller is more than $55\ \mathrm{g/Mega\ Joule\ (MJ)}$, and if using methanol from CH_4 then it is more than$70\ \mathrm{g/Mega\ Joule\ (MJ)}$, whereas one of hydrogen is zero in shipping, the same as biodiesel. Moreover, as for NO_X emission, the emission of hydrogen is below 20%, compared to HFO-fueled Tier II diesel engines which is used as a baseline (100%). This value is sufficient to comply with Tier III NO_X limits. Therefore, hydrogen is the cleanest fuel produced and can reassure the ship holders that their vessels comply even with the strictest rules of the IMO and they can drift in all the ECA's zones without any doubt. This is a matter of great importance as the environmental policies from both the IMO and some flag-states (Norway) getting stricter and stricter and the operation of their ships may be questionable in the future. To be more specific, EU has already announced the obligation for every vessel passing by or anchoring to a EU Port has to use fuel with specifications that are equivalent to the ULSFO (Ultra Low Sulfur Fuel Oil, <0.1% Sulfur content). What this means is that there are two possible scenarios for the marine companies.

The first scenario advocates the completion of all the necessary modifications of a preexisting propulsion powertrain system in order to enable current engines to run on ULSFO or LNG (Dual Fuel Technology) or to cover the expenses for the installment of a complete Exhaust Gas Reduction (EGR) system (SCR or Scrubbers for instance) although this alternative is ephemeral and not applicable to some regions (U.S.A., Norwegian Seas, etc.).

The second scenario refers to the all-out modification of the propulsion power system of the ship (what is known as retrofitting) and the supply chain of the ship so that it can be feasible for it to be powered with zero-emission fuels (Hydrogen) or environmentally-friendly techniques (Fuel Cells).

From the abovementioned analysis, it is concluded that is quite purposeful to assess the technical and economical possibilities of HFCs to power ships, even though at this preliminary stage should be confined to limited power and energy demands due to its recent emergence as a fuel and low commercialization and tests of Fuel Cell technology on ships.

Secondly, the energy content of hydrogen fuel is much higher than that of other fuels. According to the classification society DNV GL, the energy content of hydrogen is $120{,}21\ \mathrm{MJ/ton}$, (Lower Heating Value) which is around three times higher than that of any other fuel, as shown in Figure 5.47. Thus, high energy efficiency could be achieved by utilizing hydrogen as fuel.

What is more, hydrogen can be the primary fuel for the totality of fuel cell types which have a minimum overall efficiency of 50%; and this number grows periodically year after year. Therefore, it can be the driving force of a mechanism with great efficiency and close to zero emissions (or complete zero if PEMFC is used).

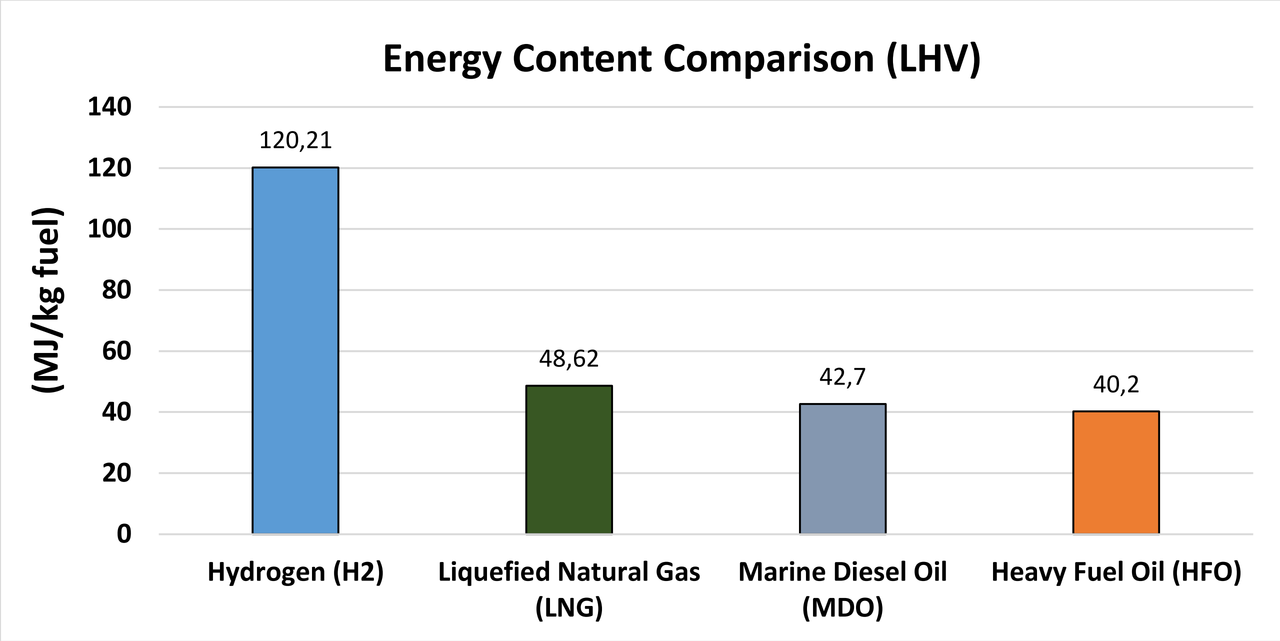

Figure 5.47 A comparison of energy content (LHV) between Hydrogen, LNG, MDO and HFO [DNVGL, 2018]

5.3.1.1.1 The Fuel Reformers: Overcoming Hydrogen Storage Inefficiencies

In view of the problems concerning hydrogen storage, the use of different energy carriers that are easier to handle is a significant and still open research task. The main interest of current research about automotive applications is concentrated on liquid hydrocarbons, although they require an additional on-board process to extract hydrogen from the supply fuel to operate the fuel cell (“reforming procedure”).

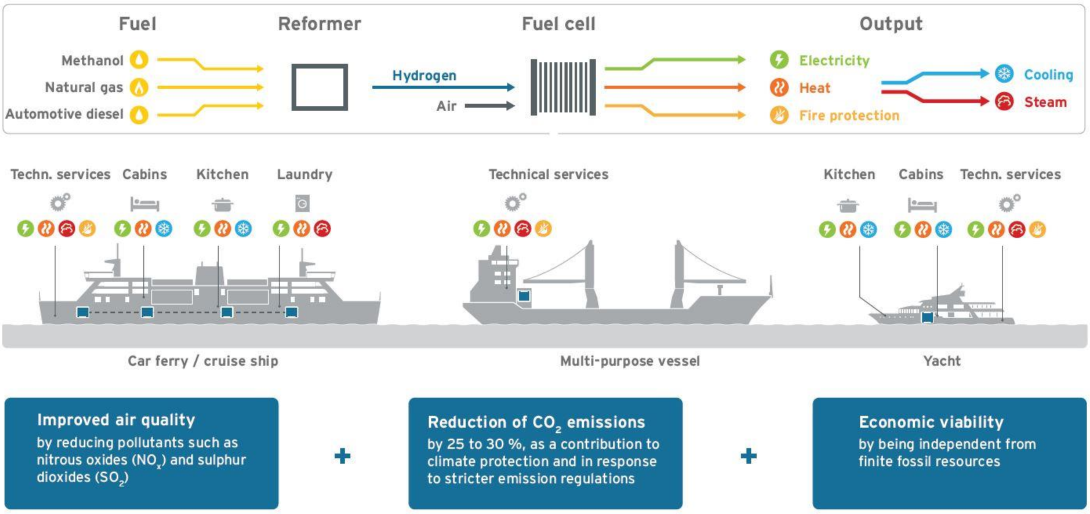

Figure 5.48 Fuel Cell Potential in Marine industry [e4ships, 2019]

The advantages are that: **(i)** there is no need for special storage systems, **(ii)** until the production and distribution of hydrogen is better established, the existing infrastructure for fossil fuels can be used, and **(iii)** the consumer acceptance is likely to be higher. The refueling operation does not change for the user from how it is today. This would clearly favor the adoption of this new technology.

Some drawbacks of on-site reformers are that: **(i)** the resulting vehicle is not a zero-emission vehicle (CO_2 emissions), **(ii)** the propulsion system is more complex and more expensive, **(iii)** the tank-to-wheel efficiency is lower since the reforming requires energy, **(iv)** the fuel cell is likely to have a shorter life span due to the impurities in the reformer gas, and especially **(v)** the system exhibits poor response times, which makes the use of reformers critical during transient operation. The use of reforming-based fuel-cell systems as small, stationary auxiliary power units for trucks and camper vans, where efficiency and response time is not an issue, seems to be more promising [Lino Guzzella and Antonio Sciarretta, 2013].

With the exception of the alkaline fuel cell, which must use pure hydrogen fuel, all the others can run with a reformed fuel. Reformation is an endothermic process (as shown in Figure 5.49), which produces hydrogen for consumption in these other fuel cell types.

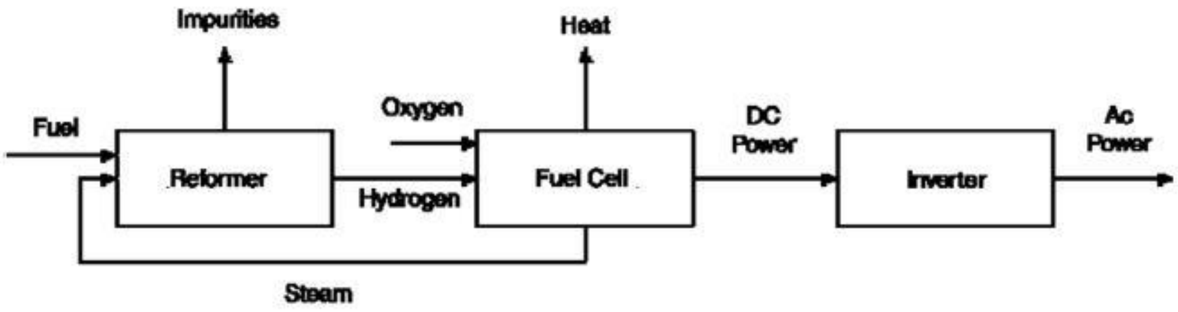

Figure 5.49 Simplified Schematic Plan of a FC utilizing Refined Hydrogen from a Reforming Unit

The fuel processor or reformer plays two important roles. The first one is to convert the fuel stock into a hydrogen-rich gas to be used in the fuel cell. Its second duty is to minimize pollution from the cell electrodes; sulphur and the carbon monoxide should be eliminated by using desulphurisers and reducers that transform the CO to CO_2. The water vapor produced in the reforming process also removes the hydrogen-rich gas, before placing it in the cell. The fuel processor requires different technologies for each fuel. As there is no fuel cell energy or heat available when at the initial stages, an additional source of energy is needed to start the fuel processor and cell.

This source of energy must generate vapor for the reformer and preheat the fuel stock. For systems that run on a larger scale, start-up periods of several hours are sometimes necessary. **This is a factor that may affect whether fuel cells are an option for certain types of vessels.**

One of the challenges of fuel cell applications on commercial ships is the capability of using commercially available fossil fuel, instead of pure hydrogen. It has been foreseen that conventional liquid fuels, such as LNG or methanol, will be a long-term solution for fuel cell applications on ships. This solution requires a fuel reformer to extract hydrogen from marine fuels. However, in this research feasibility analysis will be conducted for pure Hydrogen and LNG fuel sources.

5.3.2 LNG as a Maritime Fuel: Prospects and Policy

Liquefied natural gas (LNG) is now being used by ships, as an alternative marine fuel – also and precisely because it lowers emissions. LNG is regarded as the marine fuel of the future and as an important way of meeting stricter environmental regulations. This fuel's carbon footprint and emissions of sulfur and nitrogen compounds are significantly better than those of marine fuels based on crude oil. As it can be assumed that the thresholds for nitrogen oxide and sulfur dioxide emissions will continue to be lowered to protect the environment, experts expect that LNG will increasingly be used as a marine fuel. To date there are no internationally binding rules and standards for the worldwide use and storage of LNG, however these are currently being developed by various committees and organizations, including the Society for Gas as Marine Fuel (SGMF), IMO and ISO. For this reason, LNG as a marine fuel has not yet been covered or defined in DIN ISO 8217 even though it is used to fuel ships.

The combination of growing liquefied natural gas (LNG) supplies and new requirements for less polluting fuels in the maritime shipping industry has heightened interest in LNG as a maritime fuel. The use of LNG as an engine ("bunker") fuel in shipping is also drawing attention from federal agencies and is beginning to emerge as an issue of interest in Congress.

In 2008, the International Maritime Organization (IMO) announced a timeline to reduce the maximum sulfur content in vessel fuels to 0.5% by January 1, 2020. Annex VI of the International Convention for the Prevention of Pollution from Ships requires vessels to either use fuels containing less than 0.5% sulfur or install exhaust-cleaning systems ("scrubbers") to limit a vessel's airborne emissions of sulfur oxides to an equivalent level. An option for vessel operators to meet the IMO 2020 standards is to install LNG-fueled engines, which emit only trace amounts of sulfur. Adopting LNG engines requires more investment than installing scrubbers, but LNG-fueled engines may offset their capital costs with operating cost advantages over conventional fuels. Savings would depend on the price spread between LNG and fuel oil. Recent trends suggest that LNG may be cheaper in the long run than conventional fuels.

LNG bunkering requires specialized infrastructure for supply, storage, and delivery to vessels. To date, the number of ports worldwide that have developed such infrastructure is limited, although growth in this area has accelerated. Early adoption of LNG bunkering is occurring in Europe where the European Union requires a core network of ports to provide LNG bunkering by 2030. LNG bunkering is also advancing in Asia, led by Singapore, the world's largest bunkering port. Asian countries, together with Australia and the United Arab Emirates, have about 10 coastal ports offering LNG bunkering, with another 15 projects in development

5.3.2.1 LNG-Fueled Engines

One option for ship owners to comply with the IMO 2020 sulfur standards is to switch to engines that burn LNG as a bunker fuel. LNG-fueled vessels emit only trace amounts of sulfur oxides in their exhaust gases—well below even the 0.1% fuel-equivalent threshold in some of the ECA zones—so they would be fully compliant with the IMO standards. As a secondary benefit, using LNG as an engine fuel also would reduce particulate matter (PM) emissions relative to both high- and low-sulfur marine fuel oils. Furthermore, LNG vessels have the potential to emit less CO_2 than vessels running on conventional, petroleum-based fuels. However, LNG vessels would have the potential to result in more fugitive emissions of methane, another GHG, because methane is the primary component of natural gas.

Installing an LNG-fueled engine can add around $5 million to the cost of a new ship[10]. Retrofitting existing ships appears to be less desirable because of the extra space required for the larger fuel tanks (new ships can be designed with the larger fuel tanks). The costs of retraining crews to work with LNG engines could also factor into a vessel operator's decision about switching to LNG. However, apart from their lower emissions, LNG-fueled engines may offset their capital costs with fuel cost advantages over engines burning petroleum-derived fuels. These savings would depend on the price spread between natural gas and fuel oil—which has been volatile in recent years. The likelihood that switching to LNG will produce long-term fuel costs savings relative to conventional fuels is, therefore, a critical consideration for many vessel owners.

[10] Reuters, "New Fuel Rules Push Ship Owners to Go Green with LNG," August 15, 2018.

5.3.2.2 LNG vs. Petroleum-Based Fuel Costs

Recent energy sector trends suggest that LNG may be cheaper in the long-run than petroleum based low-sulfur fuels. However, these price movements are correlated to some extent. Many existing long-term LNG contracts link LNG prices to oil prices (although such contract terms are on the decline), even in the spot market. Starting in 2008, the advent of shale natural gas production dramatically decreased natural gas prices in the United States. Natural gas spot prices in the United States at the Henry Hub—the largest U.S. trading hub for natural gas—averaged around $4/MMBtu (million British Thermal Units) in 2018, about a quarter of the peak in average price a decade before (Figure 5.50).

Figure 5.50 Average Monthly Henry Hub Natural Gas Spot Price - Dollars per MMBtu

Source: U.S. Energy Information Administration, "Henry Hub Natural Gas Spot Price," online database, accessed October 12, 2018, https://www.eia.gov/dnav/ng/hist/rngwhhdM.htm.

Notes: MMBtu = Million British thermal units.

Liquefying natural gas into LNG adds around $2/MMBtu to the production cost. Including additional producer charges and service costs would bring the total cost of LNG available at a U.S. port (based on the 2018 average price in Figure 5.50) to approximately $6/MMBtu[11].

Shipping of LNG from the United States to Asia or Europe adds from $1 to $2/MMBtu, so, based on the 2018 average cost in Figure 5.50, LNG delivered to a port overseas would cost on the order of $7 to $8/MMbtu under long-term contracts, depending upon timing and

[11] "LNG Prices and Pricing Mechanisms," slide presentation, Platts, February 6, 2017, https://www.platts.com/IM.Platts.Content/ProductsServices/ConferenceandEvents/americas/liquefied-natural-gas/presentations2017/Chris_Pederson.pdf.

location[12]. Higher or lower prices could occur for specific long-term contracts and in the LNG spot market (i.e., for individual cargoes), based on the location and the supply and demand balance at the time. In general, the U.S. market will have the lowest-priced LNG. Northern Asia will have the highest LNG prices due to the region's comparative lack of pipeline gas supplies and its distance from LNG suppliers.

Figure 5.51 compares LNG spot market prices in the Japan LNG market—the highest-priced LNG market—to spot prices for two common petroleum-based bunker fuels, low-sulfur gas oil and high-sulfur fuel oil. As the figure shows, over the last five years, Japan LNG generally has been cheaper than low-sulfur fuel and more expensive than high-sulfur fuel on an energy-equivalent basis (i.e., per MMbtu). However, Japan LNG and high-sulfur fuel prices converged in 2018. As it can observed, spot prices for LNG deliveries to the Japan market fell below $6/MMBtu in 2016 from a high above $16/MMBtu in 2013. Likewise, low-sulfur gas oil prices have doubled, and high-sulfur fuel oil prices have tripled, since 2016.

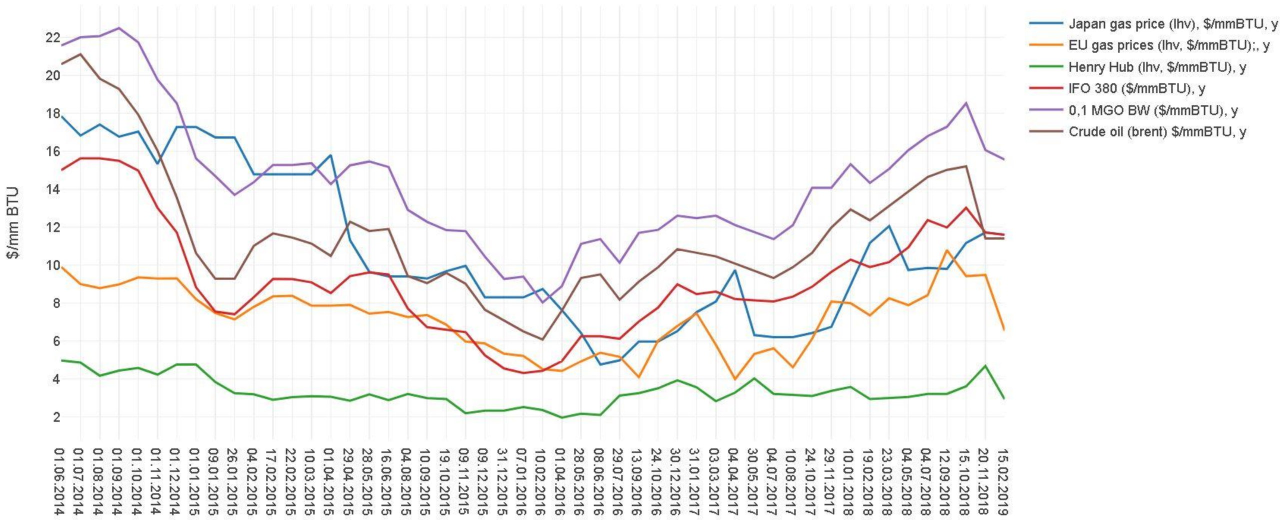

Figure 5.51 Maritime Fuels Cost Comparison [DNV GL, 2019]

Notes

The values represent the first month futures contract price at the end of each month. They are not monthly averages. Natural gas prices typically are quoted in $/MMbtu vs. $/metric ton for the other two fuels. The prices for gas oil and fuel oil are converted to $/MMbtu for direct comparison based on energy content.

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[12] Timera Energy, "Deconstructing LNG Shipping Costs," February 26, 2018, https://timera-energy.com/deconstructing-lng-shipping-costs/.

Blurry Points

Although fuel prices as shown in Figure 5.51 indicate favorable economics for LNG versus low sulfur fuel, if prices for high-sulfur fuel oils collapse as some expect after the 2020 IMO regulations enter into force, it is possible that LNG could lose its price advantage over residual fuel oils. Likewise, the price spread between low-sulfur gasoil and high-sulfur fuel oil would increase, incentivizing more carriers to install scrubbers to capitalize on the savings in fuel costs by continuing to burn high-sulfur fuel. An additional complication is the variability of LNG prices by region. Many shipping lines are global operators seeking low-priced fuel worldwide, but unlike the global oil market, natural gas markets are regional. Because the price of LNG can vary significantly by region, the relative economics of LNG versus other bunker fuels would also vary by region.

Another uncertainty in the market for LNG bunkering is the discrepancy between the spot price for traded LNG and the price for LNG sold as bunker fuel in ports. Added costs associated with marketing, storing and transporting LNG in bunkering operations would likely require ports to charge a rate for LNG bunker fuel above spot market prices. These additional overhead costs are likely to vary among ports.

5.3.2.3 Global Developments in LNG Bunkering

A key requirement for ocean carriers to adopt LNG as an engine fuel is the availability of LNG bunkering facilities. Because LNG is extremely cold (-260 °F ~ 162 ℃) and volatile, LNG bunkering requires specialized infrastructure for supply, storage, and fuel delivery to vessels. Depending upon the specific circumstances, LNG bunkering could require transporting LNG to a port from an offsite liquefaction facility for temporary storage at the port, or building an LNG liquefaction terminal on site. Alternatively, LNG could be delivered from offsite facilities directly to vessels in port via truck or supply vessel (Figure 5.52). Truck-to-vessel LNG bunkering, in particular, provides some fueling capabilities without large upfront capital investments. LNG tanker trucks could also bring LNG to a storage tank built on site at the port, which could then bunker the LNG to arriving ships via pipeline. Supplying LNG using tanker trucks in this way may face capacity limitations due to truck size, road limitations, or other logistical constraints, but it has been demonstrated as a viable approach to LNG bunkering at smaller scales. The predominant method of bunkering today with high-sulfur fuel is vessel to vessel, either by a tank barge or smaller tanker.

Figure 5.52 LNG Bunkering Options [Holden, 2014]

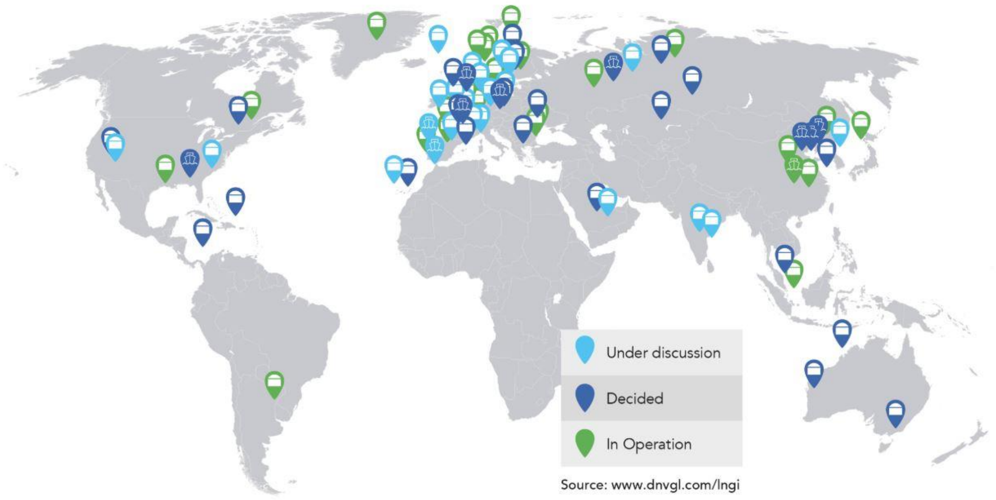
The type of infrastructure needed to temporarily store (if needed) and deliver LNG within a given port would depend on the size and location of the port, as well as the types of vessels expected to bunker LNG.

Truck to ship bunkering is best suited for supporting smaller and mid-sized vessels, such as ferries or offshore supply vessels (OSVs) that support offshore oil platforms. Liquefaction facilities built on site can provide the greatest capacity of any LNG bunkering option, for example, to provide fuel for large vessels in transoceanic trade. However, constructing small scale liquefaction facilities to produce and deliver LNG on site requires considerable planning and significant capital investment, in one case on the order of $70 million for a mid-sized port [Newman, 2017].

Each LNG bunkering option in Figure 5.52 may be a viable means to begin LNG bunkering service in a given port. However, ports may face practical constraints as bunkering increases in scale. For example, a container port of significant size typically has multiple terminals, so even with an onsite liquefaction facility; it may need additional infrastructure or supply vessels for moving LNG to other port locations where a cargo ship might be berthed. There may also be port capacity and timing constraints upon the movement of LNG bunkering barges trying to refuel multiple large vessels in various locations around a crowded port. To date, the LNG bunkering operations already in place or in development are comparatively small, but scale constraints could become a factor as LNG bunkering grows and might require additional bunkering-related port investments.

5.3.2.3.1 LNG Bunkering in Europe

Early adoption of LNG bunkering occurred in Europe, where the first sulfur ECAs were created in 2006 and 2007. Through Directive 2014/94/EU, the European Union requires that a core network of marine ports be able to provide LNG bunkering by December 2025 and that a core network of inland ports provide LNG bunkering by 2030. This mandate has been promoted, in part, with European Commission funds to support LNG bunkering infrastructure development. In addition, the European Maritime Safety Agency published regulatory guidance for LNG bunkering in 2018.



Picture 5.34 Global Infrastructure for LNG Bunkering

Serving existing ECAs, the LNG bunkering infrastructure is currently concentrated in north west Europe (for example, in the ports of Rotterdam, Stockholm and Zeebrugge) and the US Gulf and East coast (including the ports of Jacksonville and Fourchon). These will make up the bunkering nodes around which a global LNG-fuelled shipping industry will be developed. Current EU policy requires at least one LNG bunkering port in each member state. About 10% of European coastal and inland ports will be included, a total of 139 ports. **Coastal port LNG infrastructure will be completed by 2020 and for inland ports by 2025.**

Over 40 European coastal ports have LNG bunkering capability currently in operation—primarily at locations on the North Sea and the Baltic Sea, and in Spain, France, and Turkey. These locations include major port cities such as Rotterdam, Barcelona, Marseilles, and London. Another 50 LNG bunkering facilities at European ports are in development.

Some LNG bunkering operations in Europe are associated with existing LNG marine terminals, which already have LNG storage and port infrastructure in place. However, many smaller operations—including most of the projects in development—employ trucking, dedicated bunkering vessels, on-site liquefaction, and other means to extend LNG availability beyond the ports with major LNG terminals. LNG bunkering is not so advanced in South America, although with nine operating LNG marine terminals (one for export), and another six in development, South America also could support significant LNG bunkering operations in the near future [Brazilian Ministry of Mines and Energy, 2018][13].

5.3.2.3.2 Safety of LNG Bunkering in Ports

While the LNG industry historically has had a good safety record, there are unique safety risks associated with LNG in vessel operations. Leakage of LNG during LNG shipping or bunkering can pose several hazards. LNG is stored at temperatures below -162 °C (-260 °F), far below the -20°C at which the carbon steels typically used in shipbuilding become brittle[14]. Consequently, extreme care must be taken to ensure that LNG does not drip or spill onto ship hulls or decking because it could lead to brittle fracture, seriously damaging a ship or bunkering barge.

LNG spilled onto water can pose a more serious hazard as it will rapidly and continuously vaporize into natural gas, which could ignite. The resulting “pool fire” would spread as the LNG spill expands away from its source and continues evaporating. A pool fire is intense, far hotter and burning far more rapidly than oil or gasoline fires, and it cannot be extinguished; all the LNG must be consumed before it goes out. Because an LNG pool fire is so hot, its thermal radiation may injure people and damage vessels or property a considerable distance from the fire itself**. Many experts agree that a large pool fire, especially on water, is the most serious LNG hazard**. Leaks of boil-off gas (the small amount of LNG that vaporizes in storage) can also release natural gas into a port area and cause fires or explosions. Major releases of LNG from large LNG carriers would be most dangerous within 500 meters of the spill and would pose some risk at distances up to 1,600 meters from the spill. While a bunkering barge or a vessel using LNG for fuel contains far less LNG than large LNG carriers, LNG spills in bunkering operations could still be a significant concern.

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[13] Brazilian Ministry of Mines and Energy, International LNG Market: Impacts on Brazil, Fig.3

[14] Society for Gas as a Marine Fuel, Gas as a Marine Fuel: An Introductory Guide, September 2017, p. 26, https://www.sgmf.info/assets/docs/sgmf-guide.pdf

Risks associated with bunkering LNG are complicated in ports seeking to engage in "**simultaneous operations**" during the bunkering process. Simultaneous operations entail loading and unloading cargo and personnel from a ship, maintenance, and other logistical operations performed while a ship is bunkering. Accidents that occur during such operations (for example, the operation of heavy machinery near pipes transporting LNG) can result in a spill of LNG which can threaten workers positioned near the site of operations.

5.3.3 Economic Analysis and Market Trends of Hydrogen

5.3.3.1 Production and Delivery Costs

The production costs include all conversion costs other than the feedstock costs. Although hydrogen has some advantages, in practical use the cost of hydrogen is significantly large. Table 5.17 shows estimated hydrogen production-only costs (i.e. not including delivery if centralized production) by some of the production methods discussed in this entry that are either used at present or that are possible in the future. These estimates are all as reported by the US Energy Information Administration.

Table 5.17 Estimated hydrogen production costs for a production of 1000 kg per day [US Energy Information Administration, 2018]

Technology and fuel	Production capacity (1,000 kg/day)	Hydrogen production cost ($/kg)			
		Capital	Feedstock	O&M	Total
Central SMR of natural gas	380	$0.16	$1.15	$0.14	$1.47
Distributed SMR of natural gas	1.5	$0.40	$1.72	$0.51	$2.63
Central coal gasification with CCS	308	$0.83	$0.56	$0.43	$1.82
Central coal gasification w/out CCS	284	$0.57	$0.56	$0.09	$1.21
Biomass gasification	155	$0.37	$0.52	$0.55	$1.44
Distributed electrolysis	1.5	$0.96	$5.06	$0.73	$6.75
Central wind electrolysis	124.5	$1.46	$1.69	$0.65	$3.82
Distributed wind electrolysis	0.5	$3.00	$3.51	$0.74	$7.26
Central nuclear thermochemical	1,200	$0.76	$0.20	$0.43	$1.39
Nuclear S-I	343.5	$2.61	$0.35	$5.31	$7.27
Nuclear HyS	343.5	$1.48	$0.22	$2.25	$4.95
Nuclear HTSE	343.5	$1.05	$0.03	$3.15	$4.23
Single-bed aqueous PEC	1	–	–	–	$1.63
Dual bed aqueous PEC	1	–	–	–	$3.19
Fixed panel PEC	1	–	–	–	$4.05
Tracking concentrator PEC	1	–	–	–	$10.36

Hydrogen delivery to the site of use and storage adds a considerable high cost depending on delivery distance and mean of transport as well as the current H2 in stock.

Distribution costs, or delivery costs, include all costs associated with getting the hydrogen from the production plant to the vessel. What follows is summary of the results that was extracted from the Global Hydrogen Resource Analysis[15] which conducted in 2014. This analysis used GPAT (The Global Pathways Analysis Tool) in order to calculate least-cost pathways for H_2 supply for eight participating countries: France, Germany, Norway, Spain, Sweden, Denmark, Japan, and the United States. The pathways include consideration of feedstock, conversion, distribution (regional and long-distance), and carbon costs. Hydrogen production costs are calculated based on country-supplied data on feedstock availability for hydrogen production by type, cost, and quantity from 2010 to 2050, and assumptions about hydrogen production technology assumptions (efficiencies, costs, etc.).

For on-site production options (distributed H2 production), the estimated costs include all compression, storage, and dispensing costs. The estimate is based on a 1500 kg/day H2 onsite natural gas reforming system. The estimated delivery cost for this system is 13.75 $/GJ (1.65 $/kg)[16]. The cost breakdown includes capital (55%), fixed operating and maintenance (23%), and variable O&M including utilities (22%).

For the centralized options, the default delivery cost is 21.50 $/GJ (2.58 $/kg) and include compression (25%), storage (26%), pipeline transport (32%), liquefaction (8.8%), and refueling station (8. 2%).This option assumes pipeline transport within an urban setting with more than one million people, market penetration of 50%, 700 bar cascade, and liquid storage.

For longer distance transport of H_2, such as would be the case between regions or countries, the following cost equation is widely used for the estimation of delivery cost through pipeline distribution.

Specifically, the cost is assumed to be a function of distance:

$$\mathbf{Costs}\ (\$/\mathbf{kg}) = \mathbf{0.7982} + \mathbf{0.00206} \times \mathbf{Distance}\ (\mathbf{km}) \quad \textbf{(5.4)}$$ [17]

Hence, moving H_2 1,000 km through pipelines would add an additional 23.82 $/GJ (2.86 $/kg) to the delivered costs.

[15] GHRA conducted by Thomas E. Drennen and Susan M. Schoenung for the purposes of Sandia National Laboratories and IEA – HIA (Hydrogen Implementing Agreement)

[16] H2A:02D_Future_Forecourt_Hydrogen_Production_from_Natural_Gas_1500_kg_per_day_version_3.0.xls

[17] Global Hydrogen Resource Analysis, Final Report of Task 30, Subtask A, of the International Energy Agency (IEA), Hydrogen Implementing Agreement (HIA).

Table 5.18 summarizes the default production costs, distribution costs, conversion efficiencies and well-to-tank GHG emissions for each technology used.

Table 5.18 Default production costs, distribution costs, conversion efficiency, and GHG emissions[18] [Global Hydrogen Resource Analysis – HIA – 2014]

Pathway	Production cost (excluding feedstock) $/GJ ($/kg)	Feedstock cost ($/kg)	Distribution Cost $/GJ ($/kg)	Total Cost ($/kg$H_2$)	Feedstock conversion efficiency (MJ H_2/MJ Feedstock)	Well-to-Tank GHG emissions (kg CO_2e/kg H_2)
Natural Gas: Distributed SMR	6.67 (0.80)	1.72	13.75 (1.65)	4.17	71.9%	14.3
Natural Gas: Centralized SMR	3.25 (0.39)	1.15	21.50 (2.58)	4.12	53.6%	14.7
Coal: Centralized gasification	10.75 (1.29)	0.56	21.50 (2.58)	4.43	53.6%	44.7
Coal: Centralized gasification with CCS	14.67 (1.76)	0.56	21.50 (2.58)	4.9	53.6%	7.5
Biomass: Centralized gasification	8.92 (1.07)	0.52	21.50 (2.58)	4.17	49.6%	3.1
Distributed Electrolysis	(1.69)	5.06	21.50 (2.58)	9.33	72.5%	2.9

As shown in Fig. 5.53, the final price of natural gas, biogas, and hydrogen in the market presents €1.103/kg, €1.103/kg and €9.5/kg respectively (feedstock prices and salesman profits included) [EC, 2017].

[18] For onsite options (Natural Gas: Distributed SMR) distribution costs include compression, storage, and dispensing costs. For the centralized options, distribution costs include compression, storage, pipeline transport from centralized facility (excludes interregional distribution costs), and the refueling station.
Well-to-tank greenhouse gas emission estimates for each source are from H2A.

At Hydrogen Analysis **(H2A)** hydrogen production models provide transparent reporting of process design assumptions and a consistent cost analysis methodology for hydrogen production at central and distributed (forecourt/filling-station) facilities.

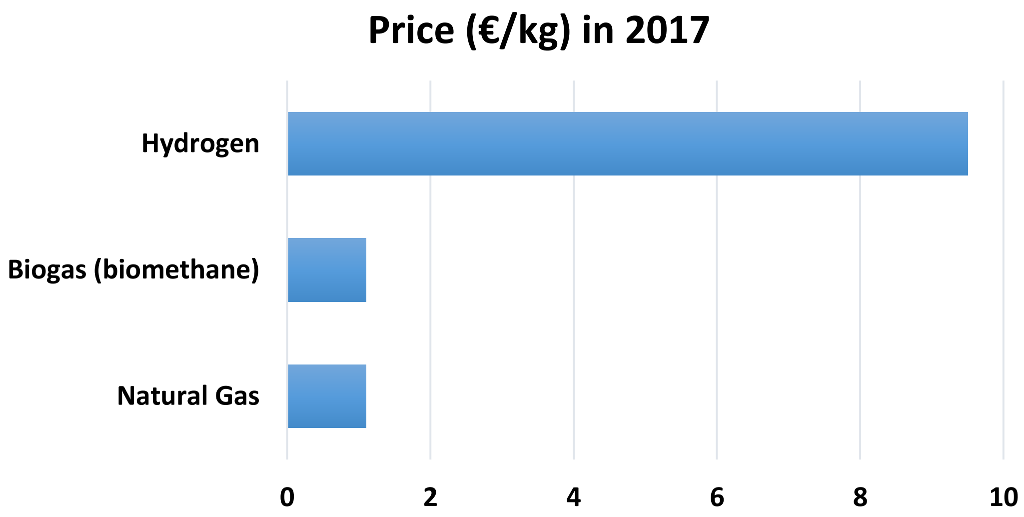


Figure 5.53 A price comparison between Natural Gas, Biogas and Hydrogen [EC,2017]

The reason why the price of hydrogen is extremely higher is that the infrastructure for hydrogen production, transportation and distribution is required. Due to the low volumetric energy density comparatively, hydrogen must be controlled and managed under a high pressure to liquefy at very low temperature [IEA, 2005].

5.3.3.2 Advantages

First of all, hydrogen has an advantage of energy content of fuels and energy efficiency so that running costs in utilizing hydrogen for customers could be cheaper than one in other cleaner fuel. EC estimates that the hydrogen price (€) per 100 km, combined with fuel cost of hydrogen, is 4.275, which is lower than LNG and biogas [EC, 2017]. In terms of running cost, hydrogen is a cost-competitive energy source.

Secondly, hydrogen demand will progressively increase based on the assumption that the market share of hydrogen-fueled vehicles will grow. As previously mentioned, some societies and industries have shifted into “hydrogen society” policies believing that hydrogen is the fuel of the future. As a result, and thanks to the increase of its demand, the price of hydrogen may go down in the future. National Renewable Energy Laboratory (NREL) estimates that hydrogen fuel prices may fall by $2/kg in the range from 2020 to 2025 [California fuel cell partnership, 2018].

Japan also estimated the distribution cost will be reduced due to the expanding supply chain to Australia. Transport cost could be reduced by $2.46/GJ in the range from 2025 to 2035 [Drennen & Schoenung, 2014]. Availability of low cost materials and economy of scale can help decreasing production, distribution and transport cost, which leads to lower hydrogen price.

The volatility of the bunker fuel markets and **the global LNG market** lead to considerable unpredictability about the relative prices among fuels going forward. LNG may become increasingly price-competitive versus low-sulfur fuel as the 2020 IMO sulfur standards take effect. As discussed above, many analysts predict prices for low-sulfur gas oil, which are already higher than those for high-sulfur fuel oil, to increase significantly after 2020 due to a standards driven rise in demand.

Lastly, the fossil fuel price historically fluctuates. According to the Institute of Energy Economics (IEE), Japan, the LNG price follows the lead of the crude oil price track, and the price in 2016 was $7.23/MBtu, which is less than half of the price of more than $15/MBtu, as shown in Figure 5.54 [IEE, 2017]. This is because OPEC (Organization of the Petroleum Exporting Countries) member's decision for production cut of oil, politics, supply and demand balance and long-term contract affecting to the oil price [EIA, 2018]. Further, LNG prices are typically affected by its long-term contracts that are linked to crude oil or petroleum product prices [EIA, 2015]. Therefore, in the future, the fossil fuel price could be higher than that of hydrogen.

Figure 5.54 Crude oil and LNG prices [IEE, 2017]

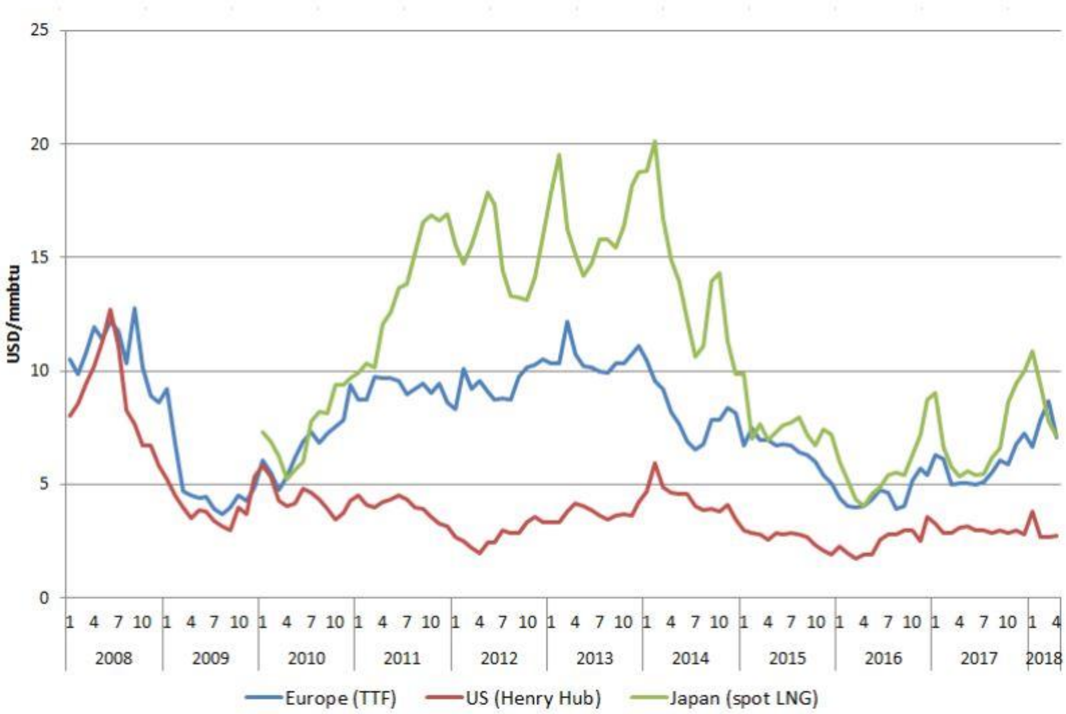


Figure 5.55 **European, US and Japanese wholesale gas prices [REUTERS, 2018]**

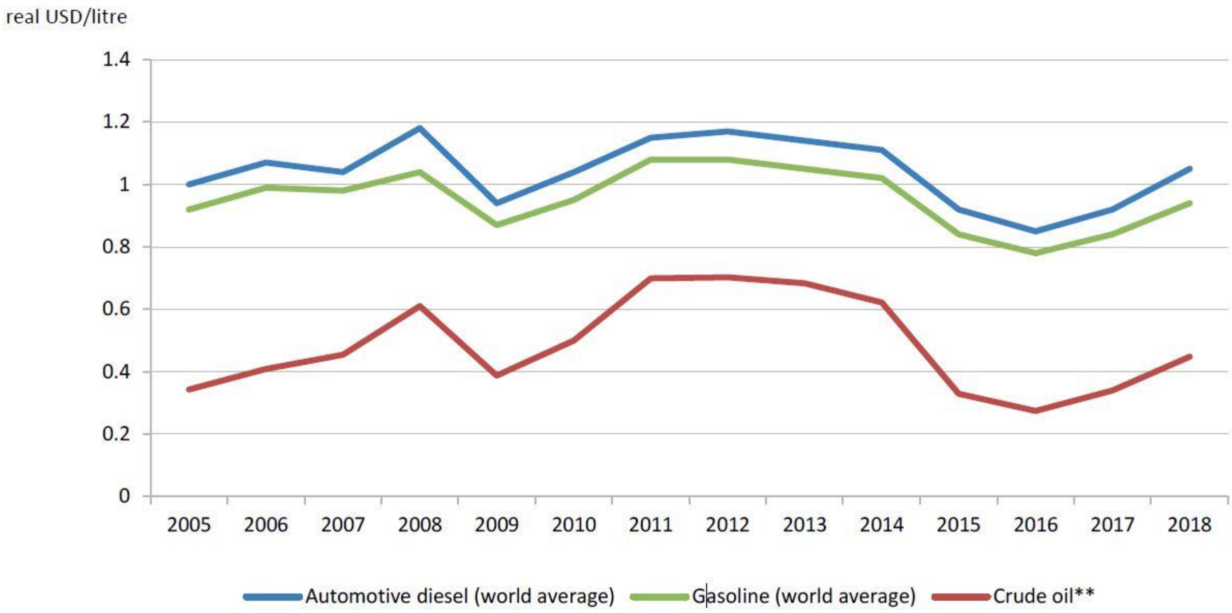


Figure 5.56 **Global fuel price changes, 2005-2018 [International Energy Agency, 2018]**

5.4 Hydrogen Fuel Cells (HFCs)

5.4.1 Status

As mentioned in the previous part, FCs are matured technologies and the most widespread used devices for the conversion of hydrogen into electricity. Hydrogen is not necessary to be used for FCs; however, the use of hydrogen as source for FCs generates important synergies and maximizes the potential benefits in terms of energy efficiency, energy security and preventing CO2 or other pollutant emissions (IEA, 2015). Currently, rising and fluctuating fossil fuel prices and a strong incentive for the reduction of environmental impacts have caused strong motivation for the development of fuel cells for maritime application (Tronstad, Åstrand, Haugom & Lanhfeldt - Study in the use of Fuel Cells in Shipping - 2017). Technology maturity of fuel cells is enough so that they have been widely commercialized in other areas, such as buildings, houses and vehicles. However, in the maritime sector, lack of commercial viability could become a barrier in practical use of fuel cells.

Although there are some types of fuel cells that have already been developed, put into practice, analyzed and assessed. Three types of fuel cells will be dealt with in this research, i.e. Solid Oxide Fuel Cell **(SOFC),** Proton Exchange Membrane Fuel Cell **(PEMFC)** and Molten Carbonate Fuel Cell **(MCFC).** While Alkaline Fuel Cells (AFCs) are a well-proven technology, they are more complicated and heavier than PEM based fuel cell stack systems. Moreover, the disadvantages of the AFC for mobility applications are that a separate solution of >25 weight % of KOH must be supplied to the fuel cell stack and ceramic pumps must be used to move the corrosive KOH electrolyte through the system. In addition, CO_2 must be kept out of the system in order to avoid the loss of electrolyte. Potassium hydroxide will react with CO_2 to form potassium carbonate (K_2CO_3), leading to a loss in power output. Managing the flow and containment of highly corrosive KOH is a severe logistical issue for AFC systems. Another drawback of ACFs is that they are not commercially available at the power scale needed for the purposes of this diploma thesis. Other types of HFCs have not been demonstrated as maritime applications that can serve a commercial solution (availability, secure operation, approved efficiency) at the current stage.

5.4.2 A brief comparison of HFC Types

The main principles of HFCs have already been explained in previous chapters. This section offers a different approach in the comparison of different types of HFCs that are commercially available in current market. The basis of a feasibility analysis is the investigation of whether an applied technology is feasible, applicable and economically beneficial for the investors. For that reason, the research will focus on the operability of those different HFCs types inserting four major parameters for the onboard operation on ships; **[1]** their gravimetric power specification, **[2]** volumetric power specification, **[3]** operating temperatures (as well as warm-up periods), **[4]** longevity, and **[5]** cost of investment of the HFC systems.

The fuel cell types can be divided into two regimes of operating temperature: low-temperature fuel cells that operate in the range 50°C to 220°C (proton exchange membrane, and alkaline fuel cells), and high-temperature fuel cells that operate above 650°C (molten carbonate, and solid oxide fuel cells). Although high-temperature fuel cells are undesirable because it can take hours to heat up large units, we will examine them for their gravimetric and volumetric power density, and assess them for market track record.

We will discuss the fuel cells in terms of two power specifications (specs):

The **gravimetric power** specification which is defined as:

$$\textbf{Gravimetric Power Spec.} = [\textbf{Output Power}]/[\textbf{Fuel Cell Mass}](\textbf{kW/kg}) \qquad \textbf{(5.5)}$$

The **volumetric power** specification that is defined as:

$$\textbf{Volumetric Power Spec.} = [\textbf{Output Power}]/[\textbf{Fuel Cell Volume}](\textbf{kW/m}^3) \qquad \textbf{(5.6)}$$

Ideally, one would like a gravimetric specification of infinity, as we want maximal output power for minimal fuel cell mass. Similarly, we want the volumetric power spec to be as large as possible to maximize power production within the limited space onboard a vessel.

In principle, one should really compare the gravimetric and volumetric specs of the fuel cell system, where the system is comprised of the power plant plus all hardware associated with providing fuel to the fuel cell. However, for simplicity, and because some fuel cells have highly undesirable properties (such as GHG emissions) which eliminate them from further consideration, we will restrict the analysis to the fuel cell power plants themselves.

5.4.2.1 Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFCs) are commercially available units fueled by NG. Bloom Energy is the primary commercial manufacturer of SOFCs in the ~ 200 kW range. There are no commercially available solid oxide fuel cells that run on hydrogen. As a result, SOFCs emit CO_2 when run on fossil-based natural gas. Operation on biogas would reduce the GHG emissions considerably.

The efficiency SOFC could be as high as 85% or higher, if a heat recovery system can be applied. There are two kinds of SOFCs, i.e. planar and tubular. The tubular SOFC is more stable in terms of thermal cycling, whereas the planar SOFC is recognized as the more suitable design due to high energy density. Combing SOFCs with a battery will reduce thermal strain and achieve a more flexible operation.

The investment cost of a HFC system is very sensitive to the production volume MW/year (affects the overall manufacturing cost of the stacks) of the SOFCs industry and the installed volume of the facility.

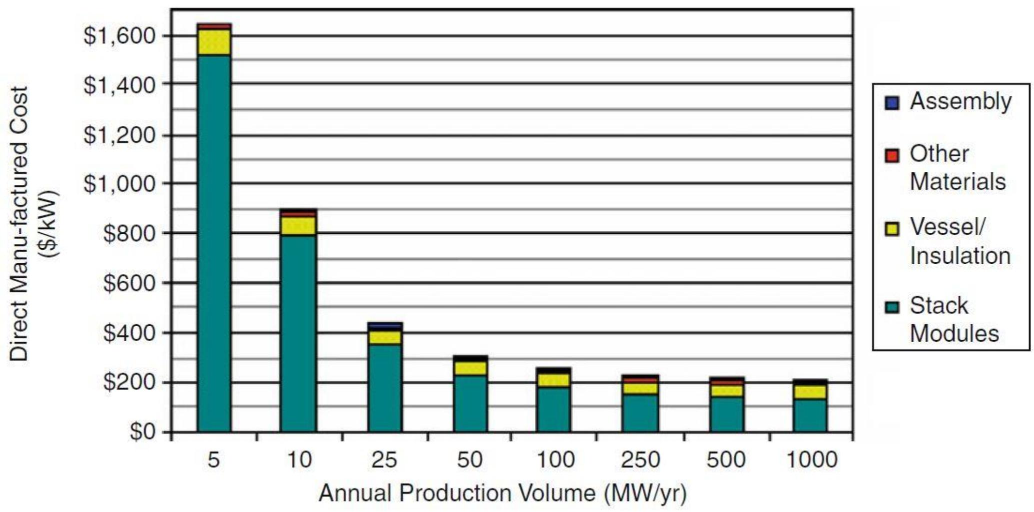


Figure 5.57 Manufacturing cost of planar SOFC Stacks (Economy of Scale in FCs Production) [IEA, 2015]

Progressive development of SOFC technology will contribute to a longer lifetime, with more than 60,000 hours (current technology dictates a lifetime of 40,000 to 60,00 hours of lifetime), which may make them improve operational flexibility and lead to reducing investment costs to below 2,000 $/kW (current factory cost for SOFC system is up to 3000 – 4000 $/kW) by between 2025 to 2035 [IEA, 2015].

5.4.2.1.1 Commercial Availability

A picture of an array of Bloom Energy ES5 – YA8AAN 300 kW solid oxide fuel cells is shown in Picture 5.35. SOFCs have been generally used in large scale power production on shore, with capacities up to 10 Mega-Watt (MW). Several projects have been demonstrated regarding SOFCs as maritime application, including the Methapu, Felicitas and SchIBZ projects

Picture 5.35 Bloom Energy ES5 – YA8AAN 300 kW, each producing power at 300 kW [Bloom Energy, 2019]

The ES5 – YA8AAN has dimensions[19] 5,77 m x 2,68 m x 2,1 m, with a total volume of 32,47 m^3 . The mass of the fuel cell is 15.800 kg. Thus, the gravimetric power spec is 300kW/15800 kg = 0.01898 kW/kg. The volumetric power spec is 300kW/32,47 m^3 = 9,24 kW/m^3. Its cumulative electrical efficiency (LHV) is between the values 53 – 65 % (based on performance tests conducted and verified by ASME PTC 50 Fuel Cell Power Systems).

The ES5 is rated to emit when fueled with fossil NG:

Greenhouse Gas Emissions

- ~ 342 kg of CO_2/MWh
- 15,4 gr of CO/MWh

[19] ES5 – YA8AAN , Product Datasheet : https://www.bloomenergy.com/sites/default/files/es5-300kw-datasheet-2019.pdf

Pollutant Emissions

- 7,21 gr of VOCs/MWh
- 0,77 gr of NOx/MWh
- Negligible portion of SOx

5.4.2.1.2 Conclusions

SOFCs operate with a pressure up to 15 atm. while generate current with an average voltage of 0,9 V and current density of 300 – 100 mA/cm^2. SOFC-customized steel compositions and protective coatings have been developed to ensure the goal of at least 40,000 h stack life. An average value for the efficiency of SOFC is calculated around 55 %, and when BoP efficiency is included (0,92 – 0,95) the total efficiency of the system is approximately around 50 %.

Since the temperature of SOFC is a very high, 600 -1000 °C, the ES5 takes up to 5 hours to fully warm up to begin producing power. More importantly, cycling SOFCs on and off affects their lifetime and long term durability.

The long warm-up times are inconsistent with ferry operation that requires power to be immediately available. SOFC is comprised entirely of solid materials, and thus cracking due to thermal shock is a fundamental problem. The problem confines the SOFC to relatively small power systems so far. The only way around this would be to keep the SOFC power plant at temperature all the time, which would be inefficient. **Due to large CO_2 emissions and prohibitive warm up times, SOFC technology is not an attractive solution for the ferries**. In addition, commercially available, large scale SOFC technology has not demonstrated an ability to run on pure hydrogen.

5.4.2.2 Molten Carbonate Fuel Cells

MCFC, which has a molten carbonate salt of the electrolyte, can be operated at high temperatures between 600 - 700°C, and does not need to have external reformers. **At atmospheric pressure, MCFCs operate at 0.75 V with a current density of 0.16 A/cm^2**. As the operating pressure increases, the total efficiency of MCFCs increases accordingly. However, due to secondary chemical reactions that occur in higher operating pressures, the value of this parameter does not go beyond five atms. Currently, there are commercially available MCFCs that run on natural gas.

The MCFC has been used on the offshore vessel, Viking Lady, in the FellowSHIP project Viking Lady, which is the only commercial vessel to use fuel cell technology, was developed with 320 kW fuel cell using LNG and has been deployed in the North Sea. Like SOFCs, there are no commercially available MCFCs that have been demonstrated to operate on pure hydrogen. As a result, MCFCs emit CO_2, which is inconsistent with the zero-emission design.

5.4.2.2.1 Commercial Availability and Characteristics

Fuel Cell Energy is the primary commercial supplier of molten carbonate fuel cells in the ~ 200 kW range and above. The DFC300 Fuel Cell Module has dimensions[20] ~ 3,6 m x 3,25 x 2.8 m. The mass of the fuel cell is 15.875,73 kg. Thus, the gravimetric power spec is 300kW/15875,73 kg = 0,0189 kW/kg. The volumetric power spec is 300kW/32,76 m^3 = 9,18 kW/m^3. Its cumulative electrical efficiency (LHV) is between the values 45 - 49%.

The ES5 is rated to emit when fueled with fossil NG:

Greenhouse Gas Emissions

- ~ 444,5 kg of CO_2/MWh
- 20,1 gr of CO/MWh

[20] DFC300 , Product Datasheet :
http://www.fuelcellenergy.com/assets/PID000155_FCE_DFC300_r1_hires.pdf

Pollutant Emissions

- 4,54 gr of NOx/MWh
- 0,045 gr SOx/MWh
- 0,0091 gr of PMs/MWh

From a cold start, the DFC 300 can take almost 4-6 hours to fully warm up and suffers the same need to avoid start-stops like the SOFC. From this standpoint, the unit is incompatible with the on-demand power required for ferry operation, as described above for the SOFC. For this reason, and for the avoidance of alternating strain due to thermal stresses (which are unavoidable at the initiation and termination time of the operation), SOFC is optimal to operate constantly without cutoffs. In addition, due to large CO_2 emissions when the MCFC is run on natural gas, the unit is inconsistent with zero-emissions philosophy designs. Fuel Cell Energy makes a DFC300 300 kW fuel cell, a picture of which is shown in Picture 5.36.

Picture 5.36 FuelCell Energy DFC 300 MCFC power plant [FuelCell Energy, 2018]

5.4.2.2.2 Conclusions

Due to the high temperature, MCFC is suitable for a heat recovery system. Therefore, the total efficiency for a MCFC could be relatively high by 85% up to 90% (IEA, 2015). Moreover, the high temperature allows the MCFC, theoretically, to be flexible towards the choice of fuel, which means LNG and fluid gases from coal and hydrogen can be used.

However, there are some disadvantages of these fuel cells. However, the high temperature operation makes it vulnerable to negative effects such as corrosion and cracking of components. Another drawback is that by using hydrocarbons, CO_2 emissions possibly come from the system, and also, the subsequent heat and energy recovery systems have the potential for some NOx emissions. Even if hydrogen is used as the fuel, CO_2 will come from the circulation to regenerate carbonate in the electrolyte. On top of that, MCFCs are not suitable for vehicles because their high operating temperatures need to take a long start-up time and this makes it vulnerable to negative impacts such as corrosion and cracking of components. MCFC`s lifetime is a function of both the material and the operating pressure of the cathode.

Estimated lifetimes for NiO and $LiCoO_2$ cathodes at 7 bar ($7 \cdot 10^5$ Pa) are 3,500 and 90,000 hours, respectively. For the purposes of this diploma thesis, an average lifetime of 20,000 ~ 30,000 is considered as well as a range of overall efficiency between 50 – 85 %.

Lastly, capital investment cost is reported to be over 4000 $/kW [21] for a 1.4 MW power plant of MCFCs but this price is very sensitive to fluctuations. In terms of cost, the goal is to reach as minimum prices as 2000 – 3000$ / kW. The main parameters to achieve this reduced cost is the increase of production numbers and wider commercialization of MCFCs.

5.4.2.2.3 Comments

Although, the necessary warm-up, for period of both MCFC and SOFC is around 4-6 hours, the scientific community, in an effort to increase their popularity – competitiveness, has already suggested measures to overcome this bottleneck

[21] L. Chick, M. Weimar, G. Whyatt, M. Powell, the case for natural gas fueled solid oxide fuel cell power systems for distributed generation, Fuel Cells 15 (1) (2015) 49 - 60.

5.4.2.3 Proton Exchange Membrane (PEM) Fuel Cells

PEM fuel cells are the fastest growing fuel cell technology, due to its development and application for mobility power (i.e. fuel cell vehicles). PEMFC, which has platinum-based electrodes and the electrolyte, is a humidified polymer membrane that plays a role of an electric insulator. The operating temperature should be 50 to 100°C. Excess 100°C possibly stops the system from working because the membrane needs to keep humid. Due to their low operating temperatures, PEMFCs do not need warm up and as a result require a small amount of time for their initiation. PEMFC reacts with hydrogen and oxygen, and produces water in addition to electricity and heat. It uses **pure hydrogen (typically > 99.8% pure)** at the anode, and can operate at relatively low temperatures using a catalyst (typically platinum) to increase the reaction kinetics. Due to water production from the results of the electrochemical reaction, water management is necessary for the proper operation of PEMFC.

PEM fuel cells are dramatically quieter than internal combustion engine (ICE) technology. Since there is no combustion occurring in the fuel cell and the fuel is pure hydrogen, there is zero NOx emission, zero SOx, zero hydrocarbons (HC) and zero particulate emission. **The PEM fuel cell is certified as a zero-emissions power system by the California ARB**[22]**.**

The PEM fuel cell offers high power density, high efficiency, the potential for good cold and transient performance and is amongst the lightest and most compact of fuel cells. Furthermore, the PEM fuel cell is commercially available with an excellent performance track record.

The PEM fuel cell generates electricity with a thermal efficiency (electrical work out/fuel energy in) of 45 - 60 %, depending on the operating load.

[22] The **California Air Resources Board** (**CARB** or **ARB**) is the "clean air agency" in the government of California established in 1967.

5.4.2.3.1 Commercial Availability and Cost Analysis

PEM fuel cells deliver high power density and offer lighter weight and smaller volume than other fuel cell systems because they have been specifically developed for lower-scale mobility power applications such as vehicle power plants, and auxiliary power.

PEMFCs, due to the usability, have been utilized extensively in many applications. For instance, it is used in vehicles, the Alsterwasser passenger ship with 96 kW power and German Type 212A class submarines with 30-50 kW power respectively.

There are two major manufacturers of commercially available PEM fuel cells in the 30 – 100 kW range, Ballard Power Systems and Hydrogenics, Inc.

Automakers are also manufacturing PEM fuel cells in this size range but those units are not available for separate purchase.

Ballard Power Systems Inc. manufacturers a number of PEM fuel cells. The FC Velocity HD 100kW fuel cell is shown in Picture 5.37.

Picture 5.37 Ballard 100kW FC Velocity HD PEM fuel cell [Ballard, 2019]

The Ballard 100 kW HD power module[23] has dimensions 1.2 m x 0.869 m x 0.506 m, with a total volume of 0.528 m^3 (from Ballard's website). The mass of the fuel cell module is 285 kg. Thus, the gravimetric power spec is 0.351kW/kg while its volumetric power spec is 189.39 kW/m^3. The fuel cell module has a lifetime lower bound of 23.000 hrs of operation. has a lower. Complying with its relevant electrochemical reactions and physics, PEM FCs are Zero-emission devices - to meet the mandates set by policy makers in order to reduse transportation emissions -.

[23] Ballard FC velocity - 100HD ,Product Datasheet : http://www.ballard.com/docs/default-source/motive-modules-documents/fcvelocity_hd_family_of_products_low_res.pdf

Hydrogenics manufactures a "building block" 31 kW PEM fuel cell, the model HyPM HD30. This fuel cell is shown in Picture 5.38.

Picture 5.38 Hydrogenics 31 kW HyPM HD30 PEM fuel Cell [Hydrogenics, 2019]

The HyPM HD30 PEM fuel cell has dimensions 0.719 m x 0.406 m x 0.261 m, with a total volume of 0.0762 m^3. The mass of the fuel cell module is 72 kg. Thus, the gravimetric power spec is 0.431 kW/kg[24]. The volumetric power spec is 406,88 kW/m^3. The Hydrogenics HyPM HD 30 also forms the basis of higher power fuel cell racks (up to 3 MWs), as depicted in Picture 5.39 and Picture 5.40. Combining individual fuel cell stacks into a power rack degrades the gravimetric and power specs because of the required frame and additional balance of plant. Using the dimensions and mass for the Fuel Cell Power Rack shown in Picture 5.39, the gravimetric power spec is 0.150 kW/kg, and the volumetric power spec is 73.97 kW/m^3.

[24] "HyPM-HD Power Modules for light to heavy duty mobility," Hydrogenics, 2015. Available: http://www.hydrogenics.com/docs/default-source/default-document-library/hypm-hd-8pgjan2015-lr.pdf?sfvrsn=0

Picture 5.39 Assembly of four Hydrogenics HyPM HD30 PEM Fuel Cell into a Fuel Cell Power Rack [Ryan Sookhoo, Hydrogenics, 2019]

Picture 5.40 Assembly of three Hydrogenics HyPM HD30 PEM fuel cell into a fuel cell power rack [Hydrogenics, 2019]

5.4.2.3.2 Conclusions

However, PEMFCs have some drawbacks. The cost of platinum catalyst is relatively high, and it can be poisoned by carbon monoxide and sulphur during operation [Tronstad, 2017]. Moreover, a pure hydrogen source is needed; otherwise, a separate steam reforming is required to produce the pure hydrogen from hydrocarbons. Meanwhile, CO_2 and low levels of NOx will be emitted if hydrocarbons are used as fuel. From environmental perspectives, purification and cleaning of the hydrogen are necessary for further use in PEMFC. Furthermore, the longevity of PEMFC`s is estimated between 10.000 – 25.000 hrs. As for the capital cost, an estimation of 2,500 $/kW can be made for a power installation of more than 4.5 MW [25].

[25] Feasibility of the SF – BREEZE: Zero – Emission, Hydrogen Fuel Cell, High – Speed Passenger Ferry, Joseph W. Pratt and Lennie E. Klebanoff – Sandia National Laboratories - September 2016, United States.

5.4.4 Summary of the HFC Technologies

Table 5.19 summarizes a comparison of three types of HFCs; PEMFC, MCFC & SOFC. It lists the gravimetric and volumetric power specs for the fuel cell systems we have examined thus far while it examines the operability of each type. It is clear that the PEM fuel cell has some advantages of user-friendliness by low temperature, environmental friendliness (pure H_2 emissions) while it has the best gravimetric power and volumetric specs of the different fuel cell types. This is a consequence of the PEM fuel cell being developed for mobility applications which stress high power systems in the lightest weight and smallest footprint possible. In addition, lower-temperature operation, combined with lightweight proton exchange membranes, promote smaller and lighter fuel cell stacks. Meanwhile, MCFC and SOFC will maintain high energy efficiency and do not need to consider sensitivity of fuel impurities. Furthermore, both SOFC & MCFC systems need a steady supply of CO while the latter also requires a CO_2 supply. Therefore, a different system layout would be necessary requiring additional components in the balance of plant and adding to cost and complexity of the total system.

From the above-mentioned characteristics it is clear that in order to achieve multi-dimension benefits; societal, environmental, ergonomic and operational, the optimum selection –at first sight- is the PEMFC technology, which can meet the combined requirements of an all-electric and environmental friendly ship (it also has the ability for a rapid start-up when needed). Nevertheless, the following economic assessment attempts to identify the blurry points, spot the hazards and deal with them for every type of HFC technology, by promoting a methodology to overcome the practical difficulties in order to finally qualify the optimum fuel cell topology for a defined ship, operational profile and schedule plan.

Table 5.19 Comparison of the three examined HFC types

Aspect	Type of HFC		
Technology	**PEMFC**	**MCFC**	**SOFC**
Temperature of Operation (℃)	50 - 100 (for safe operation)	600 - 700	600 - 1000
Warm - Up Period	Rapid Start-up	Up to 5 hours to fully warm up	Up to 5 hours to fully warm up
Possible Fuels	Pure Hydrogen (typically > 99,95 % pure)	NG, Methanol, Diesel, Hydrogen	NG, Methanol, Diesel, Hydrogen
Overall Reaction	$H_{2(g)}$ + 1/2 $0_{2(g)}$ -> $H_20_{(l)}$	Using NG : $CH_{4(g)}$ +$2O_{2(g)}$ = $CO_{2(g)}$ + $2H_2O_{(g)}$	Using NG : $CH_{4(g)}$ +$2O_{2(g)}$ = $CO_{2(g)}$ + $2H_2O_{(g)}$
Bounds of System Electric Efficiency (HHV)	First years : 50 - 60 % , Decline in efficiency ~ 0,1%/1000h	First years : 60 - 70 % Decline in efficiency ~ 0,2%/1000h	First years : 60 - 80 % Decline in efficiency ~ 0,2%/1000h
Actual System Electric Efficiency (BoP included) (LHV)	55%	60%	65%
Module Power Levels (kW per Stack)	Up to 120 kW typically (50 - 100 kW)	Up to 500 kW (typically 200 kW)	Up to 250 kW (typically 200 kW)
GHG Emissions (Manufacturer's Data)	Zero - emissions	The DFC300 is rated to emit 444,5 kg of CO_2/MWh & 20,1 gr of CO/MWh when run on fossil-based NG.	The ES5 is rated to emit 342 kg of CO_2/MWh & 15,4 gr of CO/MWh when run on fossil-based NG.
Pollutant Emissions (Manufacturer's Data)	Zero - emissions	The DFC300 is rated to emit: 4,54 gr of NOx/MWh & 0,045 gr of SOx/MWh when run on fossil-based NG.	The ES5 is rated to emit 0,77 gr of NOx/MWh & ~0 gr of SOx/MWh when run on fossil-based NG.
Gravimetric Power Specification (Market Data)	1) Ballard 100 kW HD: 0.351kW/kg 2) Hydrogenic HyPM HD30 kW: 0.431 kW/kg, H_2 Fueled	300 kW MCFC NG fueled: 0.01889 kW/kg, Manufacturer: Fuel Cell Energy , Model: DFC300	300 kW SOFC NG fueled: 0.01898 kW/kg , Manufacturer: Bloom Energy , Model: ES-5700
Volumetric Power Specification (Market Data)	1)189,39 kW/m^3, 2) 406,88kW/m^3	9,18kW/m^3	9,24 kW/m^3
Capital & Installation Cost ($/kW)	Currently : 1800- 3000 $/kW Target : 1000 - 1500 $/kW	Currently : 3,000 - 5,000 $/kW Target : 2,000 - 3,000 $/kW	Currently : 3000 - 4000 $/kW Target : 1500 - 2000 $/kW
Lifetime (hours)	Currently : 10.000 -25.000 hours Target : 25.000 - 30,000 hours	Currently : 20,000 - 30,000 hours Target : 30,000 - 40,000 hours	Currently : 30.000 - 40.000 hours Target : 40.000 - 60.000 hours

6th CHAPTER

Electric Energy Analysis through a Case Study

Blue Star Paros and its Aegean Voyages

« We must free ourselves of the hope that the sea will ever rest.

We must learn to sail in high winds »

Aristotle Onassis (1906–1975)

Picture 6.41 Blue Star Paros crossing the Aegean Sea [Blue Star Ferries, 2019]

6.1 Introduction

Daily, hundreds of ships cross the magical waters of Aegean Sea to either deliver cargo and/or passengers to their destination. For the coverage of these trips, engineering stuff identifies the necessary energy requirements and calculates the marine fuel consumption accordingly. Vessel's speed, route engraving, seagoing, maneuvering and hoteling time have a direct effect on the total energy demands of the ship. All together they create what we call a voyage report that constitutes the operational profile of the specific ship and trip. The optimization of the abovementioned planning is a matter of great importance for the marine companies in their effort to strengthen and secure their profitability into the intensely competitive marine sector.

Having highlighted the importance of identifying the energy profile for a specific ship and route, in this chapter we get on-board to cross the Aegean Sea by selecting a representative of the Greek fleet, analyze its voyages and calculate its electric energy requirements for a specific case study (round trip) and operational profile. When this process is complete, we will be provided with the necessary information and therefore be ready for brainstorming, assessing the potential of establishing fuel cell technologies on-board and synergize them with compatible energy storage systems. At the end of the day, it is all about flexibility and economic prosperity.

6.2 The Ship Specification

6.2.1 Acquaintanceship with Blue Star Paros

The overall energy study is focused on a representative of the Greek marine transport sector. Blue Star Paros has been selected as the target ship. Blue Star Paros is a Ro-Ro / Passenger Ship that belongs to the fleet of Blue Star Ferries (member of the Attica Group) that during summertime (peak season for the tourism) provides services by completing round trips among the Ports of Piraeus, Siros, Tinos and Mykonos. The ship was built by Daewoo Shipbuilding & Marine Engineering Co., LTD in 2002. During her term, Blue Star Paros has been bejeweling the Greek Seas by always providing safe and pleasant shipping experiences. The main characteristics of Blue Star Paros are identified on the following page in Tables 6.20 – 6.23.

Table 6.20 Blue Star Paros' Main Characteristics

Vessel Name	Blue Star Paros
Type	Ro-Ro/Passenger Ship
Year Built	2002
Length (m)	124,2
Beam (m)	18,9
Draft (m)	5
Deadweight (t)	1896
Gross Tonnage (gt)	10438
Speed Range (knots) [average - max]	22,3 - 24,4
Passenger Capacity	1474
Garage Capacity	240 Vehicles or 360 lane meters

Picture 6.42 Blue Star Paros offering her exquisite services

As for the Main and Auxiliary Engines specifications, those can be found in the following tables:

Star Paros' Auxiliary Engines

Main Engines – Propulsion Requirements	
4 x Wärtsilä 6L38B	4-stroke,turbocharged and intercooled diesel engine with direct injection of fuel
Engine Output (MCR at 600 rpm Idle speed at 320 rpm)	Each engine contributes 4.350 kW Total Output = 17.400 kW
Fuel Consumption at 100, 85, 75 and 50% Load - HFO	183, 180, 180 and 186 g/kWh
Leak Fuel quantity - HFO, at 100 % Load	1,7 kg/h
Oil Comsumption at 85 % Load	0,70 g/KWh
Fully Compliant	IMO Tier II & III
Regulations	Annex VI of MARPOL 73/7

Table 6.21 Blue Star Paros' Auxiliary Engines

Auxiliary Engines – Electric Power Supply	
3 x Wärtsilä 6L20	4-stroke, non-reversible, turbocharged and intercooled diesel engine with direct injection of fuel
Engine Output (MCR at 1000 rpm)	Each engine contributes 1080 kW
Fuel Consumption at 100, 85, 75 and 50 % Load LSFO	194.9, 191.3, 191.5 & 198,5g/kWh respectively
Leak Fuel quantity - LSFO at 100 % Load	3,24 kg/h
Oil Comsumption at 85 % Load	0,35 g/kWh
Fully Compliant	IMO Tier II & III
Regulations	Annex VI of MARPOL 73/7

6.2.2 Round Trip Schedule

As abovementioned, the determination of vessel's round trip specifications is mandatory for the precise calculation of ship's energy requirements. For that purposes, I kindly requested from Attica's Group Technical personnel a single voyage report for a typical trip in order to specify the different operating conditions of the ship. Piraeus Port is the starting point of the trip while Mykonos Port is its final destination. To complete the round trip, the ship executes two similar routes; the first starts at 7:30 from Piraeus Port to finally reach Mykonos at 13:30, and after a stay of 1:15 ship begins its way back to Piraeus. The following tables summarize the different phases of the round trip.

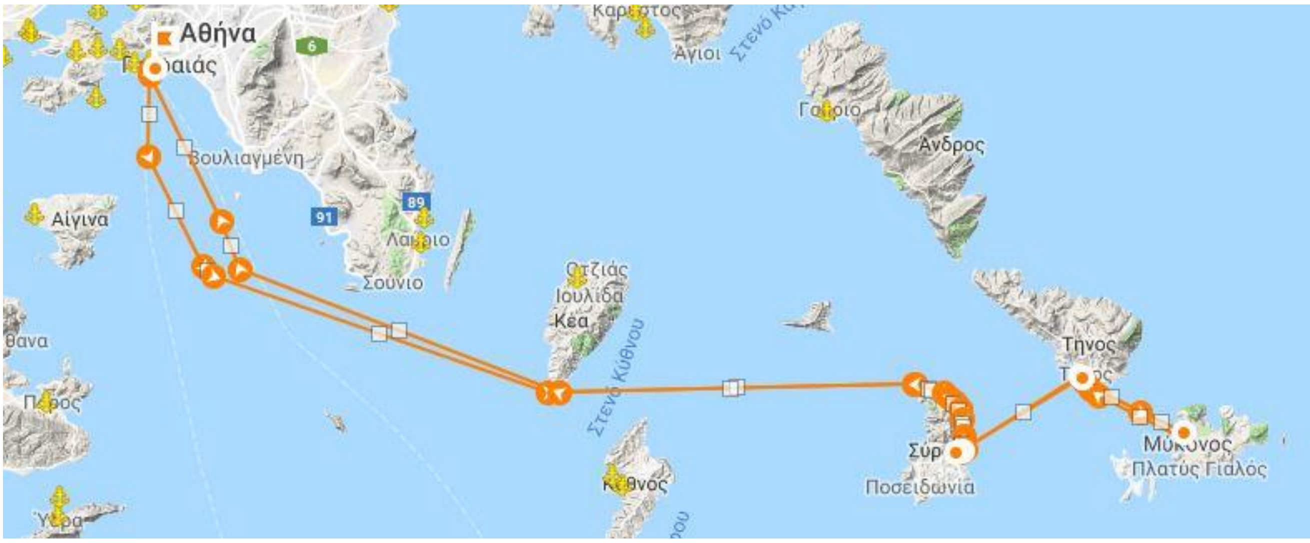
Table 6.23 Blue Star Paros' 1st half of its Round Trip

Single Voyage Report	1st half of the Round Trip		Piraeus → Syros → Tinos → Mykonos	
Route Schedule				
Depart From Piraeus	Unberths	7:30	Port Out	7:38
Arrival At Syros	Port in	11:20	Berths	11:25
Depart from Syros	Unberths	11:40	Port Out	11:45
Arrival At Tinos	Port in	12:15	Berths	12:20
Depart from Tinos	Unberths	12:26	Port Out	12:31
Arrival At Mykonos	Port in	12:55	Berths	13:00
Stay in Port of Mykonos	From 13:00 until 14:15			

Table 6.24 Blue Star Paros' 2nd half of its Round Trip

Single Voyage Report	2nd half of the Round Trip		Mykonos → Tinos → Syros → Piraeus	
Route Schedule				
Depart From Mykonos	Unberths	14:15	Port Out	14:18
Arrival At Tinos	Port in	14:45	Berths	14:50
Depart from Tinos	Unberths	14:56	Port Out	15:01
Arrival At Syros	Port in	15:28	Berths	15:33
Depart from Syros	Unberths	15:44	Port Out	15:50
Arrival At Piraeus	Port in	19:32	Berths	19:44
Stay in Port of Piraeus	From 19:44 until 7:30			

Furthermore, for the sake of completeness, via the online platform Marine Traffic (which has a great load of data from the preexisting round trips of Blue Star Paros) we can perceive an estimation of vessel's daily path across the Aegean Sea. This route is depicted in Picture 6.43.



Picture 6.43 Daily Path of Blue Star Paros across the Aegean Sea [Marine Traffic, 2019]

6.3 Modularity of Energy Calculations

At the following subsections, there is a presentation of the modular structure of energy calculations that characterize the operational profile of Blue Star Paros. Its voyage report and Electric Balance Calculation (EBC) work as an information generator for our case study. Their combination composes the framework of this thesis and even though EBC overestimate the electric demands (its primary application refers to the dimensioning of ship's cables and other electrical installations) it indicates the maximum possible energy levels of ship's operation. Besides, this is a preliminary project, and at this stage it is rather to overestimate energy's demands – and be on the safe side of the study – than risk the integrity of ship's electric network (specifically on Ro-Ro / Passenger ships which feature uncertainties on electric demands due to lighting and HVAC energy fluctuations [Heating, Ventilation, and Air Conditioning]).

6.3.1 Electric Balance Calculation

The dawn of fuel cell technology in marine sector rose almost a decade ago. As described analytically in the second chapter of this thesis, there have been some significant steps towards the standardization of fuel cell technology and its commercialization. However, despite the fact that the process of its progress is fast-paced, fuel cell technology has mostly been enclosed in laboratories and practiced in pilot programs with limited demands for energy output. What is more, marine environment follows a fully stochastic model where there is nothing but uncertainty, which are addressed with logical assumptions and statistical regression methods (time window of the seas and the weather), about the sailing conditions of ships. Henceforth, it is quite an endeavor to design a fuel cell system (which mainly operates at steady conditions) to cope with the uncertainties and transient phenomena of marine operations.

For the abovementioned reasons, when it comes to the encompassment of FC technology in marine transport sector, it is advisable to carry out small but effective steps. The moment you consolidate a basis on which you can rely, you can progress further to reach new heights (scale up the venture) and fulfill new ambitions. As fuel cells have only been used for the coverage of small to mediocre power demands (in and order of magnitude of 3 – 5 MW) it is not prudential to overcome this threshold and demand from the FC plant to accumulate decades of MWs. Thus, for the purposes of this diploma thesis, FC technology is applied to fulfill base power demands (300 kW – 2 MW) while a suitable storage system (batteries) manages to cope with the transient power phenomena (mostly during maneuvering phase).

As a sequence, this diploma thesis focuses on identifying scenarios for a feasible removal of the installed Diesel Generators (that run on LSFO and emit GHG and surely pollutants), that operate as Auxiliary Engines, and the incorporation of FC technology as an alternative. The first step for the actualization of this project is to identify the necessary electric power demand of the round trip. Electric Load Calculation is probably the most significant document for this estimation that secures a regular operation of the ship. In a way similar with the one that I accessed a single voyage report, I was permitted to access an authorized Electric Balance Calculation of Blue Star Paros. Table 6.25 summarizes the electric energy consumers, their steady and periodic power demand (categorized as essentials and non-essentials demands) and suggests the number of the operating D/G and their loading factor at each operational mode.

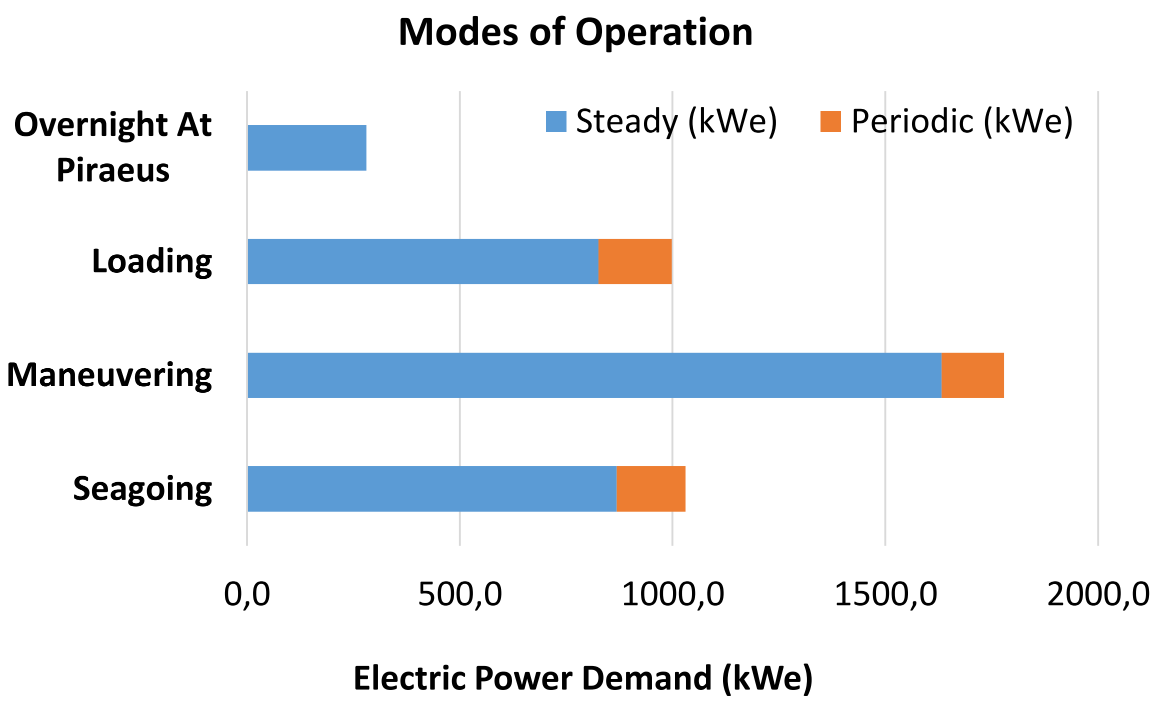


Figure 6.58 **Blue Star Paros' Electric Power Demand in kWes for each Mode of Operation [Blue Star Ferries, 2019]**

Table 6.25 Blue Star Paros' Electric Balance Calculation [Blue Star Ferries, 2019]

Consumer	No in Total	No in Use	Abs (kW)	AT SEA (Total)				MANEUVERING (Total)				LOADING (TOTAL)				EMERGENCY (TOTAL)		
Date: 01.01.2012				Steady		Periodic		Steady		Periodic		Steady		Periodic		Fire	Flood	Black Out
Revision 01				ESS	NON	ESS	NON	ESS	NON	ESS	NON	ESS	NON	ESS	NON			
Consumption for Group																		
1. Auxiliary Machinery for Propulsion	95	60	777	90,4	10,7	39,8	0,0	130,1	10,7	20,0	5,3	29,3	7,0	21,4	12,2	19,8	19,8	52,6
2. Auxiliary Machinery for Ship	24	20	170	0,0	0,5	11,0	13,3	1,3	0,5	11,1	13,3	1,3	0,5	11,1	15,6	0,0	0,0	0,0
3. HVAC - Heating, Ventilating and Air-Conditioning	233	105	1.279	125,4	423,6	0,0	21,2	125,4	425,0	1,6	21,2	125,4	430,1	1,6	4,4	9,1	17,9	19,1
4. Galley, Laundry & Workshop	42	42	250	0,0	0,0	0,0	40,0	0,0	0,0	0,0	40,0	0,0	0,0	0,0	40,0	0,0	0,0	0,0
5. Cargo Deck & Hull	46	27	1.996	1,6	0,0	17,3	3,8	669,0	0,0	10,6	7,3	20,5	0,0	43,8	7,3	156,4	29,0	17,6
6. Lighting	11	10	174	137,0	0,0	0,0	0,0	137,0	0,0	0,0	0,0	137,0	0,0	0,0	0,0	29,3	29,3	29,3
7. Navigation, Radio & Automation	6	6	48	19,2	0,0	2,3	1,0	19,2	0	4,9	1,0	16,8	0,0	2,3	1,0	18,8	18,8	18,8
Sub Total (kW)	457	270	4.695	373,6	434,8	70,4	79,3	1.082,0	436,2	48,2	88,1	330,3	437,6	80,2	80,5	233,4	114,8	137,4
				808,4		149,7		1518,2		136,3		767,9		160,7				
Total (kW)				958,1				1.654,5				928,6						
Average Total Efficiency				0,93				0,93				0,93				0,93		
Transient Periodic Operations (kW)		*Preferential Trip 10 %*		83,27				57,01				94,86						
		Maximum Scenario 25 %		94,62				64,78				107,80						
Generatol Load (kW)				1.030,2				1.779,0				998,5				251,0	123,4	147,7
Generator Capacity																		
1. Ship's Generator (kW), 380V 50Hz 3PH, 3 Sets				1.020				1.020				1.020						
2. Emergency Generator (Kw), 380V 50 Hz 3 PH, 1 Set																300		
Number of Running Generators without Non Essential				1				2				1				1		
1. Load % of Running Generators				46,8%				59,6%				43,3%				83,7%	41,2%	49,2%
2.Number of Standby Generators				2				1				2				0		
Number of Running Generators with Non Essential				2				3		2		2						
1. Load % of Running Generators				50,5%				58,0%		87,2%		48,9%						
2.Number of Standby Generators				1				0		1		1						

6.3.1.1 Electric Load Profile

The trip is divided into four phases: 1) Sea-going period, when the vessel travels with average speed in the middle of the sea - it consists a steady operation -, **2) Maneuvering time**, which signifies the transient periods of the trip (abrupt increase in power demand), **3) Loading period**, when the vessel is benched at ports (steady state) and **4) Rest period - overnight at Piraeus Port -**, which signifies the overnight the low-power demand phase of the round trip. In respect with the Electric Load Balance, Figure 6.69 shows the Electric Load Profile of the round trip for Blue Star Paros.

- Sea-going Period, **Light Blue**
- Maneuvering Time, **Dark Blue**
- Loading Period, **Green**
- Overnight at Piraeus, **Black**

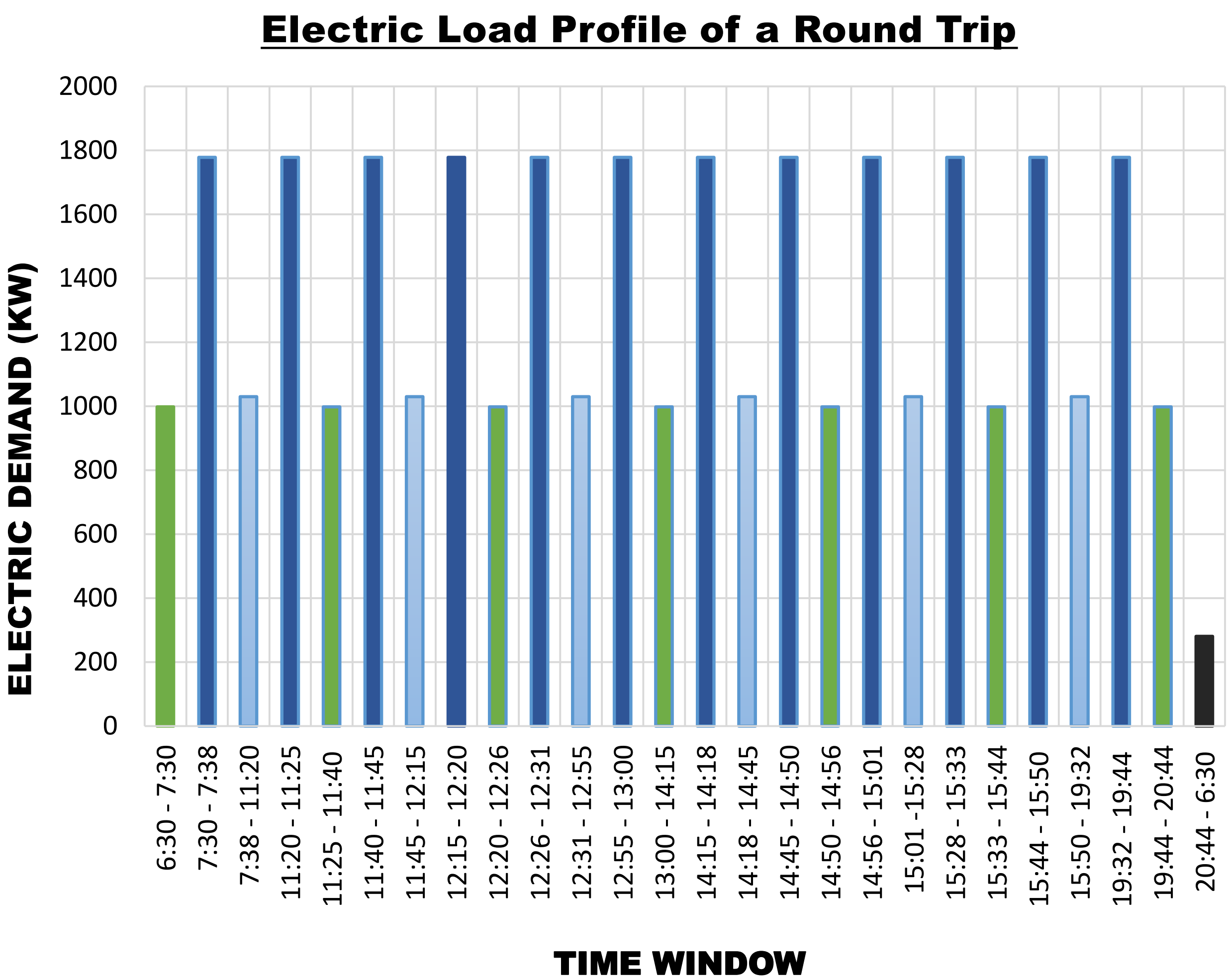


Figure 6.59 Blue Star Paros' Electric Load Profile of a Round Trip [Blue Star Ferries, 2019]

6.3.2 Electric Energy Consumption

At this stage that both the round trip planning and electric balance calculation are determined, we have the necessary information to structure the electric energy consumption profile of the ship. Table 6.26 and Table 6.27 summarize the electric energy requirements for the first and second half of the round trip respectively.

Table 6.26 Blue Star Paros' Electric Analysis - 1st half of the Round Trip

Electric Analysis 1st half	hours:minutes	hours demand	Power Demand (kWe)	Energy Requirements (kWeh)
Seagoing Time	4:36	4,60	1.030,2	4.738,92
Maneuvering Time	0:33	0,55	1.778,8	978,34
Port Time	0:21	0,35	998,4	349,44
Stay in Port of Mykonos	1:15	1,25	998,4	1.248,00
Total Time	6:45	6,75	Peak Power 1.778,8 kW	Total En.Req 7.314,70 kWh
Average Vessel's Speed	23,13 knots	**Total En.Req = 26.332,92 MJ**		

Table 6.27 Blue Star Paros' Electric Analysis – 2nd half of the Round Trip

Electric Analysis 2nd half	hours:minutes	Time Window (hrs)	Power Demand (kWe)	Energy Requirements (kWeh)
Seagoing Time	4:36	4,60	1.030,2	4.738,92
Maneuvering Time	0:36	0,60	1.778,8	1.067,28
Port Time	0:17	0,28	998,4	279,55
Overnight at Piraeus	Loading Period 2:00	2,00	998,4	1.996,80
	Rest Period 9:46	9,77	280,5	2.740,49
Total Time	17:15	17,25	Peak Power 1.778,8 kW	Total En.Req 10.823,04 kWh
Average Speed	23,13 knots	**Total En.Req = 38.962,93 MJ**		

The final results for the whole trip and each mode of operation can be found gathered in Table 6.28. As it is sensible, the majority of the electric energy is absorbed during sea-going periods (52.3 %), a significant amount of energy is required for in-port (loading) operations of the ship (21.4 %) while overnight at Piraeus holds a percentage of 15.1% of the total energy demand. As it is logical, maneuvering demands hold the last energy position (11.3 %) as they refer to transient conditions that last for a limited amount of time.

Table 6.28 Blue Star Paros' Electric Energy Consumption for a Round Trip

Components	Modes Of Operation			
	Sea going	Maneuvering	Loading	Overnight at Piraeus
Electric Demand (kWe)	1.030,2	1.778,8	998,4	280,5
Total hours	9,20	1,15	3,88	9,77
Energy Consumption (kWeh)	9.477,84	2.045,62	3.873,79	2.740,49
Total Energy Requirements (kWeh)	18.137,74			
Total Energy Requirements (MJ)	65.295,85			
Percentage Of Energy Consumption	52,3%	11,3%	21,4%	15,1%

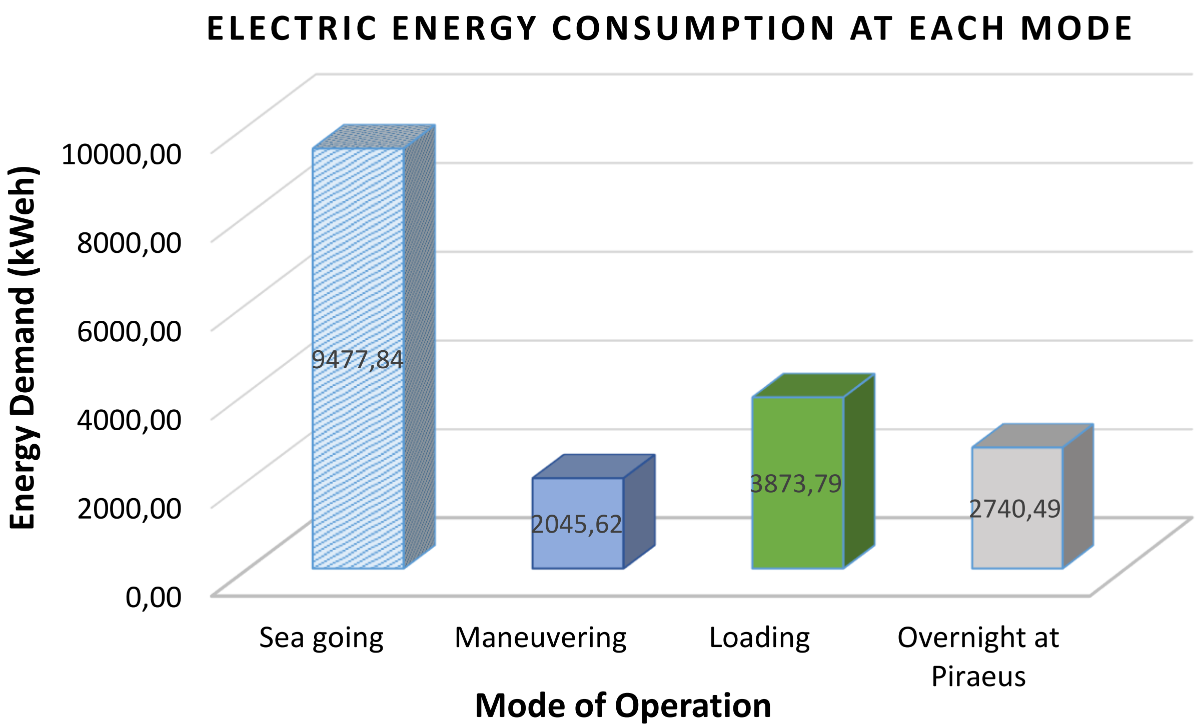


Figure 6.60 Blue Star Paros' Electric Energy Consumption at each Operation Mode for a Round Trip

6.3.3 Marine Fuel Consumption

When it comes to overall efficiency of an installed energy system, the primary aspect that someone should calculate is the total fuel consumption that it is daisy-chained with the operating costs of the unit. Knowing the manufacturer (Wartsila Vaasa) and model number (6L20) of the installed diesel generators, we educe all the essential information from their project guide. However, because the load of D/G does not always coincide with guide's values, a cubic interpolation has been conducted to estimate the necessary values. The generated function is analytical and has the following form:

$$\mathbf{FOC} = \mathbf{5,94} * \mathbf{10^{-5}Load^3} - \mathbf{0,00505Load^2} - \mathbf{0,354Load} + \mathbf{221} \; \left[\frac{g}{kWh}\right] \quad \textbf{(6.1)}$$

Where, FOC stands for Fuel Oil Consumption and is a function of D/G's Load.

Figure 6.61 shows the generated curve (green line), data points that were derived from D/G's project guide and real operating points.

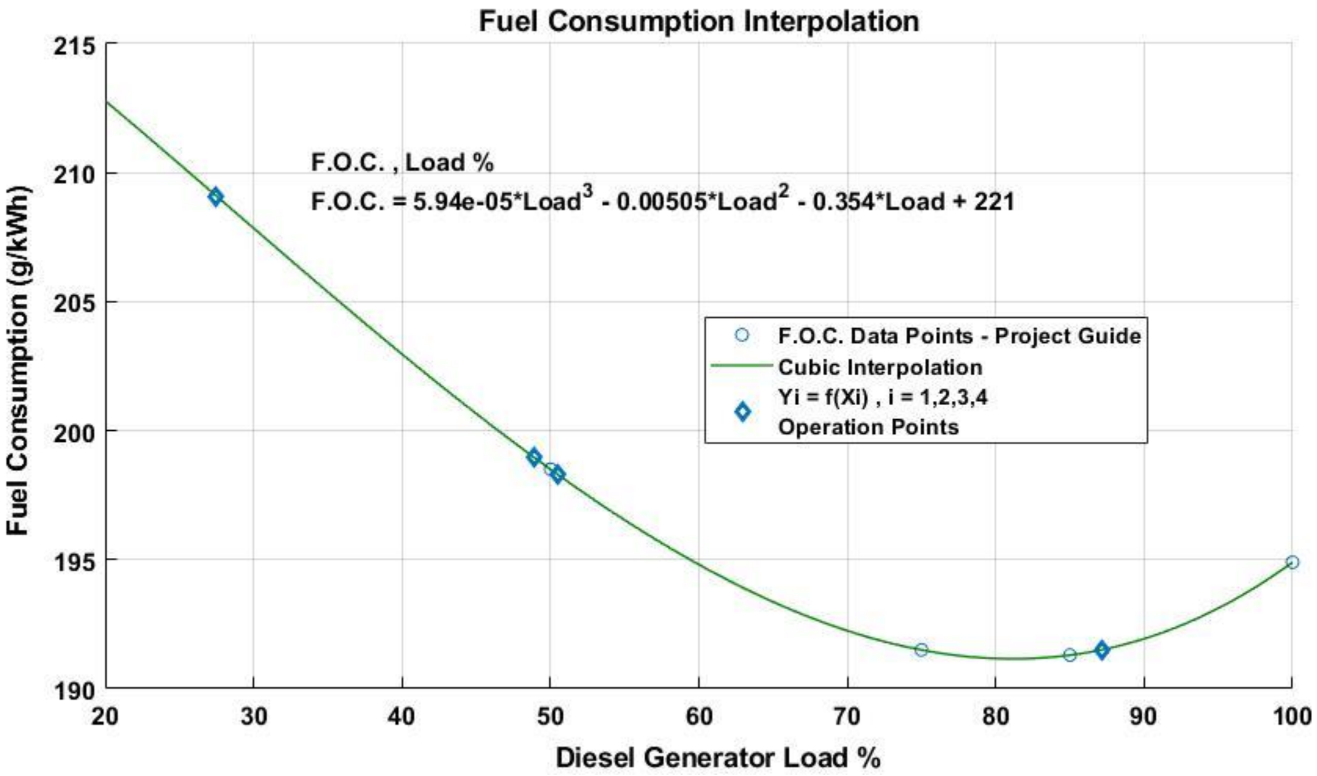


Figure 6.61 Fuel Oil Consumption [F.O.C.] calculation using Matlab Interpolation

Based on this information, Table 6.29 presents the total fuel consumption (Low Sulfur Fuel Oil, with a maximum of 1% in sulfur content) of the round trip, its purchase cost [LSFO prices - Ship & Bunker for the Port of Piraeus, 2019] as well as the required volume of ship's storage tanks [LSFO density - Shell, 2019].

Table 6.29 Round Trip: Fuel Oil Consumption

Mode of Operation	Module	Value	Total (kWh) at each operating mode	Fuel Quantity (MT)	Total LSFO Cost ($)	Necessary Tank Capacity for LSFO (m^3)
Values with * calculated using Cubic Interpolation			Fuel Oil Specification: LSFO < 1 % Sulfur Content	Average LSFO Density: 890 (kg/m^3)	LSFO Contract Price 475$/MT	10% tolerance
Fuel Consumption at 100% load	g/kWh	194,9	-	-	-	
Fuel Consumption at 87,2% load, Maneuvering *	g/kWh	191,2	2.045,62	0,391	225	0,439
Fuel Consumption at 85% load	g/kWh	191,3	-	-	-	
Fuel Consumption at 75% load	g/kWh	191,5	-	-	-	
Fuel Consumption at 50,5% load , At Sea *	g/kWh	197,9	9.477,84	1,876	1.079	2,107
Fuel Consumption at 50% load	g/kWh	198,5	-	-	-	
Fuel Consumption at 48,9% load, At Ports *	g/kWh	198,6	3.873,79	0,769	442	0,864
Fuel Consumption at 27,5% load, Overnight At Piraeus *	g/kWh	208,7	2.740,49	0,572	329	0,643
Clean Leak fuel Quantity, 100 % load	kg/h	3,24	Total Leak Fuel Quantity70 kg	**Total LSFO Quantity 3,686 MT**	**Total LSFO Cost 2.072 $**	**Total Tank Capacity for LSFO 4,054 m^3**
Total Energy Requirements	kWh	18.137,74				
Oil Comsumption at 85 % Load	g/kWh	0,35	Total Lub.Oil Quantity 6,34 kg			

The above calculations conducted using the following formulas:

- $\mathrm{FOC_i} = 5{,}94 * 10^{-5}\mathrm{Load_i^3} - 0{,}00505\mathrm{Load_i^2} - 0{,}354\mathrm{Load_i} + 221$ (6.4)
- $\mathrm{FuelQuantity} = \sum_1^4 \mathrm{EnergyDemands_i} \times \mathrm{FOC_i}$ (6.3)
- $\mathrm{Total\ LSFO\ \ Cost} = \mathrm{FuelQuantity} \times \mathrm{Price_{LSFO}}$ (6.4)
- $\mathrm{Tank\ Capacity} = \mathrm{FuelQuantity} \times \mathrm{FuelDensity_{LSFO}}$ (6.5)

6.3 Greenhouse Gases and Pollutant Emissions

Development of technology is, by common sense, the cornerstone for the evolution of our societies. The term evolution is indissolubly connected with both the protection of human health & ecosystems and the improvement of system's overall efficiency. To achieve that, researchers have to identify new ways to either satisfy the same energy demands with decreased numbers in GHG and pollutants (Scrubbers, EGR, etc.) or develop, commercialize and apply new techniques and powertrain systems that eliminate these drawbacks of internal engine machines techniques that bring a fresh new breath to the preexisting energy systems). Fuel Cell technology is a promising solution that has the potential to achieve both of abovementioned measures of optimization, as its efficiency is not permitted from Carnot's maximum rule and is characterized by low-emission operations (sometimes is zero-emission – PEMFC). Therefore, for the comparison of a FC configuration with an existing one – arrangement of DGs –, in terms of their environmental and societal impact, is crucial to estimate GHG and pollutant emissions of each scenario and alternative. The following subsection develops a methodology for the calculation of D/G's GHG and pollutant emissions.

6.3.1 Carbon Dioxide (CO_2) Emissions

Blue Star Paros, like any other commercial ship which crosses European waters, is equipped with Marine Fuel Monitoring System. Monitoring, Reporting and Verification regulation was introduced by the European Union in order to reduce emissions from shipping. MRV is designed to gather data on CO_2 emissions based on ships' fuel consumption. Deploying these reports, Table 6.30 presents the measured values of CO_2 emissions for both Main Engines and Diesel Generators. After that, those values are compared to the ones relating to default CO_2 Emission Factor (with direct calculation from relative chemical reactions of the applied LSFO).

To complete the necessary calculations, the following CO_2 Emission Factor is used [DNV GL, 2019

$$CO_{2_{EmissionFactor}} = 3.140 \left[\frac{kg\ CO_2}{ton\ fuel}\right] \tag{6.6}$$

Table 6.30 CO_2 Calculations for a Round Trip

<table>
<tr><th>CO_2 Measurements</th><th>Total (g)</th><th>MRV - CO_2 Emissions Main Engine (kg)</th><th>Default E.F. - CO_2 Emissions Main Engine (kg)</th><th>MRV - CO_2 Emissions Diesel Generators (kg)</th><th>Default E.F. - CO_2 Emissions Diesel Generators (kg)</th></tr>
<tr><td>Running Total</td><td>82.394.000</td><td>75.467,07</td><td>77.471,12</td><td>6.926,93</td><td>7.117,71</td></tr>
<tr><td>InPorts Total</td><td>3.770.000</td><td rowspan="2">2.114,42</td><td rowspan="2">1966,90</td><td>2227,81</td><td>2415,72</td></tr>
<tr><td>At Piraeus</td><td>2.692.800</td><td>2.120,57</td><td>2.039,88</td></tr>
<tr><td>Total CO_2 Emissions (kg)</td><td>88.856.800</td><td>77.581,49</td><td>79.438,01</td><td>11.275,31</td><td>11.573,31</td></tr>
<tr><td colspan="2">Deviation %</td><td colspan="2">2,34</td><td colspan="2">2,57</td></tr>
</table>

6.3.2 Nitrogen Oxide (NO_X) Emissions

The calculation of NO_X emissions is conducted in accordance with Ship's Statement of Compliance that was approved from BUREAU VERITAS after the conduction of numerous tests of the installed Diesel Generators. Engine's actual NO_X Emission Values (g/kWh) have been measured on parent engines for different loads (at 100%, 85%, 50% and 25%). To identify the Emission Values for the operating loads, a 4th Degree Interpolation is deployed. Figure 6.62 shows the produced curve (blue line), data points that was derived from D/G's measurements and the real operating points.

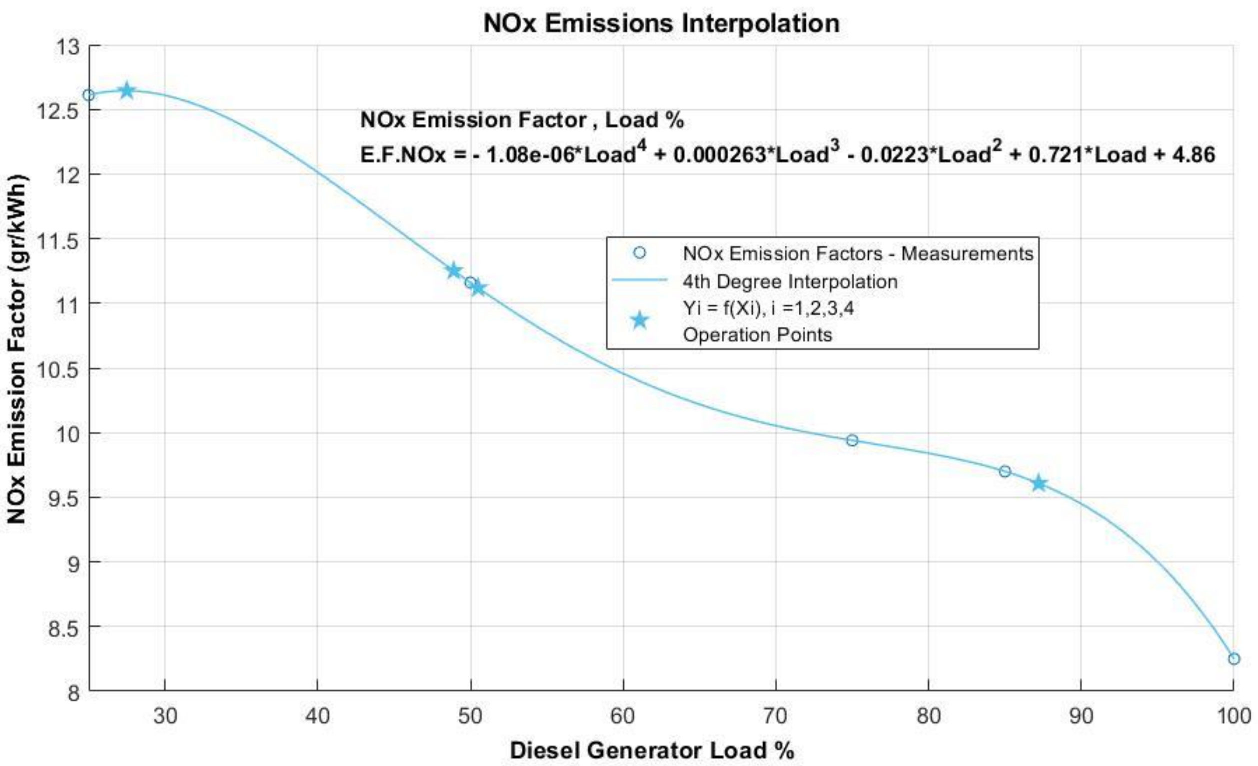


Figure 6.62 NOx Emissions Calculation using Matlab Interpolation

The generated function is analytical and has the following form:

$$\mathbf{E.F.NOx} = -\mathbf{1.08} * \mathbf{10^{-6}Load^4} - \mathbf{0.000263Load^3} - \mathbf{0.0223Load^2} + + \mathbf{0.721Load} + \mathbf{4.86} \left[\frac{\mathbf{g}}{\mathbf{kWh}}\right] \quad \mathbf{(6.7)}$$

Where, E.F. stands for "Emission Factor" and it is a function of D/G's Load. Table 6.31 summarizes the overall results.

Table 6.31 NOx Emissions Calculations

Mode of Operation	Diesel Generator's NOx Emission Factor (g/kWh)	Total (kWh) at each operating mode	NOx Emissions (kg)
At 100 % Load	8,25	-	-
At 85 % Load	9,70	-	-
At 87,2% load, Maneuvering *	9,61	2.045,62	19,66
At 75 % Load	9,94	-	-
Fuel Consumption at 50,5% load , At Sea *	11,10	9.477,8	105,20
Fuel Consumption at 50% load	11,16	-	-
Fuel Consumption at 48,9% load, At Ports *	11,30	3.873,79	43,77
Fuel Consumption at 27,5% load, Overnight At Piraeus *	12,60	2.740,49	34,53
At 25 % Load	12,61	-	-
Total NOx Emissions (kg)			203,17
Values with * calculated using 4th Degree Interpolation			

6.3.3 Sulfur Dioxide (SO_2) Emissions

Pollutant emissions of SO_2 depending on the specifications and quality of fuel. It is produced by the sulfates contained in diesel fuel and it's independent from combustion's efficiency. For the present there is not any after-treatment system like a catalytic converter to eliminate SO_2. Nowadays, most of oil distributors and customers prefer Low and Ultra Low Sulfur Fuel oil for diesel engines to prevent harmful effect of SO_2 emissions. The significance of these emissions can be realized from the fact that IMO [MARPOL Protocol] has specifically declared Sulfur Emission Control Areas (SECAs) to minimize and control emissions coming from the marine vessels' exhausts that pollute the environment. Currently the global cap is 3.5 %m/m on the sulfur content in fuel but after 1 January of 2020 this limit is due to decrease to unparalleled low levels to reach 0.50 % m/m. The sulfur limit for fuels in SECAs is 0.10% m/m and was activated after the 1st of January of 2015.

Emissions of SO_2 may be calculated by means of the following equation:

$$\mathbf{E_{SO2}} = \mathbf{2} \times \mathbf{S} \times \mathbf{FC_m}\ [\text{tons SO}_2] \qquad \textbf{(6.8)}$$

Where:

E_{SO2} = emissions of sulfur dioxide for the period concerned [kg],

S = mass fraction of sulfur in fuel

FC_m = fuel consumption of fuel type m for the operational profile considered [kgs]

The maximum allowable sulfur content of LSFO is 1%. Therefore, this value is used for the calculations as to cover the worst-case scenario.

For a total fuel consumption of 3.686 kgs the value of SO_2 emissions is calculated:

$$\mathbf{E_{SO2}} = \mathbf{73,72\ kg}$$

6.3.4 Particulate Matter (PM) Emissions

Particulate Matter (PM) emissions in the exhaust gas are resulted from combustion process. They may be originated from the agglomeration of very small particles of partly burned fuel, partly burned lube oil, ash content of fuel oil, and cylinder lube oil or sulfates and water [Maricq, 2007]. Most particulate matters are resulted from incomplete combustion of the hydrocarbons in the fuel and lube oil. Therefore, PM emissions are highly sensitive to the efficiency of combustion process and do not exclusively depend on sulfur content. However, the higher the sulfur content of the fuel the higher the PM emissions. The difficulty here lies to the calculation of the exact number of its value as there is neither a predetermined Emission Factor (like NO_X analogs that was provided from D/G's statement of compliance) nor an exact arithmetic bond between PM emissions and Fuel Oil Consumption.

For the abovementioned reasons as well as the lack of on-board measurements of Blue Star Paros PM's emissions a bibliographic fuel-based standardized factor is applied for the relative calculation. According to a modern survey [Lindstad and Sandaas, 2016] on 4-stroke diesel engines it was assumed that potential PM emissions from the fuel burnt in electric engines can be quantified using the following formula:

$$\mathbf{E_{PM}} = \mathbf{0.0024} \times \mathbf{FC_m} \quad [\text{tons PM}] \tag{6.9}$$

Where:

E_{PM} = emissions particulate matter for the period concerned [tons],

FC_m = fuel consumption of fuel type m for the operational profile considered [tons]

For a total fuel consumption of 3.686 tons the value of PM emissions is calculated:

$$\mathbf{E_{PM}} = \mathbf{8,846\ kg}$$

6.3.5 Carbon Monoxide Emissions (CO)

Carbon monoxide results from the incomplete combustion where the oxidation process does not occur completely. This concentration is largely dependent on air/fuel mixture and it is highest where the excess-air factor (λ) is less than 1.0 that is classified as rich mixture. Diesel engines are lean combustion engines which have a consistently high air–fuel ratio (λ > 1). So, the formation of CO occurs but is minimal in diesel engines. Due to its nature, for the exact reasons which is difficult for PM emissions, is quite an arduous task to calculate CO emissions.

For the exact reasons that it was practically unfeasible to calculate the PM emissions, a bibliographic formula is also applied for the calculation of CO emissions [Lindstad and Sandaas, 2016]

Emissions of CO may be calculated by means of the following equation:

$$\mathbf{E_{CO} = 0,0074 \times FC_m} \quad [\text{tons CO}] \qquad \textbf{(6.8)}$$

Where:

E_{CO}	=	emissions of carbon monoxide for the period concerned [tons],
FC_m	=	fuel consumption of fuel type m for the operational profile considered [tons]

For a total fuel consumption of 3.686 tons the value of CO emissions is calculated:

$$\mathbf{E_{CO} = 27,275\ kg}$$

6.3.6 Summary of GHGs and Pollutants

Table 6.32 offers an overview of the calculative emission numbers of Blue Star Paros' voyages. Round Trip calculations include go and come operations while a Summer Season is composed of 180 identical round trips [Blue Star Ferries, 2019].

Table 6.32 Blue Star Paros' Emission numbers

Blue Star Paros' Emissions		
Pollutants	**Round Trip (kg)**	**Summer Season (tons)**
NOx	203,166	36,570
SO_2	73,715	13,269
PM	8,846	1,592
CO	27,275	4,909
GreenHouse Gases	**Round Trip (kg)**	**Summer Season (tons)**
CO_2eq	11.573,307	2.083,195

6.4 CapEx & OpEx of Installed D/Gs

As mentioned in **§ 6.2.1**, Blue Star Paros is equipped with three alike diesel generators for the necessary on-board electricity production. The pros of this topology is its low Capital and Operational Expenses while its cons refer to their high pollutants emissions, especially during Loading – Unloading operations at ports. A diesel generator is a reliable device that can offer instantaneous electric power and cope with great torque demands, even in harsh conditions and in low speeds. For these reasons, the current electric generation configuration of Blue Star Paros is not equipped with additional energy storage systems as it seems as an exaggeration. Nevertheless, for safety issues, a 300 kW spare D/G accompanies the trio in a standby condition (in the next chapter, the same D/G is suggested to cover the emergence operations in the proposed HFCs Hybrid topologies).

For a detailed and rigorous comparison between alternative powertrain topologies it is essential to identify the Capital Expenditure (CaPex) and Operational Expenditure (OpEx) of a suggested option. This subsection enlightens the reader with the necessary information - for the accomplishment of this task -, used in this diploma thesis. Table 6.33 offers exactly this information for the case of the conventional scenario, while it mentions the source that each informative part was derived. The numbers derived from the source mentioned as DNV GL, 2019 is an outcome of personal communication of the author with the stuff of the Norwegian Classification Society at each facility in Piraeus.

CapEx includes:

- Capital and Installation Costs for the necessary components of the proposed configuration (total plant of Diesel Generators + LSFO tanks)

  As the productive life a modern D/G is approximately estimated around a 25-year operation lifespan, there is not a scheduled replacement for them. This fact combined with its low capital cost (~ 400 $/kW) is exactly what have led to the spread and establishment of D/G on-board.

OpEx includes:

- Fuel Oil Costs; which in Blue Star Paros' case, refer to Low-Sulfur-Fuel-Oil (LSFO)
- Lubricating Oil Costs; calculated using Wartsila's Product Guide.
- Maintenance Costs; expenses that burden the company at the end of each season.

The majority of the abovementioned costs have a unitary hue, and as a result it only takes a deduction using multiplication with the appropriate number to calculate the necessary requirements.

Table 6.33 CapEx and OpEx of Blue Star Paros' current D/G Configuration

Diesel Generator Configuration			
Aspect	Unit	Value	Sources
CapEx Costs			
Specific Capital and Installation Cost	$/kW	400	*DNV GL, 2019*
Total Installed Power (3 Sets of 1020 kW)	kW	3.060,00	*Ship's Electric Balance Calculation*
LSFO Tanks	$/m³	1.000,00	*DNV GL, 2019*
LSFO Fuel Tolerance	%	0,10	
LSFO Storage Tanks CapEx	$	4.555,44	
Total CapEx Cost	$	1.228.555,44	-
OpEx Costs for a Round Trip			
Total Fuel Oil Demand for Round Trip	ton	3,686	*Project Guide, Wartsila 6l20*
Fuel Oil Cost	$/ton	480	*Bunkerworld Prices, 2019*
Total Expenses for Fuel Oil	$	1.769,17	-
Total Demand for Lub. Oil	kg	6,35	*Ship's Operating Profile*
Lub. Oil Cost	$/ton	1.681,00	*Bunkerworld Prices, 2019*
Total Expenses for Lub Oil	$	10,67	-
Total Round Trip Expenses	$/RoundTrip	1.779,84	-
Total Summer Period Costs			
Number of Trips during a Summer Season	-	180	*Blue Star Ferries, 2019*
Total Running Cost for a Complete Season	$	320.371,07	-
Maintenance Cost	$/Period	25.000,00	*DNV GL, 2019*
Total Expenses for a Single Summer Season	$	345.371,07	-

Figure 6.63 presents a summary of details for Blue Star Paros' Aegean voyages.

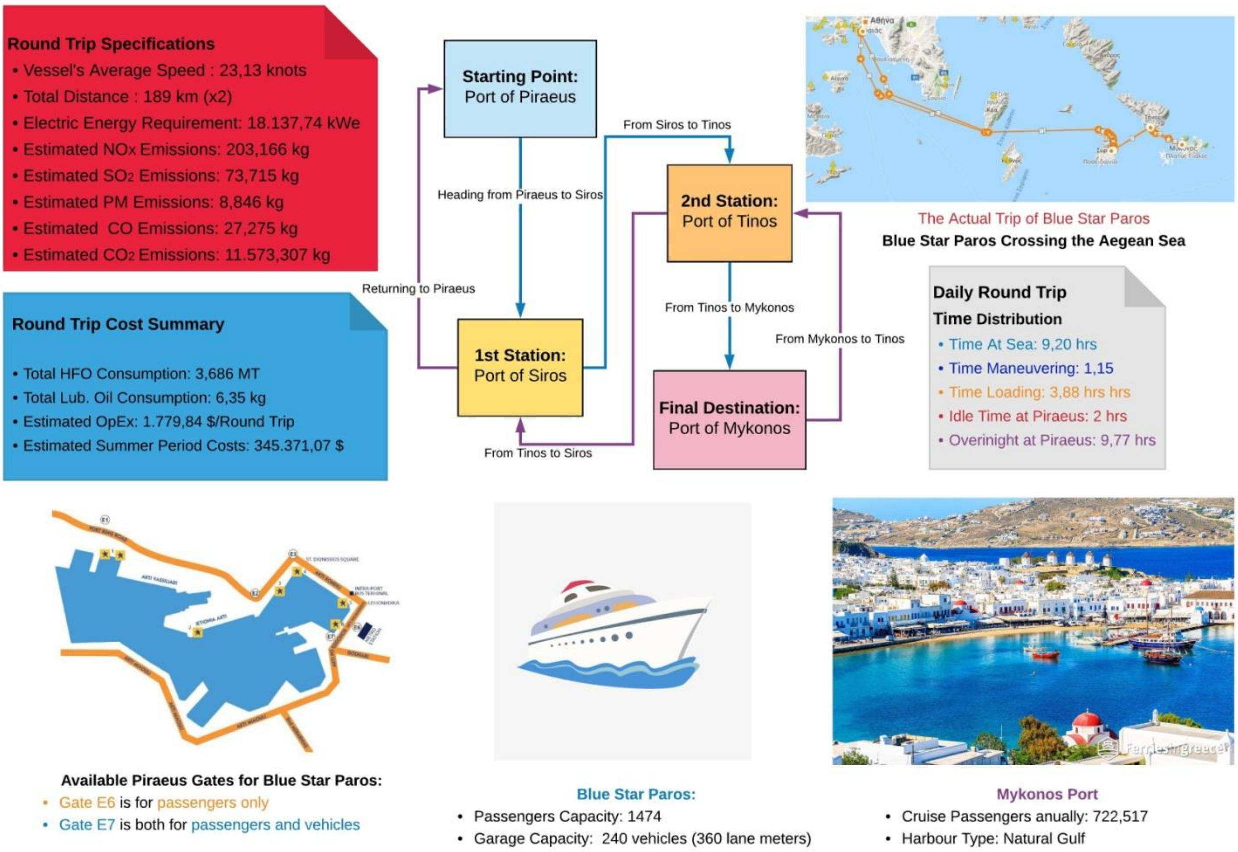


Figure 6.63 Layout of Blue Star Paros' Aegean Voyages

7th CHAPTER

Economic Analysis through a Case Study

Fuel Cell Embarkation: A Pathway for a Smarter, Greener World

« The ultimate resource in economic development is people. It is people, not capital or raw materials that develop an economy »

Peter Drucker (1909–2005), the father of management thinking.

Picture 7.44 **In many people's beliefs, HFC technology is the golden mean for the decarbonization of transportation sector [Hyundai, 2019]**

7.1 Introduction

Economy is the basis of our society. When economy is stable, society develops. An ideal economy combines the spiritual and the material, and the best commodities to trade in are sincerity, love and technology. Laying the foundations for a sustainable development is the key for the creation of a greener, smarter and more humanistic world. But what exactly is sustainable development? Most of the times it refers to economic growth that is conducted without depletion of natural resources or harassment of physical environment and ecosystems. The 2030 Agenda for sustainable development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart there are 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries – developed and developing - in a global partnership. They all recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health, technological progress, spur economic growth – all while tackling climate change and working to preserve our oceans and forests.

Hybrid technology may be the cornerstone for the revolutionization of modern transport and power supply. In power engineering, the term “hybrid” describes a combined power and energy storage system for the fulfillment of energy requirements. Practically, it is a synergy of two or more modes of electricity generation that provides a high level of energy security through the mix of generation methods, and often will incorporate a storage system (most commonly batteries) to ensure maximum supply reliability and security.

As also mentioned in previous chapters, the main purpose of this diploma thesis is the conduction of an economotechnical analysis corresponding to Fuel Cells’ “embarkation” on ships, technologies fueled by Hydrogen or LNG sources for electric generation in order to fulfill energy requirements of a typical Ro/Pax ferry. This section, focuses on the development of a methodology that narrows down the wider spectrum of possibilities of this endeavor using modular argumentation and practical details. Finally, it ends up reaching three feasible alternative hybrid topologies, analyzing their economic potential and comparing their societal costs.

7.2 Modular Research Methodology

7.2.1 Fuel Supply

The backbone of a power system's network is its fuel supply. To achieve a feasible but also practical configuration one's has to identify the bottlenecks, the possibilities and the advantages of each alternative option. It this diploma thesis, the "competitive" fuels are: 1) Low-Sulfur-Fuel-Oil (LSFO) that is the primary power source of Blue Star Paros' current electric topology - using 3 DGs -, 2) Liquefied Hydrogen (LH2) and 3) Liquefied Natural Gas (LNG). The word "liquefied" specifies the means of transportation used for the delivery of the fuel from the production or distribution unit onto the ship. It also determines the on-board storage and conditioning methods of the fuel using appropriate fuel tanks (possibly IMO Type C tanks). **The benefits of a liquefied fuel are highlighted in § 5.2.4.4** and include aspects as well-to-tank emissions, power storage and conditioning demands, transportation security, on-board crew and passengers' safety, economic advantages and mainly background projects implemented at maritime sector (especially from LNG projects) that work as a database for future applications. Capital and installation costs for a LSFO, LH2 or LNG tank as well as their constant power demands are estimated after personal communication with DNV GL. Furthermore, to secure a safe operation, an additional 10% of the required fuel was taken into account for the calculation of the necessary dimensions of the tanks.

In addition, opportunity cost generated by losing a certain amount of space for cargo instead of installation of HFCs is not considered as capital cost of HFCs since the whole project is oriented towards Ro/Pax and it is not feasible to speculate the losses in passenger numbers due to a specific loss in payload capacity.

7.2.2 Fuel Cell Technologies

As mentioned in **Chapter 2**, Fuel Cell technology composes a revolutionary method for the production of direct current (DC) electricity. Despite their superiority in terms of efficiency and societal cost, for the time being, fuel cells have mainly been confined in laboratory units and their commercial expansion is limited and at a preliminary stage. This diploma thesis, manages to shed light and identify the main types of FC technology that will play an important role in the short run in marine sector. The whole **§ 5.4 section** detects the most promising FC technologies , compares and comments on their physical abilities, peculiarities and commercial status. The three FCs qualifiers are**: 1) Proton-Exchange-Membrane (PEMFC)**, **2) Molten Carbonate (MCFC)** and **3) Solid Oxide (SOFC).** Each one of these FC technologies has each physical – operational confinements.

As mentioned in **§ 5.4.4,** PEMFC requires an almost crystal-clear and pure Hydrogen fuel supply. That indicates that a PEMFC topology can only be established either by using a LH2 supply or by employing an external reformer unit outside the FC configuration that generates pure Hydrogen. The first suggestion is quite simple, as its nature simulates the supply and on-board storage and conditioning requirements of an LNG analog topology. The second option is really a painstaking task as it requires a meticulous research. Typical SMR operates at a temperature range of 450 – 500 ℃ and as a result they require a great amount of thermal energy. As PEMFC, for a safe performance, operates approximately at 100℃, there will not be a sufficient thermal energy from the byproducts of PEFC's operation to satisfy the SMR requirements. As a result, there will be an additional demand for vapor which dictates an extra cost for the whole system (possibly by adding an external boiler at PEMFC's topology). Besides, reformer's CapEx is extremely high ~ 3000 – 5000 $/kW [IEA, 2019], a crucial detail that makes this scenario economic disadvantageous. For the abovementioned reasons, for the purposes of this diploma thesis, the PEMFC topology is combined with a direct LH2 supply pathway and the external costs of transport and delivery are all included in the sale price of LH2. After personal communication with DNV GL at their Piraeus' department, it was concluded that the additional total power demand for the on-board storage and conditioning of LH2 is constant and equals to 150 kW (overnight at Piraeus Port is excluded).

As for the SOFC & MCFC systems, they both need a steady supply of CO while the latter also demands a CO_2 supply. That implies that, some kind of byproduct physical impurities are essential for the stable operation of those systems. Therefore, it is both practically irrational and economically disadvantageous to use LH2 as their fuel source as this would require a different system layout with additional components in the balance of plant and adding to cost and complexity of the total system. Conclusively, SOFC & MCFC configurations are combined with LNG fuel supplies while its additional total power demand for the on-board storage and conditioning of LNG is constant and equals to 100 kW (overnight at Piraeus Port is excluded).

7.2.3 Hybrid Synergy

7.2.3.1 Background

Hybrid power supply has recently become a realistic option for many maritime applications due to the development of power dense lithium-ion battery technologies, developed for the automotive industry. Lithium-ion batteries (LIB) provide power and energy dense energy storage with good life cycle performance and have thus enabled electrical, hybrid and plug-in hybrid vehicles in the automotive market. Particularly, lithium-ion polymer batteries and lithium iron phosphate batteries provide high capacity at high discharge currents. What is more, hybrid power supply has been applied to a great variety of floating means of transportation. In these applications the total electrical load varies significantly over time and in some cases has steep power increases and decreases. Therefore, the use of energy storage, such as batteries and super capacitors, can provide peak shaving, load leveling, frequency control and improving quality of power supply, and enable switching off all engines to reduce noise for a limited period. Moreover, batteries can be recharged from the shore grid, when the ship is moored alongside, reducing local emissions. Finally, batteries can provide back-up power during failures of diesel generators, negating the need for spinning reserve.

As mentioned in **Chapter 3**, fuel cell modules operate efficiently when performing on constant load conditions. In contrast, their main drawback is its difficulty to cope with steep power demands or intensive fluctuations of electric needs. In this regard, hybrid systems – especially when their primary electric source is composed of a FC system - using an energy storage system (ESS) have gained attention as an alternative solution to solve performance and environmental issues in the marine industry, and research regarding hybrid systems has already been performed. For example, Choi et al., 2016, proposed a fuel cell–battery hybrid system for a boat.

In addition, major ports have been expanding shore power facilities (or Alternative Maritime Power (AMP)), which can supply electric power for ships from land-based electric power plants while staying at a port. Notably, low voltage AMP facilities have already been installed in many dominant ports worldwide. Additionally, high voltage (3.3kV, 6.6kV, 11kV, etc.) AMP facilities are being installed in major ports for large ships such as in the U.S., Canada, European countries, China, etc., and the European Union (EU) requires European ports to offer shore-based electricity to ships by 2025. Taken all this into account, it is sensible to add cold-ironing operations at the Port of Piraeus in hybrid's technology arsenal and Blue Star Paros' can be benefited from a cold-ironing operation during its overnight at Piraeus Port when FC modules are turned-off. The 280,5 kWe power demand is within the scope of a feasible deployment of cold-ironing supply.

7.2.3.2 Energy Planning

In this paper, as described in **Chapter 6**, a medium size Ro/Pax was selected as a target ship in order to specify its electric requirements. The target ship was fitted with three gensets as power sources. This conventional configuration is replaced by three proposed hybrid systems. In these proposed hybrid systems, the diesel generators are replaced with a FC configuration and a Lithium – Ion Battery, that serves as an Energy Storage System. The dimensioning and analysis of a super capacitor is beyond the scope of this paper as its main applications are currently limited in laboratories and there is not a crystallized commercial basis on which an investor can rely on and shape economic scenarios (possibly in the next decade, SCs due to its greater power density and longer life cycle, when compared to LIBs, will play a leading role in research and application projects). The basic concept behind these suggested topologies is to construct an energy plan oriented to achieve the maximum utilization of the beneficial nature of each component of the hybrid system.

The main pillars of this methodology are:

[1] **Fuel Cell Modules** that operate on steady conditions - as possibly - to secure safe operating conditions and maximum efficiency. The only time window that Fuel Cells are turned-off is during overnights at Piraeus' Port. To secure optimum operability and efficiency of the synergy between FCs and LIB anytime there is a surplus in the power of FCs that works as a refueling source for charging the battery. This is the core of our Energy Storage System planning.

It is mentioned that the identification of the optimum electric pathway supply between the FCs and the LIB is beyond the scope of this diploma thesis since it is a rigorous optimization problem that requires arithmetic analysis and fuzzy logic operations (and its solution is only visible when the route path, the loading and operation profile of the ship is constant and predetermined).

[2] **A Lithium-Ion-Battery** that assists Fuel Cell Modules during maneuvering phases of the ship, when there is an instantaneous need for extra electric power supply.

[3] Electric power demands during overnight sessions at Piraeus' Port, are covered by on-shore power facilities, simulating possible **cold-ironing operations** in the near future.

It is declared that the additional costs that arise from cold-ironing operations burden Port's authorities and will be managed within the scope of port's competitiveness planning.

7.2.3.3 Conventional System

A simple layout of our conventional power system is shown in Figure 7.64. Even though three gensets are installed as power sources, the number of gensets in operation is different depending on the power required for each operation mode. Blue Star Paros' Electric Balance Calculations, Operational Profile, pollutants and GHGs' emissions are shown in detail in **Chapter 6**. In the proposed hybrid topologies, there will be no need for a genset. However, for safety issues, it is concluded that is thoughtful to keep on-board the emergency 300 kW diesel generator to cope with emergency conditions (such as fires, floods or blackouts). In this kind of configurations, a transformer unit is essential to transform the generated convenient voltages into different levels and then distribute around the necessary AC Loads.

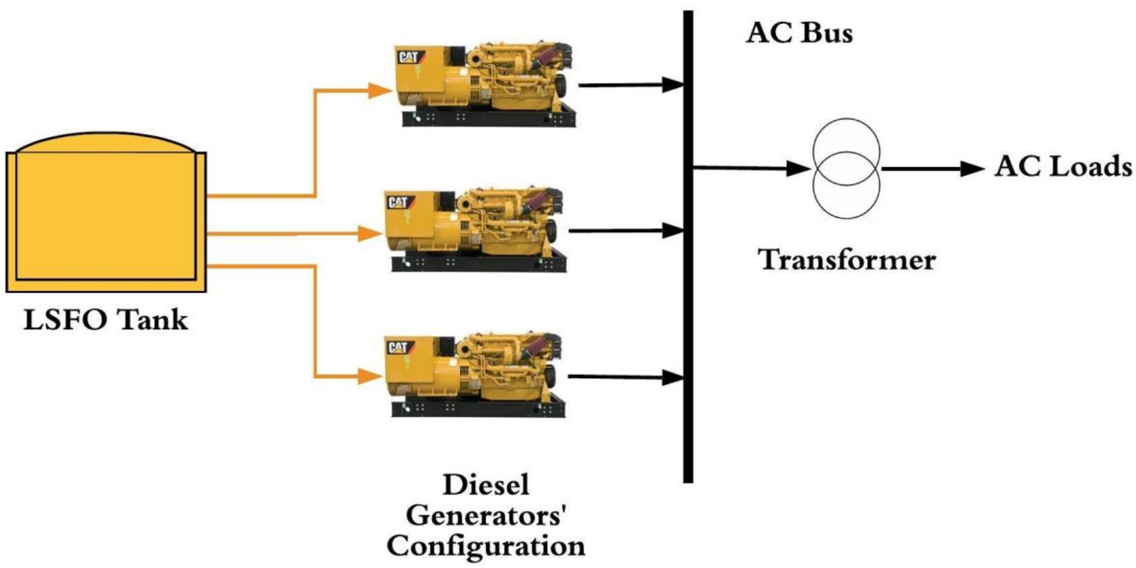


Figure 7.64 The Layout of Blue Star Paros' conventional power system [Author, 2019]

7.2.3.4 Proposed Topologies

The main purpose of the proposed systems is to reduce harmful pollutant emissions and decrease the carbon footprint of ship's operation (in accordance with IMO's 2020 and forth policy regime) and shed light to the economic potential of FC technology in applications of this scale. Three alternative scenarios will be examined for their economic potential. Their common point is LIB's stack. Their differences are oriented towards the type of the installed FC technology and subsequently their fuel source. In port in/out operations (maneuvering mode), when additional power is required for a short period of time, a LIB was selected as an auxiliary power source. During overnight periods at Piraeus, cold-ironing operations take place. Charging / Recharging phases occur based on possible power surpluses or deficiencies in electric demand. The main additions to the convention electric power flow system includes: **1)** The installation of two DC/DC Converters and one DC Bus, **2)** The installation of a DC/AC Inverter, **3)** a well-programmed Energy Control System that controls electric flow direction and secures system's overall efficiency (the expenses referring to an appropriate ECS is beyond the scope of this paper). The layout of the proposed power system is shown in Figure 7.65 .

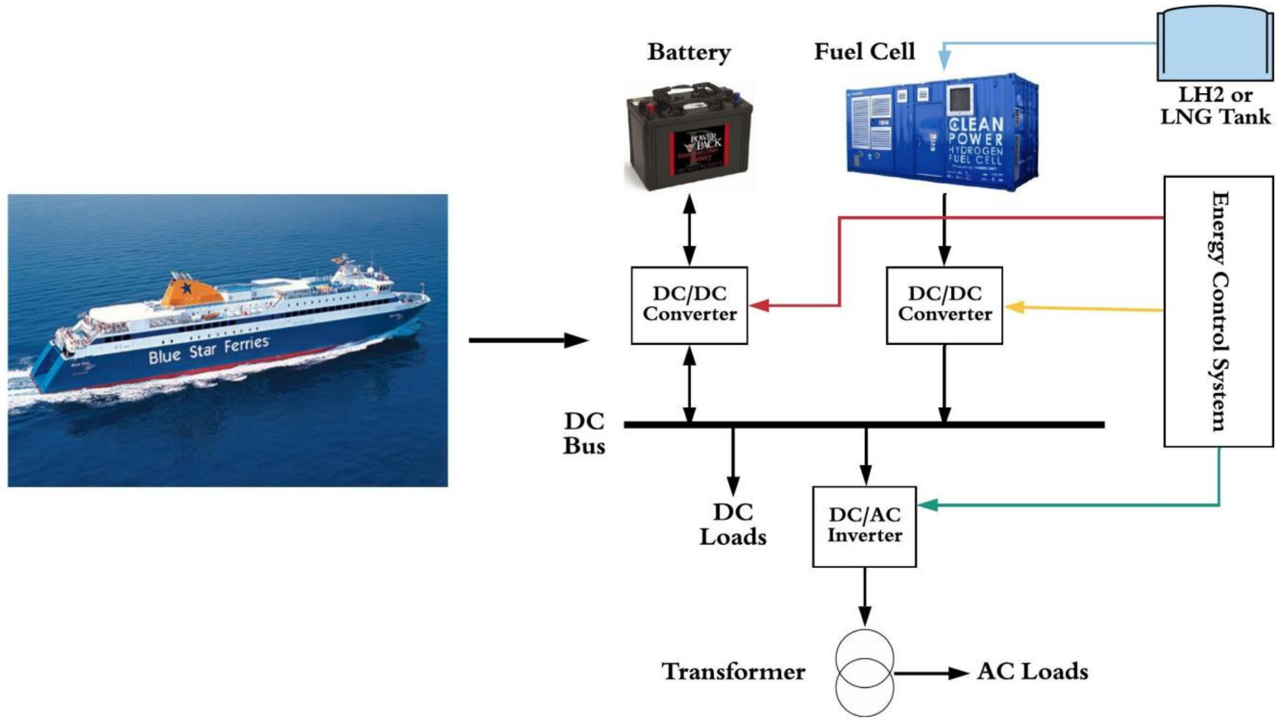


Figure 7.65 Layout of the proposed power system [Author,2019]

7.3 Proposed Scenarios

This unit aims to provide the reader with all the necessary information referring to the proposed hybrid topologies that work as a replacement for the current conventional D/G topology.

Subsection 7.3.1 is oriented to reveal all the fundamental details that correlates the proposed scenarios with concurrent economy trends. It also contains valuable information concerning efficiency indexes, lifespan estimations and future targets of the studied sizes. It is a database that assists this research and on which all the economic analysis is grounded.

To continue, **Subsection 7.3.2** offers a laconic but pithy presentation of the proposed hybrid scenarios. As often happens, it is useful to gather data and frame them into intelligible informative blocks that unified create concentrated source of knowledge. These structures - tables - are easily accessible and understandable from the reader, that is why each of the following scenarios and analyses include one or more specific tables that their format describes precisely the route of thought, from the point of the author, and offers all the worthy calculations.

7.3.1 Required Data Related to Cost

Table 7.34 shows all the required data related to the cost for the case study. As shown in Table 7.34, all the data is connected with their literature source from which each information was derived.

Table 7.34 Required data related to cost for case study

Technology	Aspect	Comment	Value	Unit	Source
PEMFC	CapEx	Today's Price Range	1800 - 3000	\$/kW	IEA / Technology Roadmap for Hydrogen and Fuel Cells, 2015
		Average Value	1900		
		2030 Target	1500		
		2050 Target	1250		
	Operation and Maintenance Cost	Today's Price Range	30 - 50	\$/kW/year	U.S. Department of Energy / Hydrogen Program - Cost Analysis of Fuel Cell Systems, 2017
		Average Value	40		
	Lifetime	Today's threshold	20000	hrs of operation	
		2030 Target	25000		
		2050 Target	30000		
	Efficiency	Average Value	55	%	
	Fuel	HYDROGEN			
	Emissions		Zero - Emission		
MCFC	CapEx	Today's Price Range	3000 - 4500	\$/kW	IEA / Technology Roadmap for Hydrogen and Fuel Cells, 2015
		Average Value	3750		
		2030 Target	3000		
		2050 Target	2000		
	Operation and Maintenance Cost	Today's Price Range	50 - 90	\$/kW installed/year	U.S. Department of Energy / Hydrogen Program - Cost Analysis of Fuel Cell Systems, 2017
		Average Value	70		
	Lifetime	Today's threshold	25000	hrs of operation	
		2030 Target	30000		
		2050 Target	40000		
	Efficiency	Average Value	60	%	
	Fuel	LNG			
	GHG Emissions	CO_2	445,5	kg CO_2/MWh	Fuel Cell Energy, 2019
		CO	20,1	gr CO/MWh	
	Pollutant Emissions	NO_x	4,54	gr NO_x/MWh	
		SO_2	0,045	gr SO_2/MWh	
		PM	0,0091	gr PM/MWh	
SOFC	CapEx Cost	Today's Price Range	3000 - 5000	\$/kW	IEA / Technology Roadmap for Hydrogen and Fuel Cells, 2015
		Average Value	4000		
		2030 Target	2000		
		2050 Target	1500		
	Operation and Maintenance Cost	Today's Price Range	50 - 100	\$/kW installed/year	U.S. Department of Energy / Hydrogen Program - Cost Analysis of Fuel Cell Systems, 2017
		Average Value	75		
	Lifetime	Today's threshold	35000	hrs of operation	

		2030 Target	40000		
		2050 Target	60000		
	Efficiency	Average Value	65	%	
	Fuel	**L N G**			Bloom Energy, 2019
	GHG Emissions	CO_2	342	kg CO_2/MWh	
		CO	15,4	gr CO/MWh	
	Pollutant Emissions	NO_x	0,77	gr NO_x/MWh	
		SO_2	negligible	gr SO_2/MWh	
		PM	negligible	gr PM/MWh	
Hydrogen Tank	CapEx	Volumetric Cost	6000	$/m³	DNV GL, 2019
		Gravimetric Cost	0,704	$/MJ LH_2	
	Operation and Maintenance Power Demand	For Storing and Conditioning	150	kW	
LNG Tank	CapEx	Today's Price Range	4000	$/m³	
		Average Value	0,175	$/MJ LNG	
	Operation and Maintenace Power Demand	For Storing and Conditioning	100	kW	
Marine Fuels	**LSFO (< 1% Sulfur Content)**	LHV	42,7	MJ/kg LSFO	
		Average Purchase Cost	475	$/ton	Piraeus Bunker Prices, 2019
		Density	890	kg/m³	DNV GL, 2019
		Overall Environmental Damage	26,667	gCO_2eq/MJ LSFO	European Commission / Well-to-Tank emission Analysis, 2014
	LNG	LHV	48,62	MJ/kg LNG	DNV GL, 2019
		Average Purchase Cost	415	$/ton	Piraeus Bunker Prices, 2019
		Density	470	kg/m³	DNV GL, 2019
		Overall Environmental Damage	16	gCO_2eq/MJ LNG	European Commission / Well-to-Tank emission Analysis, 2014
	Liquid Hydrogen	LHV	120,21	MJ/kg H2	DNV GL, 2019
		Average Purchase Cost	5000	$/ton	IEA / Technology Roadmap for Hydrogen and Fuel Cells, 2015
		2030 Target	3000		
		2050 Target	1000		
		Density	53	kg/m³	
		Least Overall Environmental Damage	102	gCO_2eq/MJ LH2	
Electric Grid	Electricity Cost	At day time	0,119	$/kWh	Eurostat, 2018
		At day time	0,7	$/kWh	
	GHG Emissions	On Shore Wind Power	32,45	g CO_{2e}/kWh	Life Cycle Costs and Carbon Emissions University of Edinburgh, Life Cycle Costs and Emissions of Wind Power, 2015
Diesel Generator	CapEx	Based on Product Guide, Calculations at Chapter 6	400	$/kW	DNV GL, 2019
	OpEx		25000	$/year	Wartsila, Product Guide, 2018
Battery	CapEx	Average Value, 2019	250	$/kWh	Bloomberg, 2019
Converter	CapEx	Average Value	$35P_{conv}^{0,5}$	$	Bakirtzoglou, 2017
Inverter	CapEx	Average Value	200	$/kW	Charalambopoulos, 2018

7.3.2 Proposed Hybrid Power Systems

At this subsection there will be a synoptic presentation of the three alternative proposed scenarios. All three topologies and operational scenarios have the same impact on LIB and therefore LIB's operational profile is identical for each one. Epigrammatically, the constituent elements of each scenario are:

[1] LH2-fueled → PEMFC+ LIB + Cold-Ironing

[2] LNG-fueled → MCFC + LIB + Cold-Ironing

[3] LNG-fueled → SOFC + LIB + Cold-Ironing

Each proposed scenario is defined by its table that summarizes all the necessary information and calculations that represent its efficiency and operability. It contains technical details, power transactions between the FC's technology and LIB and summarizes the total expenses in $ USD for a round trip. All the necessary energetic calculations rely on the electric energy demands which was calculated in **Chapter 6** while expenses estimation based on Table 7.34.

Table 7.35 **LH2 – PEMFC Proposed Scenario**

1st Proposed Topology - P E M F C								
Period	**Installed Power**		F U E L C E L L P L A N T					
			Operation Time Window					Powered-Off
	Value	Unit	Specifications	Seagoing Time	Maneuvering Time	Port Time	Loading At Piraeus	**Overnight At Piraeus**
Sea going , Maneuvering and Port Time	F U E L C E L L		Total Hours	9,20	1,15	1,88	2,00	9,77
	1.250,00	kW	Power Demand (kW)	1.030,20	1.778,80	998,40	998,40	280,50
	Time Window		P E M F C L H 2			Efficiency		0,55
	12,23	hrs	Additional Total Power Demand (kW)	150,00				0,00
	Battery Time Window		Total Power Requirements (kW)	1.180,20	1.928,80	1.148,40	1.148,40	280,50
	1,15	hrs	Energy Supply (kWh)	15.287,50			2.301,77	0,00
Loading Time at Piraeus	F U E L C E L L		Total Energy Supply (kWh)	17.589,27	Total Energy Supply (MJ)	63.321,37	H2 (MJ/kg) - LHV	120,21
	1.150	kW	Total H2 Required (MT)	0,96	H2 Purchase Cost ($/ton)	5.000,00	Total H2 Cost ($/RoundTrip)	4.788,69
	Time Window		L I T H I U M - I O N B A T T E R Y					
	2,00	hrs	**Charging / Discharging Phases**	Seagoing Time	Maneuvering Time	Port Time	Loading At Piraeus	**Overnight At Piraeus**
	Battery Time Window		Power Surplus + , Deficit - (kW)	69,80	-678,80	101,60	2,48	0,00
	2,00	hrs	Charging Efficiency		0,95	Discharging Efficiency		0,98
Overnight at Piraeus	F U E L C E L L		Total Charging Energy (kWh)		796,55	Total Discharging Energy (kWh)		-796,55
	0,00	kW	S H O R E C O N N E C T I O N					
	Time Window		Shore Connection Power Supply (kW)	0,00	0,00	0,00	0,00	280,50
	0,00	hrs	Shore Connection Total Energy Supply (kWh)	0,00	0,00	0,00	0,00	2.740,49
	Battery Time Window		Electric Grid Cost at day time ($/kWh)	0,12	Operating hrs = 0	Electric Grid Cost at night time ($/kWh)	0,07	Operating hrs = 9,77
	0,00	hrs	**Total Expenses for a Shore Connection Energy Supply ($/RoundTrip)**		191,83		Source: EUROSTAT , 2018	
Total Expenses ($/Roundtrip)						4.980,53		

Table 7.36 LNG – MCFC Proposed Scenario

2nd Proposed Topology - M C F C								
Period	**Installed Power**		F U E L C E L L P L A N T					
			Operation Time Window					Powered-Off
	Value	Unit	Specifications	Seagoing Time	Maneuvering Time	Port Time	Loading At Piraeus	**Overnight At Piraeus**
Sea going , Maneuvering and Port Time	F U E L C E L L		Total Hours	9,20	1,15	1,88	2,00	9,77
	1200,00	kW	Power Demand (kW)	1030,2	1778,8	998,4	998,4	280,5
	Time Window		M C F C L N G			Efficiency		0,6
	12,23	hrs	Additional Total Power Demand (kW)	100,00				0,00
	Battery Time Window		Total Power Requirements (kW)	1130,20	1878,80	1098,40	1098,40	280,50
	1,15	hrs	Energy Supply (kWh)	14676,00			2201,77	0
Loading Time at Piraeus	F U E L C E L L		Total Energy Supply (kWh)	16877,77	Total Energy Supply (MJ)	60759,97	LNG (MJ/kg) - LHV	48,62
	1100,88	kW	Total LNG Required (tons)	2,0828	LNG Purchase Cost ($/ton)	415	Total LNG Cost ($/RoundTrip)	864,37
	Time Window		L I T H I U M - I O N B A T T E R Y					
	2,00	hrs	**Charging / Discharging Phases**	Seagoing Time	Maneuvering Time	Port Time	Loading At Piraeus	**Overnight At Piraeus**
	Battery Time Window		Power Surplus + , Deficit - (kW)	69,80	-678,80	101,60	2,48	0,00
	2,00	hrs	Charging Efficiency		0,95	Discharging Efficiency		0,98
Overnight at Piraeus	F U E L C E L L		Total Charging Energy (kWh)		796,55	Total Discharging Energy (kWh)		-796,55
	0	kW	S H O R E C O N N E C T I O N					
	Time Window		Shore Connection Power Supply (kW)	0	0	0	0	280,5
	0	hrs	Shore Connection Total Energy Supply (kWh)	0	0	0	0	2740,485
	Battery Time Window		Electric Grid Cost at day time ($/kWh)	0,119	Operating hrs = 0	Electric Grid Cost at night time ($/kWh)	0,07	Operating hrs = 9,77
	0	hrs	**Total Expenses for a Shore Connection Energy Supply ($/RoundTrip)**		191,83		Source: EUROSTAT , 2018	
Total Expenses ($/Roundtrip)						1056,20		

Table 7.37 LNG – SOFC Proposed Scenario

3rd Proposed Topology - S O F C								
Period	**Installed Power**		F U E L C E L L P L A N T					
			Operation Time Window					Powered-Off
	Value	Unit	Specifications	Seagoing Time	Maneuvering Time	Port Time	Loading At Piraeus	**Overnight At Piraeus**
Sea going , Maneuvering and Port Time	F U E L C E L L		Total Hours	9,20	1,15	1,88	2,00	9,77
	1200,00	kW	Power Demand (kW)	1030,2	1778,8	998,4	280,5	280,5
	Time Window		S O F C L N G			Efficiency		0,65
	12,23	hrs	Additional Total Power Demand (kW)	100,00				0,00
	Battery Time Window		Total Power Requirements (kW)	1130,20	1878,80	1098,40	1098,40	280,50
	1,15	hrs	Energy Supply (kWh)	14676,00			2201,77	0
Loading Time at Piraeus	F U E L C E L L		Total Energy Supply (kWh)	16877,77	Total Energy Supply (MJ)	60759,97	LNG (MJ/kg) - LHV	48,62
	1100,88	kW	Total LNG Required (tons)	1,9226	LNG Purchase Cost ($/ton)	415	Total LNG Cost ($/RoundTrip)	797,88
	Time Window		L I T H I U M - I O N B A T T E R Y					
	2,00	hrs	**Charging / Discharging Phases**	Seagoing Time	Maneuvering Time	Port Time	Loading At Piraeus	**Overnight At Piraeus**
	Battery Time Window		Power Surplus + , Deficit - (kW)	69,80	-678,80	101,60	2,48	0,00
	2,00	hrs	Charging Efficiency		0,95	Discharging Efficiency		0,98
Overnight at Piraeus	F U E L C E L L		Total Charging Energy (kWh)		796,55	Total Discharging Energy (kWh)		-796,55
	0	kW	S H O R E C O N N E C T I O N					
	Time Window		Shore Connection Power Supply (kW)	0	0	0	0	280,5
	0	hrs	Shore Connection Total Energy Supply (kWh)	0	0	0	0	2740,485
	Battery Time Window		Electric Grid Cost at day time ($/kWh)	0,119	Operating hrs = 0	Electric Grid Cost at night time ($/kWh)	0,07	Operating hrs = 9,77
	0	hrs	**Total Expenses for a Shore Connection Energy Supply ($/RoundTrip)**		191,83		Source: EUROSTAT , 2018	
Total Expenses ($/Roundtrip)						989,71		

7.3.3 Lithium-Ion Battery's Operational Profile

The dimensioning of the necessary energy storage system is based on Blue Star Paros' Electric Load Profile and its specific Round Trip (see **§ 6.3.3.1**). With respect to each separate proposed scenario, FC module operates on different energy basis but its power surplus or deficit is managed to be identical for all scenarios. This was achieved by adding 50 more kW, due to extra power demand for LH2 storage and conditioning, to PEMFC's operation during Sea going, Maneuvering and Loading Operations. The main target of LIB's operational profile was to maintain intact the State of Charge (SoC) at the beginning of each round trip. Therefore, each time Blue Star Paros' unberths from Piraeus, its LIB has a SoC of 50%. After a cycle of charging and recharging phases, in which the minimum and maximum SoC is 15,14 % and 97,81 % (values that define battery's SoC operational window) respectively, this energy control system manages to keep battery's depth of discharge at constant levels. For the scope of this thesis a battery's charge and discharge efficiency of 0,98 and 0,95 respectively is speculated. After a series of trials, it was concluded that a LIB of a maximum storage energy of 320 kWh is sufficient to fulfill the abovementioned energy plan and assist Blue Star Paros during its overall operations. Figure 7.66. shows LIB's SoC during Blue Star Paros' Round Trip.

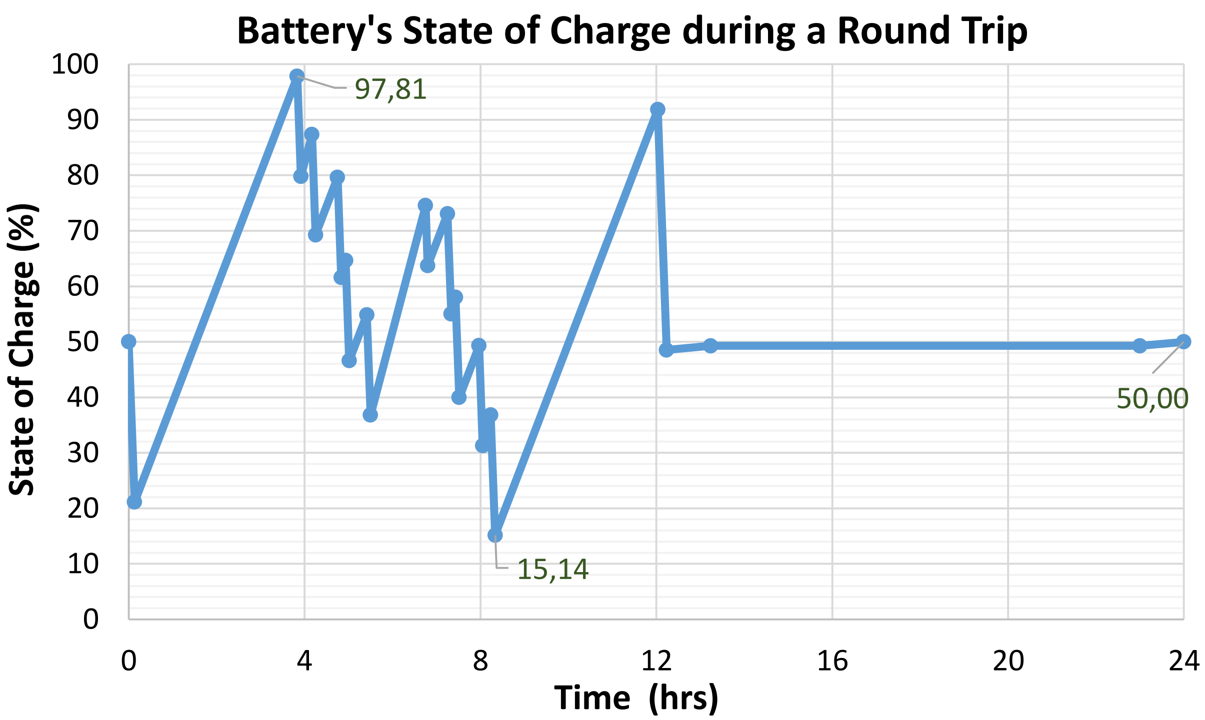


Figure 7.66 Battery's State of Charge during a Round Trip

Table 7.38 **Battery's State of Charge Profile during a Round Trip**

Potential of Storing Electric Energy								Energy Calculations		
Half	Mode of Operation	Time Window	hrs	Power Surplus + Deficit - (kW)	Energy Surplus + Deficit - (kWh)	Effect on Battery (kWh)	Sum(kWh)	**Time of Round Trip (hrs)**	**Bat's Stored Energy (kWh)**	**State of Charge (SoC) %**
1st half of a Round Trip	Maneuvering	0:08	0,13	-678,80	-90,51	**-92,35**	-92,35	**0**	**160**	**50,00**
	Seagoing	3:42	3,70	69,80	258,26	245,35	152,99	0,13	67,65	21,14
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	95,27	3,83	312,99	97,81
	Loading	0:15	0,25	101,60	25,40	24,13	119,40	3,92	255,27	79,77
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	61,68	4,17	279,40	87,31
	Seagoing	0:30	0,50	69,80	34,90	33,16	94,84	4,25	221,68	69,28
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	37,11	4,75	254,84	79,64
	Loading	0:06	0,10	101,60	10,16	9,65	46,77	4,83	197,11	61,60
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	-10,95	4,93	206,77	64,61
	Seagoing	0:24	0,40	69,80	27,92	26,52	15,57	5,02	149,05	46,58
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	-42,15	5,42	175,57	54,87
	Loading	1:15	1,25	101,60	127,00	120,65	78,50	5,50	117,85	36,83
2nd half of a Round Trip	Maneuvering	0:03	0,05	-678,80	-33,94	-34,63	43,87	6,75	238,50	74,53
	Seagoing	0:27	0,45	69,80	31,41	29,8395	73,71	6,80	203,87	63,71
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	15,98	7,25	233,71	73,03
	Loading	0:06	0,10	101,60	10,16	9,652	25,64	7,33	175,98	55,00
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	-32,08	7,43	185,64	58,01
	Seagoing	0:27	0,45	69,80	31,41	29,8395	-2,25	7,52	127,92	39,97
	Maneuvering	0:05	0,08	-678,80	-56,57	-57,72	-59,97	7,97	157,75	49,30
	Loading	0:11	0,18	101,60	18,63	17,70	-42,27	8,05	100,03	31,26
	Maneuvering	0:06	0,10	-678,80	-67,88	-69,27	-111,54	8,23	117,73	36,79
	Seagoing	3:42	3,70	69,80	258,26	245,347	133,81	8,33	48,46	15,14
	Maneuvering	0:12	0,20	-678,80	-135,76	-138,53	-4,72	12,03	293,81	91,82
	Loading	1:00	1,00	2,48	2,48	2,36	-2,36	12,23	155,28	48,53
	Overnight At Piraeus With Cold Ironing							13,23	157,64	49,26
	Rest	9:46	9,77	0	0	0	-2,36	23,00	157,64	49,26
	Loading	1:00	1,00	2,48	2,48	2,36	**0,00**	**24,00**	**160,00**	**50,00**

7.4 Economic Analysis

In the same way that economy is of paramount importance in every aspect of a modern society, so it is significant for the marine transport sector. In an era that growth comes with unparalleled fast rates, the best way to predict the future is to create it. To accomplish this ambition, one's most valuable ammunition is their ability for rational investment assessments. Aim of the present unit is to introduce a methodology specialized for the estimation and prediction of investments' future potential. As this diploma thesis refers to the replacement of a conventional power topology with one of three alternatives, economic analysis focuses on the calculation of numerical results based on validate current price trends, but also by applying sensitivity analysis' tools on crucial sizes it manages to estimate the dynamic position of its option in the near and far future. For the sake of completeness, this unit concludes with economic results that also incorporate external costs for each alternative scenario. To be more specific, in order to extend the pure economic expenses and give them a societal dimension, in the concluding results there is a coalescence of both realistic and societal costs (costs that affect both human health and the environment with its ecosystems). Besides, for the time being, it is a priori known that FC topologies is financially disadvantageous but their incorporation assists, as a general principle, societal and environmental ambitions and not economic prosperity - this will follow thereafter with the expansion of FC technology and Hydrogen supply chain -.

7.4.1 System Boundary

Table 7.39 shows the system boundary which is considered as a scope of LCC in this case study. As shown in Table 7.39, three types of HFC and auxiliary systems for HFC's will be applied to each cycle stage, ie production and installation, operation and recycle for calculation of LCC. As mentioned in **§ 7.3**, Societal Costs are considered expenses of a different dimension that does not directly affect the investors but rather via regulations, laws and social pressure they influence them to navigate to eco-friendlier policies. Therefore, it is a separate monetary index that, as its name suggests, societal – collective action towards society.

Table 7.39 The system boundary of LCC

	Fuel Type	Equipment	Life Cycle Stages			
			Manufacturing & Installation	Operation	Recycle	Societal Costs
Conventional System	Low Sulfur Fuel Oil	LSFO Tank	Production & Installation Cost - including BoP Expenditure (CapEx on board)	LSFO & Lubricant Cost + O&M Cost	Negligible for a 20-year Operation	Monetary conversion of environmental damages from Pollutants' (NO_X, SO_2, PM), CO's and GHGs' emission.
	Lubricant Oil					
HFC Technology	Hydrogen	PEMFC		Operation & Maintenance Cost (OpEx) + Replacement Cost	Platinum	
		MCFC			Neglibile	
		SOFC			Neglibile	
Hybrid Topology's Support System	Hydrogen	Hydrogen Tank		Hydrogen Supply Cost, Storage and Conditioning Cost	-	
	LNG	LNG Tank		LNG Supply Cost, Storage and Conditioning Cost		
	Electricity	Battery		O&M Cost + Replacement Cost	Aluminium, Copper, Nickel & Steel	
		2 x Converters		-	-	
		Inverter		-		
		On-shore Supply	-	Supply Cost		

7.4.1.1 Assumptions & Limitations

As occurs in most of research cases, in order to get results someone has to make assumptions and define study's limitations. In this diploma thesis, the most arduous task of the study was the finding of validate economic data and demarcation of system's boundary. At this preliminary study, having known the peculiarity of its thematology, it was considered a macroscopic view on both the system and economic analysis. This macroscopic view will lay the foundations and construct a basis for future research purposes. Consequently, possible omissions are not a part of misconduction or careless calculations but due to uncertainties that require a more rigorous approach and maybe a better insight into the economic market world (and possibly better social connections for the exact knowledge of current prices and trends).

Taken all these into consideration, the full spectrum of assumptions and limitations of this case study refers to:

1. **LH2 Infrastructure Facility**

   With no known LH2 vessel bunkering facilities in the world, estimating the cost of the facility must be done in a ground-up approach considering the components of the facility. Some of these components have known costs and other have to be estimated from other applications. Two are the most commonly discussed LH2 facilities: **1)** bunkering from *an on-site stationary tank* and **2)** bunkering directly from *a tanker truck or vessel*. In this case, the only difference in cost is due to the on-site storage tank. Because of the similarities in handling LH2 and LNG relative to other fuels, costs for LNG bunkering equipment is used as the starting point.

   The common equipment to both types of facilities is the piping manifold and loading arm. For LNG bunkering this has been estimated to cost $550,000 [The Danish Marine Authority, 2012] and is assumed to be the fully engineered and installed cost complete with all controls and associated civil work (such as foundations, fencing, etc.). As noted in **Chapter 5**, LH2 and LNG have different physical properties, one being the lower boiling point. This means that LH2 pipes are always vacuum jacketed while the standard LNG piping is not.

Standard LNG piping is insulated with a fiberglass or foam glass insulation and a welded steel outer steel jacket. There is a drastic cost difference between foam glass insulation and vacuum jacket. For example, a vacuum jacketed pipe for 150 psi will cost about $1,000/meter while foam glass insulation with stainless pipe would cost about $100-$200/meter. With the assumption that LH2 piping costs a factor of 5-times that of LNG piping, and that of the $550,000 total engineered and installed cost, 10% of this is piping cost. This would give an increased piping cost of $220,000 due to vacuum jacket versus foam insulation and a total cost of $770,000.

For a truck-to-vessel arrangement, this is all the equipment needed assuming the cost associated with the LH2 delivery trailer is borne by the LH2 supplier through the cost of LH2. The total capital cost of the “trailer fill” bunkering station would therefore be $970,000 excluding any pier renovation cost. This compares well with an estimate from one IGC of $800,000-$1,000,000 a complete direct trailer bunkering facility. Because the first facility would have approximately 40% in non-recurring engineering costs, subsequent similar facilities may have costs reduced to $400,000.

For a tank-to-vessel arrangement, the cost of the LH2 tank must be added, assuming all other components are the same. Vendor budgetary estimates were obtained for LH2 tank costs and define a 700.000 $ cost for a 5.350 kg tank of which 66.000 is associated piping costs.

2. **On-shore Supply System**

The calculation of the cost for electricity supply from on-shore suppliers at the Piraeus’ Port is beyond the scope of this diploma thesis and is neglected. Besides, as noted in **§ 7.2.3.2** this cost, as well as LH2 infrastructure facility cost, burdens Piraeus’ authorities and can be managed with national grants or other European funding programmes.

3. **Auxiliary System**

LH2 tank for PEMFC, LNG tanks for MCFC & SOFC, LSFO Tank for conventional system, and battery, inverter, converter are considered. The assumption is that the total capital and installation cost of FCs encompasses Balance of Plant (BoP) expenditure and O&M for fuel cell modules include all the care needed for the conditioning of BoP and relative tanks.

4. Recycling

The assumptions made for the benefits of associated to recycled materials are the following:

A. Scrap Metal Prices ($/kg) is derived from iScrap App National Prices which is a great resource for someone to see the trend of where scrap prices are heading. Depending on the different metals markets, some metals may be on the upward trend while others are on the downward trend. All the following calculations are based on an average values of scar metal prices. Table 7.40 summarizes all the necessary details.

Table 7.40 Recycling monetary benefits

Metal Type	Scrap Metal Price ($/kg)
Copper	2.60 - 3.60
Nickel	5.50 - 6.60
Aluminium	0.25 - 1.50
Lead	0.42 - 1.00
Brass	0.90 - 2.80
Copper Wire	3.60 - 3.90
Steel (Heavy)	0.05 - 0.14
Steel (Stainless)	0.55 - 1.00
Iron	0.04 - 0.08
Titanium	1.40 - 2.00
Gold	8800 - 23460
Silver	130 - 260
Platinum	20140 - 22360
Source : iScrap App National Prices - USA , 2019	

B. Recycling monetary benefits are added at the end of item's design life.

C. PEMFC consists of platinum that is extremely higher in cost than that of other metals included in FC. MCFC and SOFC do not include any platinum; hence, only platinum in PEMFC is considered as recycle benefit (negative cost). The assumption is that the cost of other metals, such as irons would be ignored because of their small portions in FCs and monetary value.

The weight ratio of platinum in a PEMFC is 0,2 g/kW; hence for a 1250 kW system the total weight of platinum is estimated around 0,25 kg. Therefore, PEMFC's recycling benefit is 5312,5 $.

D. For battery recycling, a lithium-ion battery system consists, in weight, of approximately 15% of aluminium, 15% copper, 2% nickel and 2% stainless steel, while other materials are considered to be disposable in response to the manufacturers' manual [Saft, 2014]

A typical Lithium-Ion Battery system with a conventional design weights around 120 kg for a registered capacity of 20,6 kWh. For the purposes of this cases study a LIB of 320 kWh is required; hence the overall weight of LIB's system is estimated around 18.641 kgs.

Table 7.41 LIB's recycling monetary benefit

Total Battery Capacity	kWh	320			
LIB's Weight	kg	18641			
Materials		**Aluminium**	**Copper**	**Nickel**	**Stainless Steel**
Percentage in Weight	-	15%	15%	2%	2%
Weight	kg	279,612	279,612	37,282	37,282
Scrap Metal price	($/kg)	0,875	3,75	6,05	0,775
Recycling benefit	$	244,660	1048,544	225,553	28,893
Total Recyling Benefit	$	1547,650			

E. Diesel Generators have a lifespan of more than 20 years, which is the time schedule of this diploma thesis. Therefore, in spite of having recyclable materials, their monetary benefit is included in overall calculations. However, for completeness purposes, Table 7.42, proposes the recycling monetary benefit for each of Wartsila's 6L20 DG.

Table 7.42 DG's recycling monetary benefit

Engine Material	Weight Ratio (%)	Wartsila 6L20 [b] (8,7 tons)	Scrap Metal Price [a] ($/kg)	Scrap Metal Profit ($)
Steel	40	3,48	0,775	2697
Cast Iron	46	4,002	0,06	240,120
Aluminium	8	0,696	1,75	1218
Copper, Bronze, Brass, Zinc	0,2	0,0174	3,75	65,250
Lead	0,1	0,0087	0,71	6,177
Plastic	0,9	0,0783	0	0
Rubber	0,9	0,0783	0	0
Paints	0,9	0,0783	0	0
Oils and Grease	3	0,261	0	0
Sum	100	8,7	**Total Recycling Profit ($)**	**4226,547**
(a) iScrap App National Prices - USA , 2019 (b) Product Guide Wartsila, 2018				

5. **Applied Prices**

As analytically described in **§ 5.3** for Marine Fuels (LSFO, LH2 & LNG) and **§ 5.4** for Fuel Cell technologies, defining purchase prices lurks many dangers. For harnessing prices' volatility someone has to use economical tools, statistical data and up-to-date information of market trends. As for LH2, the opinions about the estimation future prices are controversial. As happens in every aspect of economy, suppliers glorify their product while undermining competitive. Thus, there are some surveys that suggest a major decline in LH2 prices due to the progressive evolution of hydrogen's production methods with widespread of wind and solar energy and some others that reject every scenario of hydrogen's reduction in cost until 2050 and so due to juristic issues, lack of legal framework.

Furthermore, as highlighted in **§ 5.4.2,** fuel cell market follows the principles of what is known as" Economy of Scale" and as a result, production, delivery and maintenance costs are highly sensitive to the amount of modules produced annually. Conclusively, future projections about prices can provoke unnecessary mismanagement of current data and result in wrong calculations. For the abovementioned reasons, all the calculated future costs based on current prices and values and the only assumption made is the future value of money using an interest rate of 8%.

7.4.2 Life Cycle Cost Analysis

Life Cycle Cost (LCC) is an economic analysis used by evaluating all the costs of an investment of technology over its entire life. Calculation of all the cost is so called LCC methodology, which becomes one of the most commonly used tools to identify the hotspot of projects. By using an economic analysis technique that is known as "discounting", all projected costs would be converted into present dollars and summed to produce net Present Worth Costs (PWC). In this case study, LCC will be expressed by using NPC as its main investment assessment criterion, considering the lifespan of a Ro/Pax ship, ie 20 years. Life Cycle Cost Analysis includes all the expenses that occur during this period as an attempt to pre-estimate the corresponding expenditure and achieve an equilibrium between system's CapEx and OpEx. Most of the times, the objective aim of this analysis is the minimization of system's cycle total cost, without the violation of legal regulations, safety rules and environmental policies. LCCA's modern version has been expanded both conceptually and structurally as, among all the other, it includes the corresponding societal cost with which a technological system affects the environment and human health. This societal cost embodies all the afflicted damage towards our society and ecosystems, from raw materials' mining to processes that involve their delivery, storage and conditioning to finally reach system's decomposition, recycling or disposition of its components in the environment, with intermediate stages concerning pollutant and greenhouse gases emissions from system's operation.

At this diploma thesis there will be two separate indexes. The first will purely involve financial elements and expenses of each scenario while the second refers to what is called "societal" costs as it seems a financial and logical mismanagement to unify them into a solid economic term. The terms of mathematical formula that are used in NPC calculations are defined in Table 7.43.

Table 7.43 **Terms of Mathematical Formula**

Term	Item
C1	Capital and Installation Cost
C2	Operation & Maintenance Cost
C3	Fuel Cost (LSFO , Lubricant, LH2 or LNG)
C4	Electric Supply Cost
C5	Fuel Cell Exchange Stack Cost
C6	Battery's Replacement Cost
C7	Recycling Benefit
C8	Societal Cost

7.4.2.1 The Future Value of Money

The future value of money (along with the interest rate) is an important element for calculation of future financial transactions and forms the backbone of finance. There can be no such things as chronically investment assessment without taken into account the future value of the money.

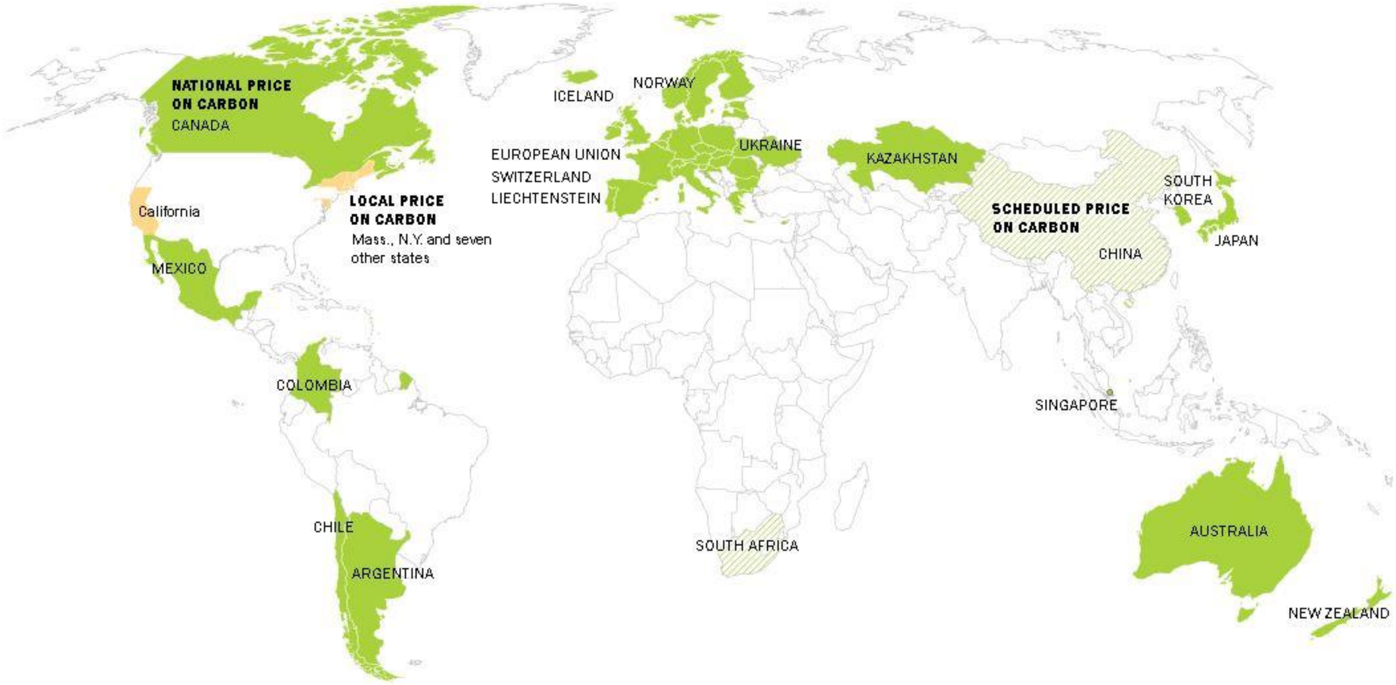
At this diploma thesis, the interest rate (r) of the investment is considered a constant and equals to 8%. Furthermore, the viability of investments will be evaluated for a specific 20-year design life, which is an average design life for a Ro/Pax ship before is decided whether it will be retrofitted, sold or set out of service after its recycling. Therefore, to determine a Present Value (PV) after a number of periods – years - (n) using a Future Value (FV) and a constant interest rate (r), the following formula is used:

$$\mathbf{PV} = \frac{\mathbf{FV}}{(\mathbf{1+r})^{\mathbf{n}}} \qquad \textbf{(7.1)}$$

As an assumption, seasonal costs are calculated at the end of each summer period.

7.4.2.2 Societal Cost

Societal assessment of environmental threats depends upon a variety of factors including physical science-based estimates of the risk of impacts and economic valuation of those impacts. Quantitative estimates of costs associated with particular policy options can inform responses, but such valuations face a myriad of issued, including the choice of which impacts to "internalize" within the economic valuation. However, it is a common practice to explore the economic damages associated with societal costs based on atmospheric release of individual pollutants and GHG gases owing to their effects on climate, air quality and subsequently human health, seas, and ecosystems. Such side effects give rise to various resource costs that can be expressed in monetary terms and exert influence on decision-making policies regarding technological matters [European Commission, 2014].



Picture 7.45 Summary map of regional, national and subnational carbon pricing initiatives [The World Bank, 2019]

As mentioned in **Chapter 1**, air pollution effects in the recent years have become an important policy issue for the European Union. Indeed, more than 40 governments wide have now adopted some sort of price on carbon, either through direct taxes on fossil fuels or through cap-and-trade programs. Economists have long suggested that raising the cost of burning coal, oil and gas can be a cost-effective way to curb on emissions.

However, in practice, most countries have found it politically difficult to set prices that are high enough to spur truly deep reductions [New York Times, 2019]. The phrase put a price on carbon has now become well known with momentum growing among countries and business to put a price on carbon pollution as means of bringing down emissions and drive investment into cleaner technological options. Taken all these into account, and citing the numerical values of European Commission's handbook, a direct link between societal cost and monetary expenses is achieved. Table 7.44 explores the economic damage towards society for each kind of emission [European Commission, 2014].

Table 7.44 Monetary Cost of Atmospheric Release [European Commission, 2014]

Societal Cost of Atmospheric Release (damages per ton of emission in $)						
Regions		**GHGs**	**Pollutants**			
		CO_2	**CO**	**NO_X**	**SO_2**	**PM**
Sea Areas	Mediterranean Sea	21	314	1850	6700	18500
Suburban Areas	EU average	64	483	10640	10241	70258
The main components of emission's total external cost are oriented towards : 1) Human Health, 2) Ecosystem Quality, and 3) Climate Change						
Source: European Commission, "Update of the Handbook on External Costs of Transport", 2014						

At this transitional time period when humanity has to take serious decisions about its future and evolution, fuel cell technology fueled with H2 or LNG supply can prescribe a realistic sustainable development with efficiency while bestowing respects to both humankind and the Earth. The last argument is exactly the driving force behind every logical technological development and of course the stimulation for the rise of Hydrogen Economy and the parallel dawn of Fuel Cell technology.

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7.4.3 LCC of current 3DGs' Topology

Total LCC is calculated utilizing all the necessary information derived from **§ 6.4**, in which there is a detailed analysis of CapEx & OpEx of Blue Star Paros' conventional electric power configuration. At this particular scenario, there is no need for DGs' replacement as their lifespan exceeds the design life of the ship. Based on these conditions, the formula of LCC with Present Worth Cost (PWC) and Societal Present Worth Cost (PWC_S) are identified at the following equations and tables respectively.

Total LCC of DGs' - conventional topology -:

=	PWC (20 years)
=	$PWC_C + PWC_{O\&M} + PWC_{Sp} + PWC_S$
=	C1, Capital and Installation Cost
+	C2, DG's Operation & Maintenance Cost
+	C3, LSFO and Lubricant Oil Supply Cost
+	C8, Societal Cost

Respectively, the PWC formula has the following form:

$$\mathbf{PWC = CapEx + \sum_{t=1}^{n=20} \frac{CF_t}{(1+r)^n}} \quad (7.2)$$

At where,

$$\mathbf{CapEx = C1} \quad (7.3)$$

$$\mathbf{CF_t = C2 + C3} \quad (7.4)$$

Mathematical Formula

For the purposes of LCC calculations a specific form of summation is regularly used. The following formula is cited as a mathematical tool and reminder:

$$\mathbf{\sum_{t=1}^{n} \frac{CF_t}{(1+r)^n} = CF_t \times \frac{(1+r)^n - 1}{r\,(1+r)^n}} \quad (7.5)$$

In accordance with the equations as set forth above, Table 7.45 presents the results.

Table 7.45 Conventional Configuration - Present Worth Cost

3 x Diesel Generator Topology		
Investment's Time Window	years	20
Rate of Interest	r	8,00%
year = 0, Purchase Cost		
D/Gs' + LSFO Tanks CapEx	$	1.228.555,44
Total Summer Period Costs		
Expenses for Lub. Oil	$	1.920,84
Expenses for LSFO	$	318.450,23
Maintenance	$	25.000,00
Total Expenses for a Single Summer Season	$	345.371,07
Present Worth Costs (PWC)		
Present worth of Capital and Installation Cost (PWC_C)	$	1.228.555,44
DGs' Present worth of O&M ($PWC_{DG\_O\&M}$)	$	245.453,69
LSFO and Lub. Oil Supply Cost (PWC_{SP})	$	3.145.450,42
Present worth of O&M ($PWC_{O\&M}$)	$	3.390.904,11
Total Present Worth Cost of a 20-year operation (PWC)	$	4.619.459,55

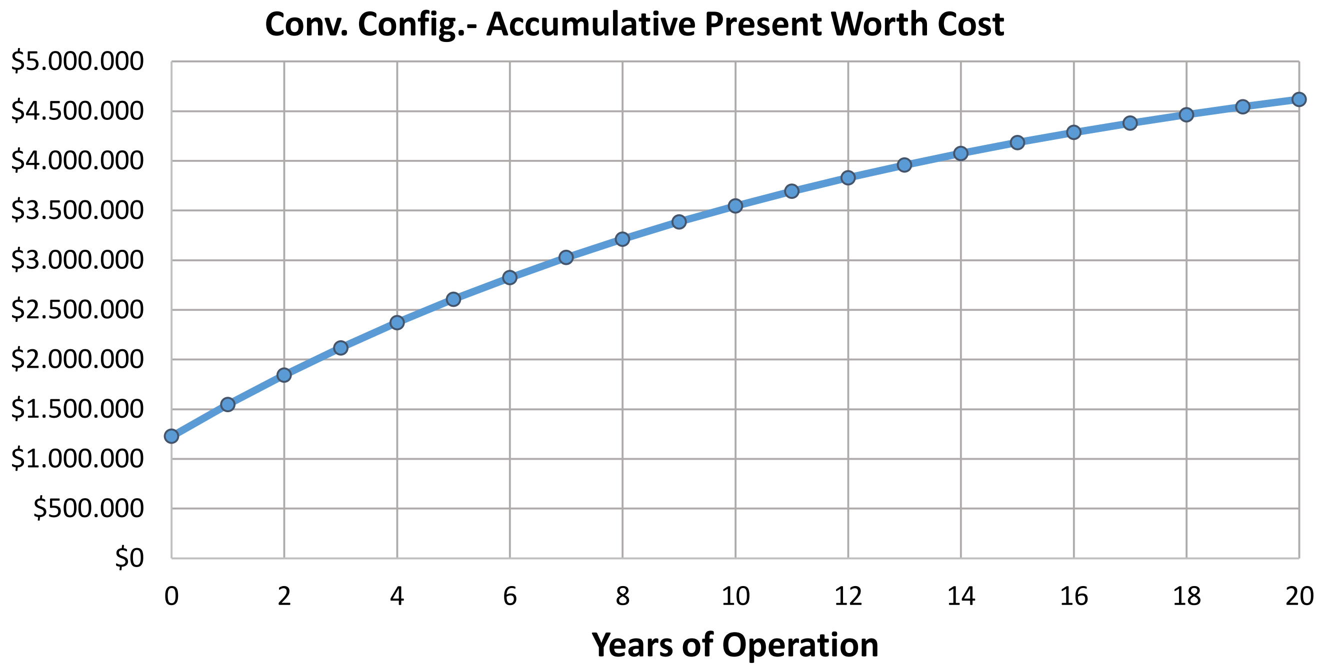


Figure 7.67 **3 DGs - Accumulative Cost over ship's lifespan**

As for the societal costs, these are calculated using the results of **§ 6.3** about pollutants' and GHGs' emissions and **§ 7.3.2.2** for their correspondence monetary terms. Table 7.46 summarizes the results.

Table 7.46 **Conventional Configuration - Present Worth Cost**

3 DGs' Social Cost of Atmospheric Release					
		Single Voyage			
Emissions (kg)	CO_2eq	CO	SO_2	NO_X	PM
Emission due to Operation	11.573,31	27,27	73,72	203,17	8,85
Emission due to Supply Transport and Storage	+ 1208,45	0	0	0	0
		Societal Cost of Atmospheric Release			
$ damages/tons of Emission	CO_2eq Emissions	CO Emissions	SO_2 Emissions	NO_X Emissions	PM Emissions
	20,68	314,06	1.850,00	6.700,00	18.500,00
Societal Damages ($)	264,35	8,57	136,37	1.361,21	163,65
Total Monetary Impact ($)				1.909,16	
Summer Period Societal Costs ($)				**348.147,79**	
Societal Present Worth Cost (PWCs)				**3.766.314,08**	

7.4.4 Fuel Cell Scenarios' LCC

These scenarios consist the core of the analysis. Their LCC values are calculated deploying information described at **§ 7.3**, in which all three scenarios methodologies and components are presented and explained in detail. Furthermore, when it comes to their economic analysis, the existing assumptions and limitations are in accordance with **§ 7.4.1.** Each scenario perspective is represented by three vital tables that collect all the pivotal results of this economic analysis. The first and second table summarize the economic prospect of each scenario while the third links it with its societal dimension using monetary conversion technique based on **§ 7.4.4.2.**

For the purposes of third's table creation, FC's operation is distinguished in three different stages; the first refers to emissions due to fuel supply , the second describes emissions due to supply, transport, storage and conditioning, while the third is relevant to operational emissions. Total results, for a summer period, are calculated and projected to the future to be compared with ones of conventional topology.

Total LCC of FC Scenarios' (LH2 - PEMFC , LNG - MCFC, LNG - SOFC):

= PWC (20 years)

= $PWC_C + PWC_{O\&M} + PWC_{SP}$ (20 years)

= C1, Capital and Installation Costs of FCs and Hybrid System's Components

\+ C2, FC's & LIB's Operation & Maintenance Cost

\+ C3, Fuel (LH2 or LNG) Supply Cost

\+ C4, Electricity Supply Cost

\+ C5, FC's Replacement Cost; PEMFC, MCFC, SOFC every 7 , 9 and 13 respectively.

\+ C6, LIB's Replacement Cost; every 6 years

\- C7, Recycling Benefit; at the end of item's design life

\+ C8, Societal Cost

Accordingly, the PWC formulas are:

$$\mathbf{PWC = CapEx + \sum_{t=1}^{n=20} \frac{CF_t}{(1 + r)^n}} \tag{7.6}$$

at where,

$$\mathbf{CapEx = C1} \tag{7.7}$$

Seasonal Costs CF_t alternate due to differentiation in time of replacement of each FC technology. The related equations of seasonal Costs, for each alternative scenario, are presented thereafter. Note that the recycling cost is negative (because its beneficial for cost assessments) and contributes at the end of item's design life.

A. LH2 - PEMFC's Scenario

$$\begin{aligned} &CF_t\ (t \neq 6{,}7{,}12{,}18{,}20) = C2 + C3 + C4 \\ &CF_t\ (t = 6{,}12{,}18) = C2 + C3 + C4 + (C5 + C6 - C7) \\ &CF_t\ (t = 7{,}14) = C2 + C3 + C4 + (C5) \\ &CF_t(t = 20) = C2 + C3 + C4 \end{aligned} \tag{7.8}$$

B. LNG - MCFC's Scenario

$$\begin{aligned} &CF_t(t \neq 6{,}9{,}12{,}18{,}20) = C2 + C3 + C4 \\ &CF_t\ (t = 6{,}12{,}18) = C2 + C3 + C4 + (C6 - C7) \\ &CF_t\ (t = 9{,}18) = C2 + C3 + C4 + (C5) \\ &CF_t(t = 20) = C2 + C3 + C4 \end{aligned} \tag{7.9}$$

C. LNG - SOFC's Scenario

$$\begin{aligned} &CF_t(t \neq 6{,}12{,}13{,}18{,}20) = C2 + C3 + C4 \\ &CF_t\ (t = 6{,}12{,}18) = C2 + C3 + C4 + (C6 - C7) \\ &CF_t\ (t = 13) = C2 + C3 + C4 + (C5) \\ &CF_t(t = 20) = C2 + C3 + C4 \end{aligned} \tag{7.10}$$

7.4.4.1 LH2 Powered – PEMFC LCC

Table 7.48 PEMFC Scenario – Summary of Costs

PEMFC LH2: All-expenses-sheet		
Aspect	Unit	Value
CapEx Costs		
PEMFC's cost per unit	$/kW	1.900,00
PEMFC's installation Unit	kW	1.250
PEMFC's CapEx	$	2.375.000,00
LH2 Tanks	$/kg LH2 Stored	84,69
LH2 Fuel Tolerance	-	0,10
LH2 Storage Tanks CapEx	$	89.217,71
Battery's cost per unit	$/kW	250,00
Battery's Capacity	kWh	320,00
Battery's CapEx	$	80.000,00
(2x) Converters' CapEx	$	67.967,45
Inverter's CapEx	$	385.760,00
Total CapEx	$	2.997.945,16
OpEx Costs for a Round Trip		
Total H2 supply	ton	0,96
H2 Fuel Oil Cost	$/ton	5.000,00
Total Expenses for H2	$	4.788,69
PEMFC'S Time Window	hrs	14,23
Shore Connection Energy Supply	kWh	2.740,49
Electric Grid Cost at night time	$/kWh	0,07
Total Expenses for Shore Electric Energy Supply	$	191,83
Total Round Trip Expense	$/RoundTrip	4.980,53
Total Summer Period Costs		
Number of Round Trips during a Summer Season	-	180,00
Total Running Expenses for a complete Season	$	896.494,85
PEMFC'S Maintentance Cost	$/kW/year	70,00
Total PEMFC's Operation	hrs	2.561,40
Maintenance Expense	$	87.500,00
Total Expenses for a Single Summer Season	**$**	**983.994,85**

Table 7.47 PEMFC Scenario – Economic Outlook

PEMFC LH2: Economic Perspective		
Investment's Time Window	years	20
Rate of Interest	r	0,08
year = 0, Purchase Cost		
PEMFC's CapEx	$	2.375000,00
LH2 Tanks CapEx	$	89.217,71
Battery's CapEx	$	80.000,00
Converters' CapEx	$	67.967,45
Inverter's CapEx	$	385.760,00
Total CapEx	$	2.997.945,16
Total Summer Period Costs		
H2's Cost	$	861.964,74
PEMFC'S Maintenance	$	91.000,00
Shore Electric Supply	$	34.530,11
Total Expenses for a Single Summer Season	$	983.994,85
PEMFC Unit Replacement		
PEMFC'S Total Time Operation per season	hrs	2.561,40
PEMFC'S Life Expectancy	hrs	20.000,00
Total Periods of Operation	years	7
PEMFC's CapEx	$	2.375.000,00
Battery's Replacement		
Battery's Life Expectancy	years	6
Battery's CapEx	$	80.000,00
Present Worth Costs (PWC)		
PEMFC'S	$	4.569.384,66
Battery's	$	182.202,59
Present worth of Capital Cost (PWC_C)	$	5.294.532,42
PEMFC'S Maintentance Cost	$	859.087,90
H2 and Electric Energy Cost	$	8.801.918,58
Present worth of Cost of O&M (PWC_{OM})	$	9.661.006,48
Present Worth Cost of LIB's Recycling	$	1.977,17
Present Worth Cost of PEMFCs Recycling	$	4.908,49
Total Present Worth Cost of a 20-year operation	**$**	**14.948.653,23**
Current Topology of 3 D/Gs		
Current Topology of 3 D/Gs, PWC	$	4.619.459,55
PEMFC, Battery and Shore Connection	$	14.948.653,23
Difference	***$***	***-10.329.193,68***

Comments

As it can be seen from the above tables, PEMFC scenario is economically exceptionally disadvantageous when compared to the conventional 3-DGs' configuration. The main reason behind this result is hydrogen's high purchase cost, which is averagely 10 times greater than of conventional fossil fuels, and as a result skyrockets system's operational costs . Another parameter that deteriorates PEMFC scenario is the short lifespan of PEMFC technology. As a result, for a timetable of 20 years of operation, there is a need for two PEMFC's replacements, and combining that with their high production and installation costs their competitiveness falls short when compared to conventional topologies. What is more, breaking down H2 and Electric Energy cost, it is calculated that only 339.021 $ or 0,0385% of the total "fuel" supply cost is due to on-shore electric energy supply.

However, in the decades to come, there will be a decline in both hydrogen's price and PEMFC's production cost. Hence, it is beneficial to project our calculations in both short or long future, in an era where scientific community would have accomplished its FC targets. For this reason, at the following chapter (**§ 7.5.1**), in an effort to investigate PEMFC's future economic potential, a biparametric sensitivity analysis is conducted in order to determine the conditions, under those, PEMFC's scenario presents economic prosperity.

In continuation of the abovementioned economic results, Table 7.49 summarizes PEMFC scenario's potential societal impact and benefit.

Table 7.49 PEMFC Scenario – Societal Cost

PEMFC - Societal Cost of Atmospheric Release					
Single Voyage					
Total Electric Energy Supply from Piraeus Grid			2.740,49	kWh	
gr/kWh Electricity	CO_2eq	CO	SO_2	NO_X	PM
Supply Factor (On Shore Wind Power)	32,45	-	-	-	-
Emissions (tons)	0,09	-	-	-	-
Total LH_2 Fuel Supply		0,96		tons	
		115.129,76		MJ	
Emissions due to Supply, Transport, Storage and Conditioning					
gr/MJ Fuel	CO_2eq	CO	SO_2	NO_X	PM
Fuel Supply Factor	102,00	-	-	-	-
Emissions (tons)	11,74	-	-	-	-
Emissions due to Operation					
Emissions (tons)	-	-	-	-	-
Societal Cost of Atmospheric Release					
$ damages/tons of emission	CO_2eq	CO	SO_2	NO_X	PM
	20,68	314,06	1.850,00	6.700,00	18.500,00
Total Emissions (tons)	11,83	-	-	-	-
Total Societal Damages ($)	244,71	-	-	-	-
Total Emissions from DGs' Topology (tons)	11,5733	0,0273	0,0737	0,2032	0,0088
Summer Period					
Emissions Abatement (tons)	CO_2eq	CO	SO_2	NO_X	PM
	-46,5942	4,9094	13,2688	36,5700	1,5923
Reduction in Percentage	-2,24%	100,00%	100,00%	100,00%	100,00%
PEMFC - Summer Period Societal Costs ($)			44.048,31		
Total Monetary Societal Earnings from MCFC's Operation					
Societal Present Worth Cost (PWCs) of MCFC ($)			**476.521,07**		
Societal Present Worth Cost (PWCs) of Current Topology - 3 D/Gs ($)			**3.717.645,81**		
Societal "Earnings" ($)			**3.241.124,74**		

Comments

Since PEMFC is a zero-emission electric device, societal earnings interlinked with its operation is particularly high. The only aspect that contributes to societal cost is electricity's supply and hydrogen's supply, transport, storage and conditioning. If the methods associated with the abovementioned features are technologically developed in the near future (particularly hydrogen's production through electrolysis from wind or solar power) PEFC will be the technology with the least carbon footprint and greatest societal benefits.

7.4.4.2 LNG Powered – MCFC LCC

Table 7.50 **MCFC Scenario: Summary of Costs**

M C F C L N G: All-expenses-sheet		
Aspect	Unit	Value
CapEx Costs		
MCFC's cost per unit	$/kW	3.750,00
MCFC's installation Unit	kW	1.200,00
MCFC's CapEx	$	4.500.000,00
LNG Tanks	$/kg LNG Stored	8,50
LNG Fuel Tolerance	-	0,10
LNG Storage Tanks CapEx	$	19.474,35
Battery's cost per unit	$/kW	250,00
Battery's Capacity	kWh	320,00
Battery's CapEx	$	80.000,00
(2x) Converters' CapEx	$	67.176,84
Inverter's CapEx	$	375.760,00
Total CapEx	$	5.042.411,19
OpEx Costs for a Round Trip		
Total LNG supply	ton	2,08
LNG Fuel Oil Cost	$/ton	415,00
Total Expenses for LNG	$	864,37
MCFC'S Time Window	hrs	14,23
Shore Connection Energy Supply	kWh	2.740,49
Electric Grid Cost at night time	$/kWh	0,07
Total Expenses for Shore Electric Energy Supply	$	191,83
Total Round Trip Expense	$/RoundTrip	1.056,20
Total Summer Period Costs		
Number of Round Trips during a Summer Season	-	180,00
Total Running Expenses for a complete Season	$	190.116,61
MCFC'S Maintentance Cost	$/kW/year	70,00
Total MCFC's Operation	hrs	2.561,40
Maintenance Expense	$	84.000,00
Total Expenses for a Single Summer Season	**$**	**274.116,61**

Table 7.51 **MCFC Scenario: Economic Outlook**

M C F C L N G: Economic Perspective		
Investment's Time Window	years	20,00
Rate of Interest	r	0,08
year = 0, Purchase Cost		
MCFC's CapEx	$	4.500.000,00
Battery's CapEx	$	80.000,00
LNG Storage Tanks CapEx	$	19.474,35
(2x) Converters' and Inverter's CapEx	$	442.936,84
Total CapEx	$	5.042.411,19
Total Summer Period Costs		
LNG's Cost	$	155.586,50
MCFC'S Maintenance	$	84.000,00
Shore Electric Supply	$	34.530,11
Total Expenses for a Single Summer Season	$	274.116,61
MCFC Unit Replacement		
MCFC'S Total Time Operation per season	hrs	2.561,40
MCFC'S Life Expectancy	hrs	25.000,00
Total Periods of Operation	years	9
MCFC's CapEx	$	4.500.000,00
Battery's Replacement		
Battery's Life Expectancy	years	6
Battery's CapEx	$	80.000,00
Present Worth Costs (PWC)		
MCFC'S	$	7.877.240,98
Battery's	$	182.202,59
Present worth of Capital Cost (PWC_C)	$	8.521.854,77
MCFC'S Maintenance Cost	$	824.724,38
LNG and Electric Energy Cost	$	1.866.592,95
Present worth of O&M Cost (PWC_{OM})	$	2.691.317,33
Present Worth Cost of LIB's Recycling	$	1.977,17
Total Present Worth Cost of a 20-year operation	**$**	**11.211.194,92**
Current Topology of 3 D/Gs		
Current Topology of 3 D/Gs, PWC	$	4.619.459,55
MCFC, Battery and Shore Connection	$	11.211.194,92
Difference	***$***	***-6.591.735,37***

Comments

As it can be seen from the above tables, despite the fact that MCFC's scenario is economically costlier comparing to conventional 3 DGs' topology, is still preferable when examined in contrast to PEMFC's scenario. This result is a synthesis of many factors. The first of all is LNG's supply cost which is at the same levels of LSFO ,and consequently, around 10 times less than that of hydrogen. Furthermore, LH2 tanks cost more than LNG ones, while their operating expenses are also higher due to disadvantageous storage properties of LH2 comparing to LNG.

At today's status, for this particular case study, MCFC scenario is $6.591.735 costlier than the conventional. As described in PEMFC's scenario, precisely because FC technology is a new technological and business venture, it is purposeful to investigate its future economic potential. This time round, sensitivity analysis has one parameter that examines MCFC's capital cost reduction, which is the main obstacle in the way of MCFC's expansion.

In continuation of the abovementioned economic results, Table 7.52 summarizes MCFC scenario's potential societal impact and benefit.

Table 7.52 MCFC Scenario – Societal Cost

MCFC - Societal Cost of Atmospheric Release					
Single Voyage					
Total Electric Energy Supply from Piraeus Grid			2.740,49	kWh	
gr/kWh Electricity	CO_2eq	CO	SO_2	NO_X	PM
Supply Factor (On Shore Wind Power)	32,45	-	-	-	-
Emissions (tons)	0,09	-	-	-	-
Total LNG Fuel Supply		2,08		tons	
		101.266,61		MJ	
MCFC's Energy Supply		16,88		MWh	
Emissions due to Supply, Transport, Storage and Conditioning					
gr/MJ Fuel	CO_2eq	CO	SO_2	NO_X	PM
Fuel Supply Factor	19,59	-	-	-	-
Emissions (tons)	1,98	-	-	-	-
Emissions due to Operation					
E.F. gr/MWh	CO_2eq	CO	SO2	NO_X	PM
	445.500,00	20,10	0,05	4,54	0,01
Emissions (tons)	7,51904583	0,00033924	0,00000076	0,00007663	0,00000015
Societal Cost of Atmospheric Release					
$ damages/tons of emission	CO_2eq	CO	SO_2	NO_X	PM
	20,68	314,06	1.850,00	6.700,00	18.500,00
Total Emissions (tons)	9,50285873	0,00033924	0,00000076	0,00007663	0,00000015
Total Societal Damages ($)	155,51	0,11	0,00	0,51	0,00
		0,0273			
Total Emissions from DGs' Topology (tons)	11,5733		0,0737	0,2032	0,0088
Summer Period					
Emissions Abatement (tons)	CO_2eq	CO	SO_2	NO_X	PM
	372,6807	4,8484	13,2686	36,5562	1,5922
Reduction in Percentage	17,89%	98,76%	100,00%	99,96%	100,00%
MCFC - Summer Period Societal Costs ($)				28.103,95	
Total Monetary Social Earnings from MCFC's Operation					
Societal Present Worth Cost (PWCs) of MCFC ($)				304.032,73	
Societal Present Worth Cost (PWCs) of Current Topology - 3 D/Gs ($)				3.717.645,81	
Societal "Earnings" ($)				**3.413.613,09**	

Comments

As observed from the previous table, MCFC's operational emissions mainly refer to CO_2eq while CO, SO_2, NO_X, and PM present an almost-zero behavior. Furthermore, emissions due to supply, transport, storage and conditioning are almost negligible comparing with those of hydrogen.

7.4.4.3 LNG Powered – SOFC LCC

Table 7.54 SOFC Scenario: Summary of Costs

SOFC LNG: All-expenses-sheet		
Aspect	Unit	Value
CapEx Costs		
SOFC's cost per unit	$/kW	4.000,00
SOFC 's installation Unit	kW	1.200,00
SOFC's CapEx	$	4.800.000,00
LNG Tanks	$/kg LNG Stored	8,50
LNG Fuel Tolerance	-	10%
LNG Storage Tanks CapEx	$	17.976,32
Battery's cost per unit	$/kW	250,00
Battery's Capacity	kWh	320,00
Battery's CapEx	$	80.000,00
(2x) Converters' CapEx	$	67.176,84
Inverter's CapEx	$	375.760,00
Total CapEx	$	5.340.913,16
OpEx Costs for a Round Trip		
Total LNG supply	ton	1,92
LNG Fuel Oil Cost	$/ton	415,00
Total Expenses for LNG	$	797,88
SOFC'S Time Window	hrs	14,23
Shore Connection Energy Supply	kWh	2.740,49
Electric Grid Cost at night time	$/kWh	0,07
Total Expenses for Shore Electric Energy Supply	$	191,83
Total Round Trip Expense	$/RoundTrip	989,71
Total Summer Period Costs		
Number of Round Trips during a Summer Season	-	180,00
Total Running Expenses for a complete Season	$	178.148,42
SOFC'S Maintentance Cost	$/kW/year	75,00
Total SOFC's Operation	hrs	2.561,40
Maintenance Expenses	$	90.000,00
Total Expenses for a Single Summer Season	**$**	**268.148,42**

Table 7.53 SOFC Scenario: Economic Outlook

SOFC LNG: Economic Perspective		
Investment's Time Window	years	20,00
Rate of Interest	r	0,08
year = 0, Purchase Cost		
SOFC's CapEx	$	4.800.000,00
Battery's CapEx	$	80.000,00
LNG Storage Tanks CapEx	$	17.976,32
(2x) Converters' and Inverter's CapEx	$	442.936,84
Total CapEx	$	5.340.913,16
Total Summer Period Costs		
LNG's Cost	$	143.618,31
SOFC'S Maintenance	$	90.000,00
Shore Electric Supply	$	34.530,11
Total Expenses for a Single Summer Season	$	268.148,42
SOFC Unit Replacement		
SOFC'S Total Time Operation per season	hrs	2.561,40
SOFC'S Life Expectancy	hrs	35.000,00
Total Periods of Operation	years	13
SOFC's CapEx	$	4.800.000,00
Battery's Replacement		
Battery's Life Expectancy	years	6
Battery's CapEx	$	80.000,00
Present Worth Costs (PWC)		
SOFC'S	$	6.564.950,04
Battery's	$	182.202,59
Present worth of Capital Cost (PWCC)	$	7.208.065,79
SOFC's Maintenance Cost	$	883.633,27
LNG and Electric Energy Cost	$	1.749.087,47
Present worth of O&M Cost (PWC_{OM})	$	2.632.720,73
Present Worth Cost of LIB's Recycling	$	1.977,17
Total Present Worth Cost of a 20-year operation	**$**	**9.838.809,35**
Current Topology of 3 D/Gs		
Current Topology of 3 D/Gs, PWC	$	4.619.459,55
SOFC, Battery and Shore Connection	$	9.838.809,35
Difference	***$***	***- 5.219.349,80***

Comments

As can be extracted from the aforementioned tables, SOFC technology is the most promising, in economic terms, among other FCs. The main reason behind its supremacy is based on its electrolyte's more endurant nature that has recorded a lifespan of 35.000 hours of operation. Consequently, for the purposes of this case study, SOFC technology requires only one replacement heading its economic potential to new heights.

However, for this particular case study, SOFC scenario is still $5.219.349 costlier than conventional. As described in MCFC's scenario, precisely because FC technology is a new technological and business venture, it is purposeful to investigate its future economic potential. Its sensitivity analysis focuses on one parameter that examines SOFC's capital cost reduction, which is the main obstacle in the way of SOFC's expansion.

As for SOFC scenario's societal results, Table 7.55 summarizes all the necessary results.

Table 7.55 SOFC Scenario - Societal Cost

SOFC - Societal Cost of Atmospheric Release					
Single Voyage					
Total Electric Energy Supply from Piraeus Grid		2.740,49		kWh	
gr/kWh Electricity	CO_2eq	CO	SO_2	NO_x	PM
Supply Factor (On Shore Wind Power)	32,45	-	-	-	-
Emissions (tons)	0,09	-	-	-	-
Total LNG Fuel Supply		1,92		tons	
		93.476,87		MJ	
SOFC's Energy Supply		16,88		MWh	
Emissions due to Supply, Transport, Storage and Conditioning					
gr/MJ Fuel	CO_2eq	CO	SO_2	NO_x	PM
Fuel Supply Factor	19,59	-	-	-	-
Emissions (tons)	1,83	-	-	-	-
Emissions due to Operation					
E.F. gr/MWh	CO_2eq	CO	SO_2	NO_x	PM
	342.000,00	15,40	0,00	0,77	0,00
Emissions (tons)	5,772197	0,000260	0,000000	0,000013	0,000000
Societal Cost of Atmospheric Release					
$ damages/tons of emission	CO_2eq Emissions	CO Emissions	SO_2 Emissions	NO_x Emissions	PM Emissions
	20,68	314,06	1.850,00	6.700,00	18.500,00
Total Emissions (tons)	7,603409	0,000260	0,000000	0,000013	0,000000
Total Societal Damages ($)	119,38	0,08	0,00	0,09	0,00
Total Emissions from DGs' Topology (tons)	11,5733	0,0273	0,0737	0,2032	0,0088
Summer Period					
Emissions Abatement (tons)	CO_2eq	CO	SO_2	NO_x	PM
	714,58	4,86	13,27	36,57	1,59
Reduction in Percentage	34,30%	99,05%	100,00%	99,99%	100,00%
SOFC - Summer Period Societal Costs ($)				21.518,87	
Total Monetary Social Earnings from SOFC's Operation					
Societal Present Worth Cost (PWCs) of SOFC				**232.794,30**	
Societal Present Worth Cost (PWCs) of Current Topology - 3 D/Gs				**3.717.645,81**	
Societal "Earnings" ($)				**3.484.851,51**	

Comments

As observed from the previous table, when it comes to environmental issues, SOFC's behavior is similar to MCFC's. Accordingly, the vast majority of its emissions mainly refer to CO_2eq while CO, SO_2, NO_x, and PM present an almost-zero behavior

7.4.5 Summary of Results

At this section, an overview of results will be presented referring to abovementioned scenarios of configurations and operational profile. The best way to assess and compare alternative scenarios is when their results are projected on diagrams and summarized in tables. On this basis, a collection of diagrams and a pair of tables are presented; covering both economic and environmental topics.

At first, Table 7.56 separates CapEx, O&M Costs, Recycling benefits to finally calculate the difference in PWCs of different scenarios.

Table 7.56 PWC Comparison of Alternative Scenarios

Component	Conventional Current Topology	Fuel Cell and Battery Topology		
	3 Diesel Generators	PEMFC & LIB	MCFC & LIB	SOFC & LIB
Present Worth of Capital Cost (PWC_C)	$1.228.555	$5.519.779	$8.521.854	$7.208.065
Present Worth of O&M Cost (PWC_{OM})	$3.390.904	$9.695.370	$2.691.317	$2.632.720
Present Worth of Recycling Benefit	-	$6.885	$1.977	$1.977
Present Worth of Cost (PWC)	$4.619.459	$14.948.653	$11.211.194	$9.838.809
Difference (PWC)	-	$ -10.329.194	$ -6.591.735	$ -5.219.350

Accordingly, Figure 7.68 presents accumulative Present Worth of Cost for each scenario for ship's 20-year lifespan .

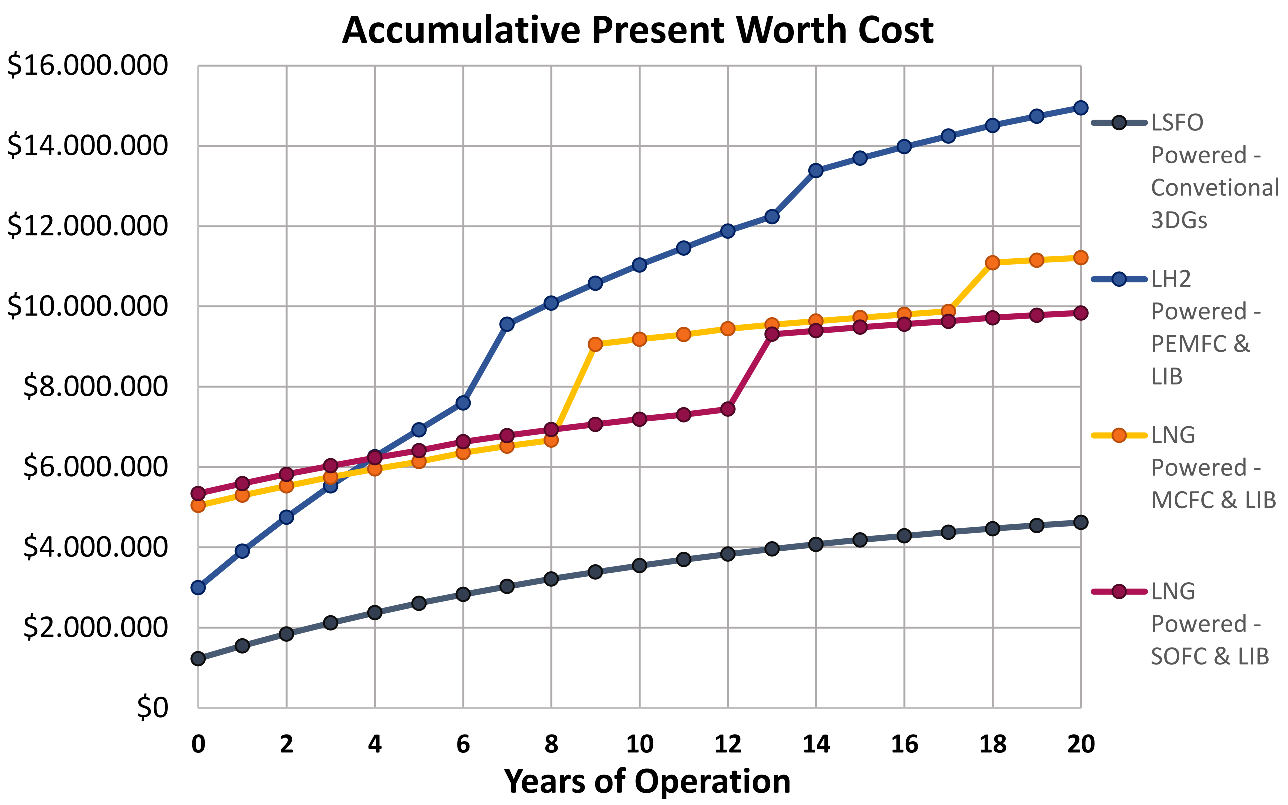


Figure 7.68 Accumulative PWC of Alternative Scenarios

Comments

As observed from Figure 7.68 with current technological status, conventional topology is by far a lot more economical than any FC and LIB scenario. In this case, both CapEx and OpEx costs are particularly reduced compared to those of FC technologies . Among FC technologies, the lowest in CapEx is PEMFC scenario. However, its O&M costs, due to hydrogen's particularly high prices, take its toll on its competitiveness as by the end of 4th year and thereon it becomes the most expensive alternative solution (due to steeper increase in $PWC_{O\&M}$). After 20 years of ship's operation, SOFC presents the greatest economic potential of the FC technologies, but this is not enough when competing against conventional topology which offers an additional potential benefit of $5.219.350. Furthermore, as it is evident from the above illustrative figure, the main drawback of FC technologies is its short lifetime compared to conventional power systems (Diesel Generators have a lifetime of 25 or more years) which results in frequent replacements of their unit, a fact that in a reasonable period of time makes their performance costlier.

Table 7.57 Present Worth of Costs Breakdown

Present Worth of Costs Breakdown	Conventional Configuration	LH2 Powered - PEMFC & LIB	LNG Powered - MCFC & LIB	LNG Powered - SOFC & LIB
PWC of CapEx (Purchase & Installation Costs + Replacement Costs if necessary)	1.228.555	5.294.532	8.521.855	7.208.066
Fuel Cells Capex		4.569.385	7.877.241	6.564.950
LIB Capex		182.203	182.203	182.203
(2x) Converters' & Inverter's CapEx		453.727	442.937	442.937
Fuel Tanks	4.555	89.218	19.474	17.976
PWC of OpEx ("Fuel" Costs + Maintenance Costs)	3.390.904	9.661.006	2.691.317	2.632.721
Fuel Supply	3.145.450	8.462.897	1.527.571	1.410.066
Electric Energy Supply		339.022	339.022	339.022
Maintenance	245.454	859.088	824.724	883.633
Total PWC	4.619.460	14.948.653	11.211.195	9.838.809
Recycling Benefit	0	6.886	1.977	1.977
from LIB		1.977	1.977	1.977
from FC Module		4.908	0	0
*** All numbers included represent costs expressed in $USD				

Table 7.58 CapEx & OpEx Breakdown

CapEx & OpEx Breakdown	Conventional Configuration	LH2 Powered - PEMFC & LIB	LNG Powered - MCFC & LIB	LNG Powered - SOFC & LIB
OpEx Share	73,4%	64,6%	24,0%	26,8%
CapEx Share	26,6%	35,4%	76,0%	73,2%
Proposed Scenarios	**LH2 Powered - PEMFC & LIB**	**LNG Powered - MCFC & LIB**	**LNG Powered - SOFC & LIB**	
CapEx Breakdown				
Fuel Cells	86,30%	92,44%	91,08%	
LIB	3,44%	2,14%	2,53%	
LIB Replacement (times)	3	3	3	
(2x) Converters & Inverter	8,57%	5,20%	6,15%	
Fuel Tanks	1,69%	0,23%	0,25%	
FC replacement (times)	2	2	1	
OpEx Breakdown				
Fuel Supply	87,60%	56,76%	53,56%	
Maintenance	8,89%	30,64%	33,56%	
Electric Energy Supply	3,51%	12,60%	12,88%	

Tables 7.57 & 7.58 offer a breakdown of the costs included in LCC analysis. It is worth noticing that in LH2-PEMFC scenario OpEx share is greater (64,6%) than that of CapEx (35,5%), a fact that justifies this scenarios' steeper increase in accumulative costs during its service. On the contrary, in both MCFC and SOFC scenarios, CapEx dominates the total Present Worth of Costs, with an average share of 74,6 which explains the slow rates of increase in their accumulative costs that is particularly significant when their FC installation requires a replacement.

Introducing environmental aspects in alternatives' comparison, Table 7.59 shows overall results covering both direct PWC values and indirect – environmental ones. We observe that even when the two PWCs' are added, the conventional configuration is still optimum in economic terms. However, as it was analyzed in **§ 7.4.2.2**, adding these two PWC is not the best practice as the first refers to expenses that burden investors' side while the second connects technology's atmospheric damages with its societal dimension using monetary terms.

Table 7.59 Summary of PWC & PWSC of Alternative Scenarios

Emissions (tons)	Conventional Current Topology	Fuel Cell and Battery Topology		
	3 Diesel Generators	PEMFC & LIB	MCFC & LIB	SOFC & LIB
CO_2	2.300,7159	2.129,7895	1.710,5146	1.368,6136
CO_2 due to Operation	2.083,1953	0	1.353,4282	1.038,9954
CO_2 due to Supply,Transport, Storage & Conditioning of Fuel	217,5207	2.129,7895	357,0864	329,6181
NOx	36,5700	0,0000	0,0138	0,0023
SO_2	13,2688	0,0000	0,0001	0,0000
PM	1,5923	0,0000	0,0000	0,0000
CO	4,9094	0,0000	0,0611	0,0468
ECONOMIC PERSPECTIVE				
Indirect PWC - Enviromental Damages ($)	3.766.314	476.521,07	304.032	232.794
Direct PWC - LCC ($)	4.619.459	$14.948.653	11.211.194	9.838.809
Overall PWC ($)	8.385.773	15.425.174,	11.515.227	10.071.603
Difference	0	-7.088.068	-3.178.122	-1.734.498

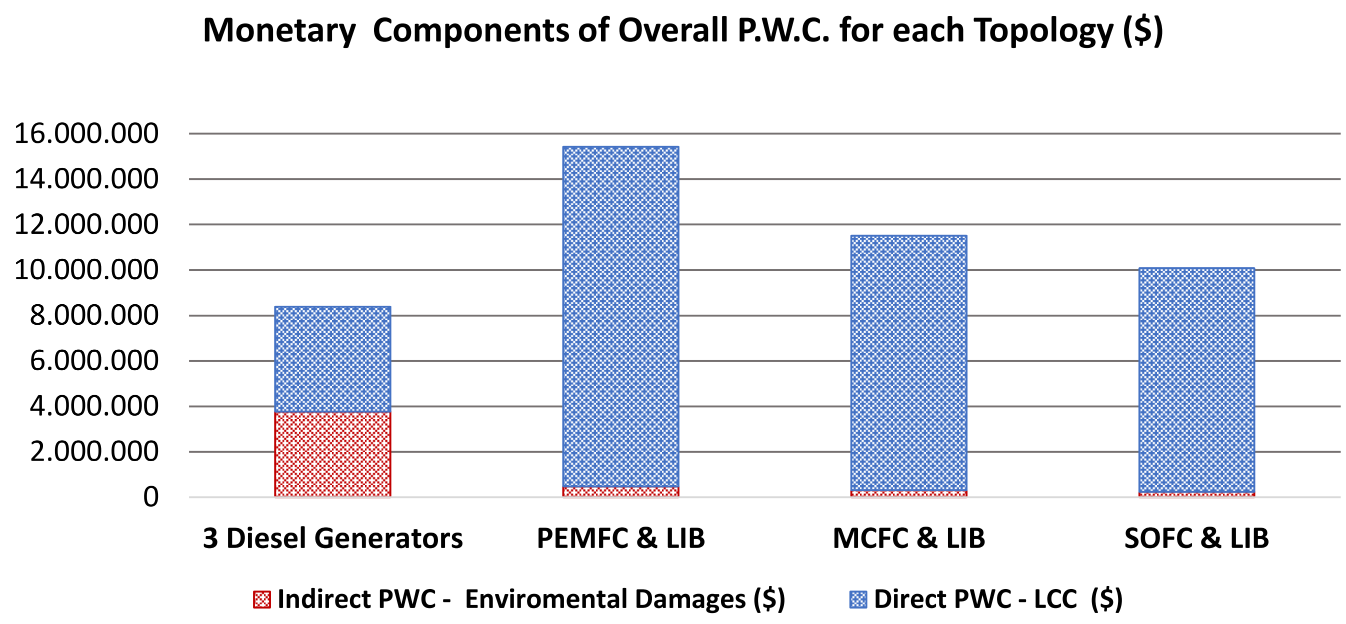


Figure 7.69 **PWC & PWSC of Alternative Scenarios**

Correspondingly, Figures 7.70 & 7.71 display different scenarios' emission rates.

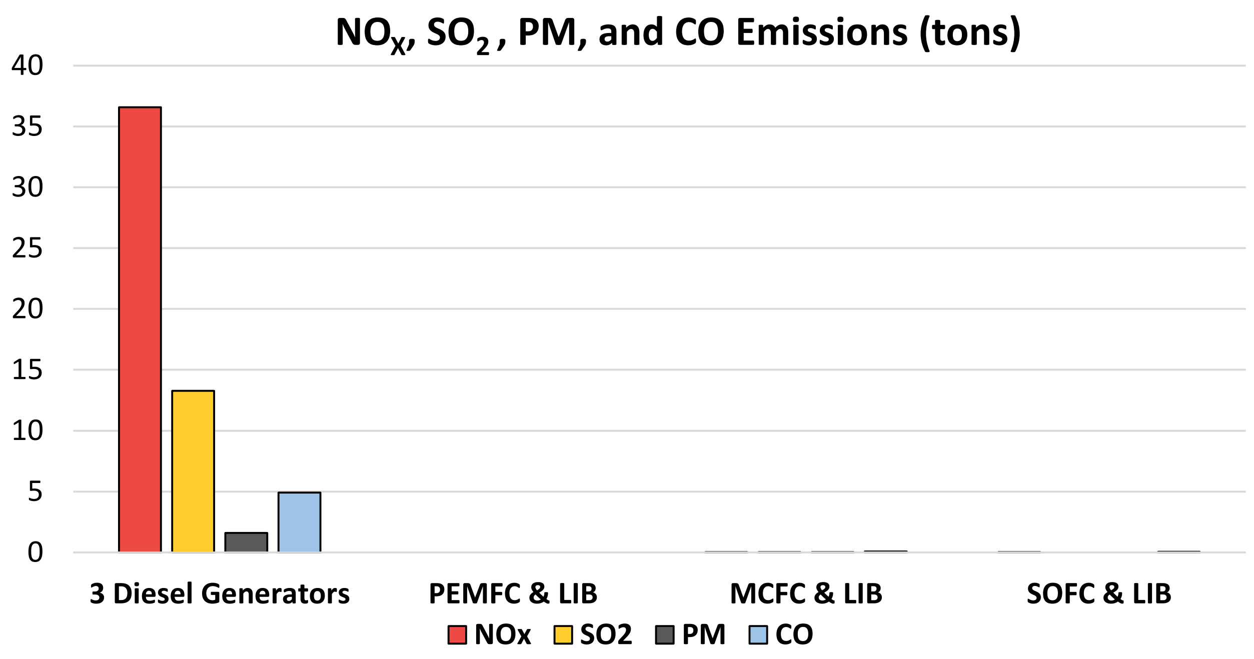


Figure 7.70 **Summary of Pollutants Emissions for a 20-year operation of Alternative Scenarios**

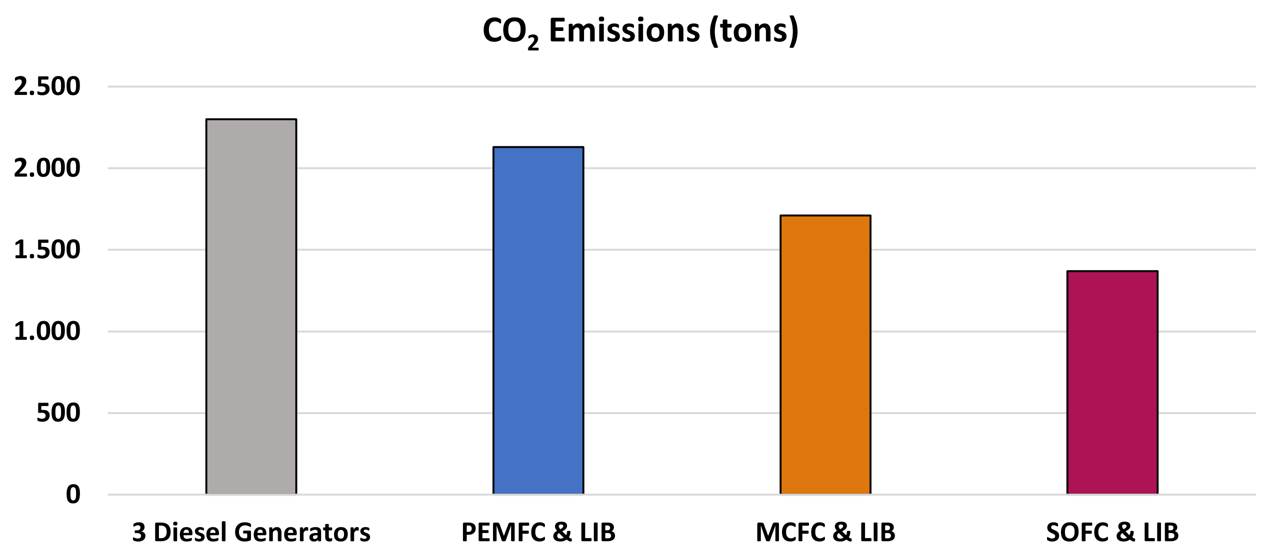


Figure 7.71 Summary of CO_2eq Emissions for a 20-year operation of Alternative Scenarios

As it was already known, FC technologies present an almost zero-pollutant behavior (PEMFC is actually a complete zero-emission technology).Their only environmental damage relates to CO2eq emissions , which in the case of PEMFC are greater even of DGs' topology while the rest two FC technologies display a better performance .

7.4.6 Sensitivity Analysis

As can be observed from **§ 7.4.4**, fuel cell scenarios' are currently economically disadvantageous when compared, at this scale, to well-consolidated conventional practices. This is completely logical, as it usually happens with newly established technologies. The main reasons behind this imbalance refer both to technological status of neoteric devices and ideas, since their characteristics have not been perfected in order to reach their full potential, and their production costs – commercial availability, as their advent catch unaware society's common knowledge about their nature and sometimes – as it happens with hydrogen's case – even international legislation.

However, time after time, newcomers find their position among others. They develop, being tested as it takes effort for a new technology to reach its threshold. Especially, when referring to FC technologies, there is a plethora of reasons that encourage public's opinion about their prospect. First of all, as mentioned in **Chapter 5**, FC devices belong to a category of items that is known as "Economy of Scale". Economies' of Scale distinctive feature is the rapid decrease in production costs – and sometimes delivery and installation costs due to wider commercialization of products – with higher production rates. As FC technology is currently at its dawn, it is foreseen to be expanded a lot further that its current commercial region and cover new grounds. When this is achieved, their CapEx would be reduced creating a more competitive status for FCs. Furthermore, with technological development comes elongation of lifespan, and of course, incline in prices of specialized materials. Electrolytes, which are the most significant component of FC's, are constantly being developed to last longer on stable operational conditions while their prices getting lower and lower. What is more, FC technological development is inextricably linked with the targets associated to the term "Hydrogen Society". More funding for the development of hydrogen production methods, especially when production comes from renewable sources like wind or solar energy, means more focusing on greener technological practices, means more space for fuel cell technology to be incorporated into power plant systems and prove their value.

Taken all these into account, a sensitivity analysis is conducted for each one of FC technologies. For the abovementioned reasons, and as commented in **§ 7.4.4**, PEMFC scenario holds a biparametric analysis while for SOFC and MCFC scenarios' a monoparametric analysis is suitable. The whole concept aims to the detection of conditions under those, FC scenarios' become economically more profitable than that of a conventional 3-DG configuration.

7.4.6.1 PEMFC – Biparametric Sensitivity Analysis

The basis of this biparametric sensitivity analysis spring from the fact that PEMFC evolution will not be one-dimensional, as it in the future is expected a simultaneous reduction in both PEMFC capital cost and hydrogen's purchase price. Therefore, it will not be defined a curve but a zone – area of economic dominance. Figures 7.72 & 7.73 show the PWC reduction of this scenario as a function of PEMFC's capital costs and hydrogen's purchase price respectively.

As we will see, the impact of separate reduction, when each acts solely, is not significant enough to overcome the economic status of conventional configurations. This is a result of PEMFC's high costs in both CapEx and OpEx terms. Therefore, it is mandatory to analyze the system biparametrically, when the two reductions of costs occur simultaneously.

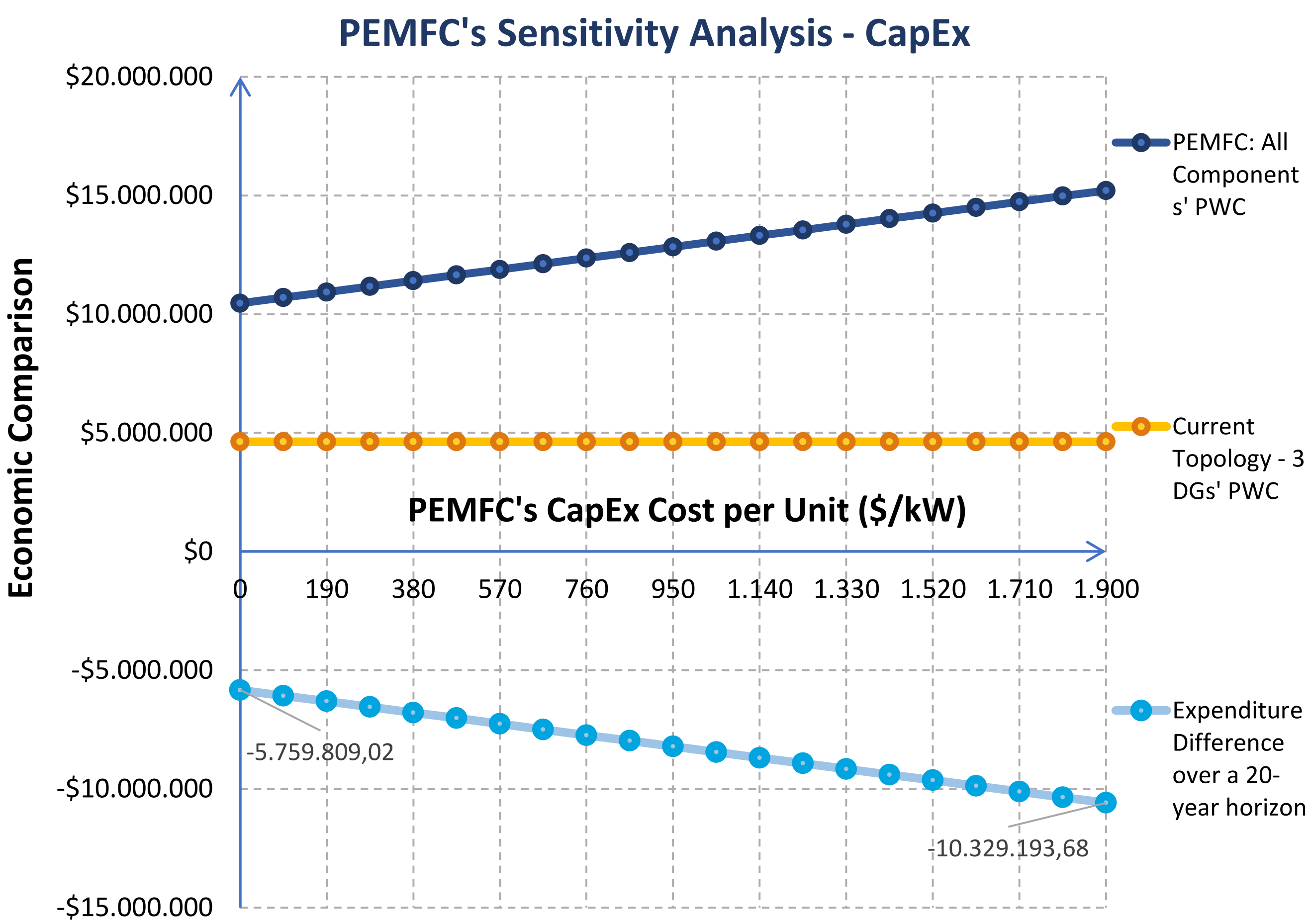


Figure 7.72 **PEMFC Scenario – Sensitivity Analysis - CapEx**

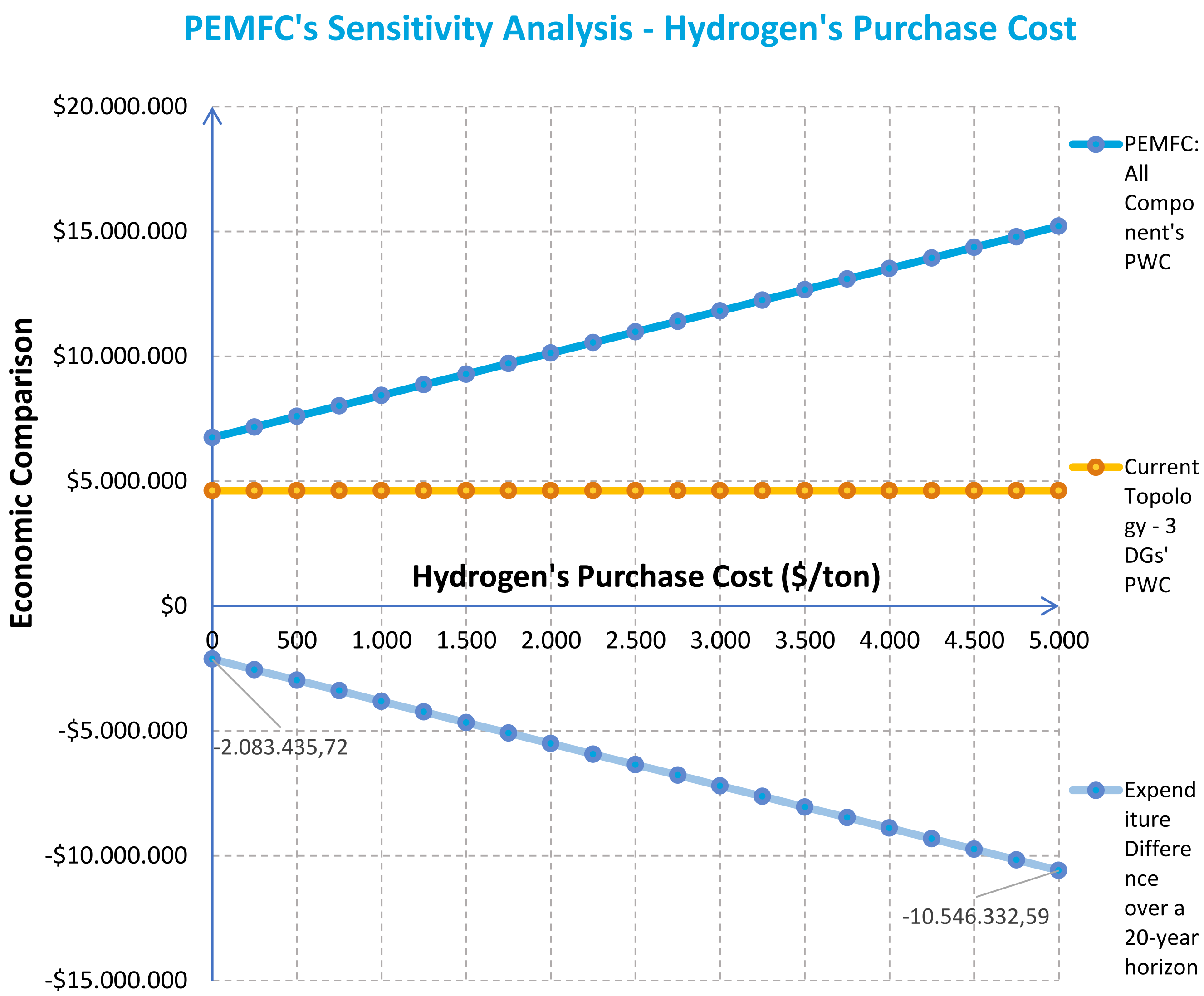


Figure 7.73 **PEMFC Scenario – Sensitivity Analysis – Hydrogen's Purchase Cost**

As it can be observed in Figures 7.74 & 7.75 , applying reductions in both directions has cumulative effects on PEMFC's economic potential. At this case, an area of economic dominance can be determined, a zone where PEMFC scenario is more profitable than that of conventional technology. Although **this zone is limited, it indicates the necessary reductions in hydrogen's prices and PEMFCs' CapEx** to make their proposed scenario a competitive solution from investors' point of view. Specifically, PEMFCs' scenario economic dominance is contained within the limits of blue area, which marginal values are 1000 $/kW and 1500 $/ton for CapEx and hydrogen's purchase price respectively.

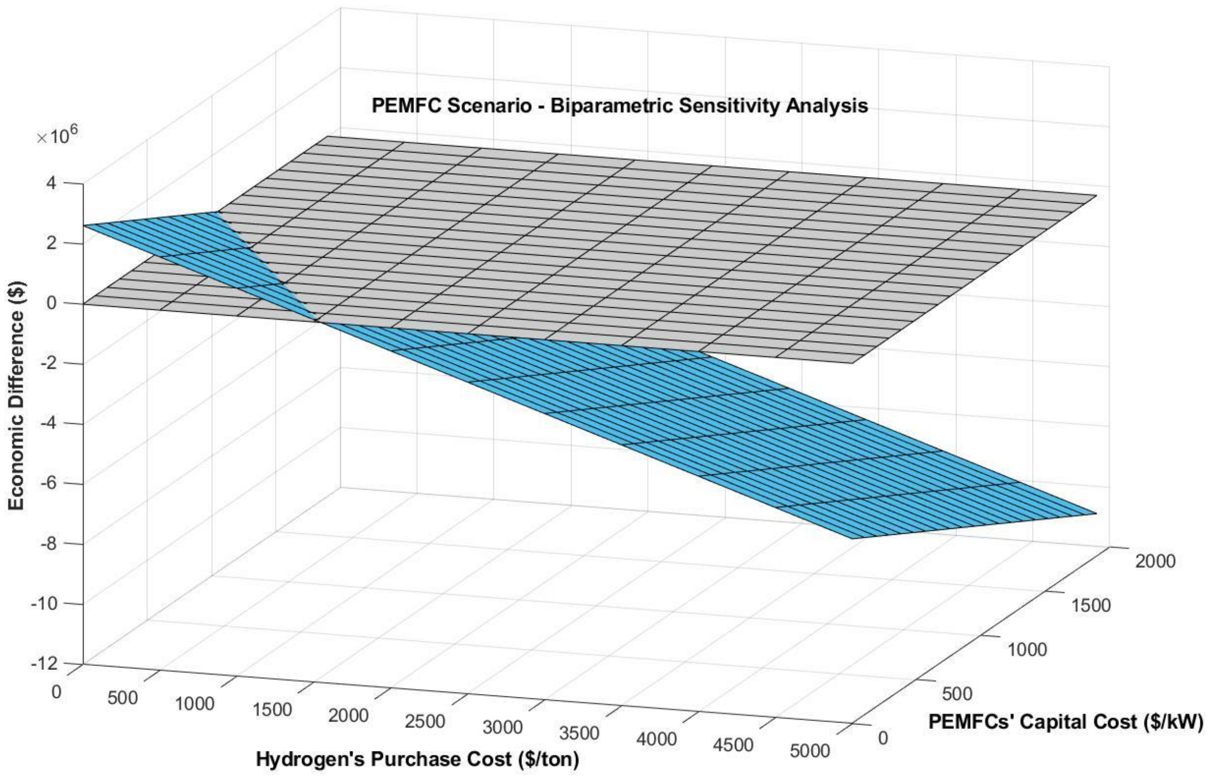


Figure 7.74 **PEMFC Scenario – Biparametric Analysis – 3D View**

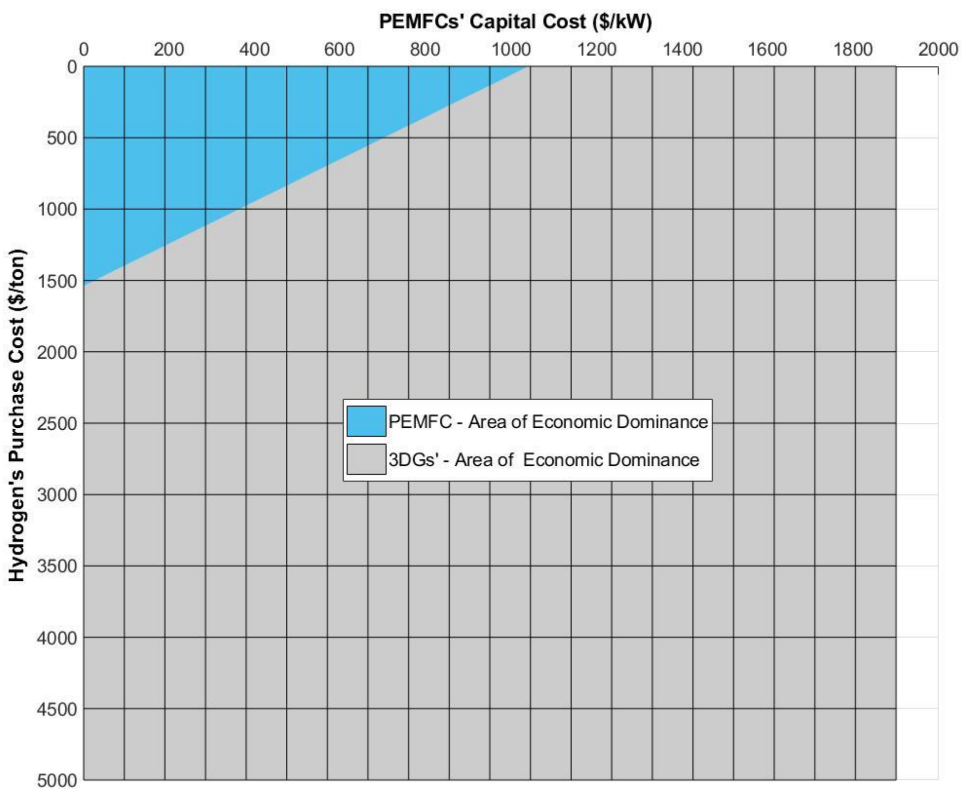
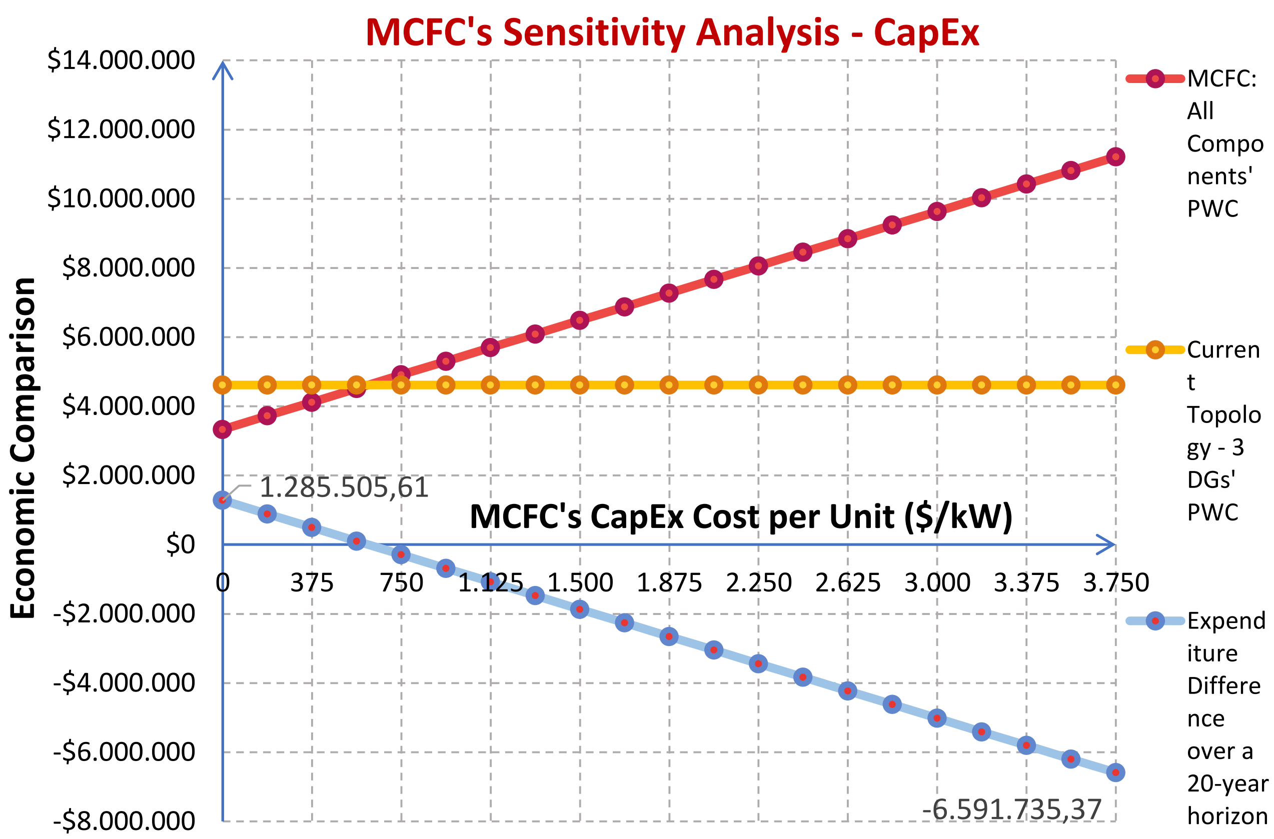


Figure 7.75 **PEMFC Scenario – Biparametric Analysis – Areas of Dominance**

7.4.6.2 MCFC & SOFC – Monoparametric Sensitivity Analysis

When it comes to MCFC & SOFC scenarios, parametric sensitivity analyses are purely oriented towards reductions in capital costs. LNG prices are already competitive and as mentioned in **§ 5.3.2**, its market trends appear similar volatility with diesel's. Therefore, there is no practical value into searching opportunities for FC technologies through LNG's declining price rates, since possible reductions are temporarily, are linked to economic trends and political affairs rather than to technological developments, and are often followed by long periods of consecutive increase. Thus, further down Figures 7.76 & 7.77, determine the necessary reductions in MCFC and SOFC CapEx so as to become economically competitive against conventional diesel generator configurations.

Figure 7.76 MCFC Scenario – Sensitivity Analysis



Solving the algebraic equations, it was calculated that **the marginal value for MCFCs' CapEx**, under which their scenario is economically dominant, **is 610,09 $/kW, which in percentage terms signifies the need for a minimum 83,74% decline in current MCFC's CapEx prices (~3750 $/kW)** so as to make this FC technology economic prosperous when compared to the pre-installed conventional configuration.

Following the same methodology, **the calculated marginal value for SOFC scenario equals to 817,46 $/kW,** which means **there is a need for a minimum 84,87% reduction in current CapEx prices (~4000 $/kW)** to bring economic equilibrium between the efficiency of SOFC scenario and that of the conventional topology.

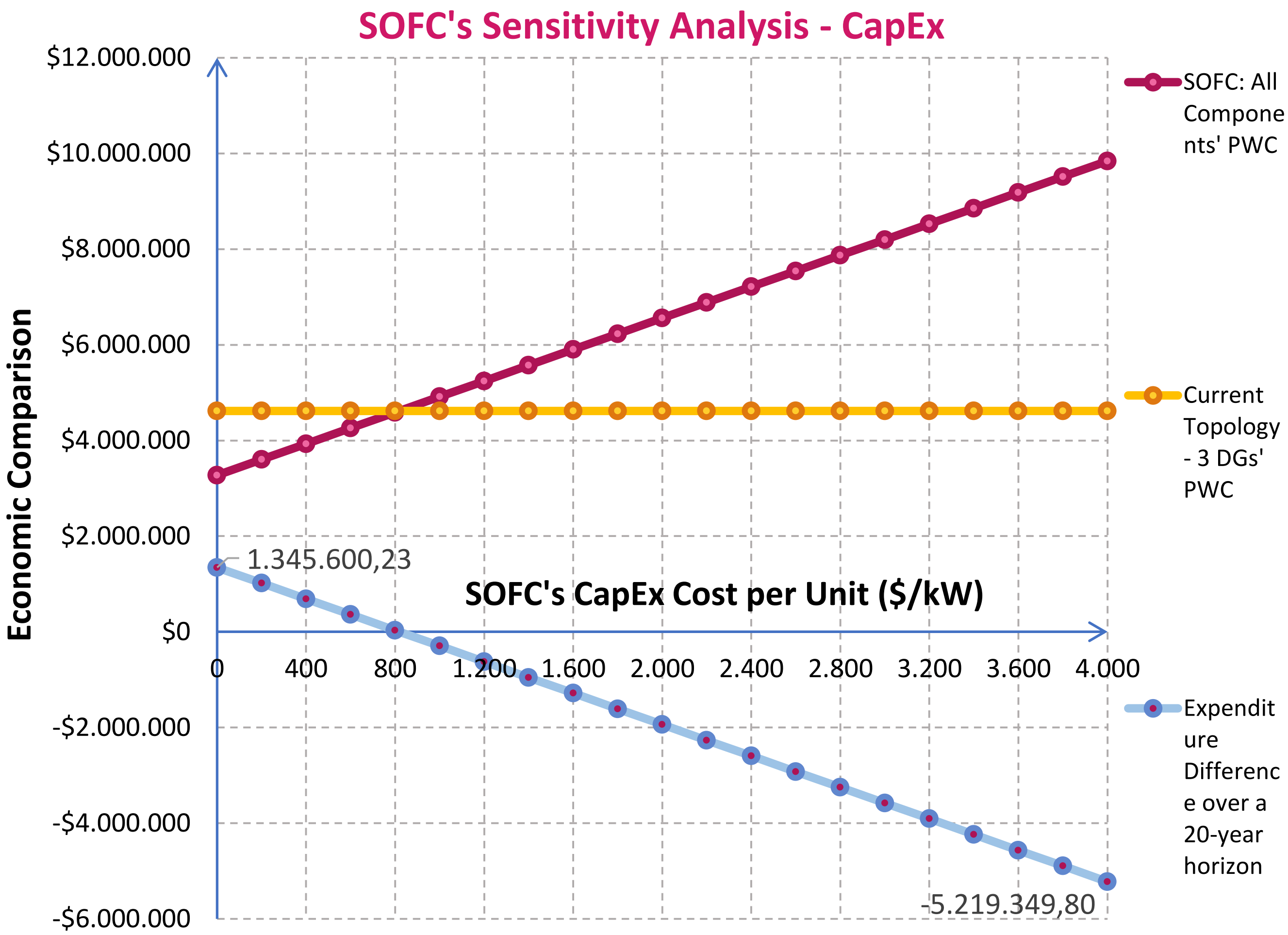


Figure 7.77 **SOFC Scenario – Sensitivity Analysis**

Comments

Note that the abovementioned analysis focuses on arithmetic results and does not make any assumptions about the date that these reductions in CapEx can be achieved. It may be no sooner than 2050 or even further before technological status, societal maturity level and FC knowledge is sufficient enough for such alterations in prices and production costs to form a realistic scenario.

Conclusions

As international environmental regulations for the shipping industry has been increasingly tightened, ship owners will be required to invest in systems and technologies which reduce emissions of GHG or air pollution or switch to alternative fuels. In these conditions, hydrogen and FCs are focused on as one of the solutions in the maritime industry. Hydrogen fuel, compared to heavy oil fuel, has advantages of environmentally-friendliness because it discharges only clean water. However, most hydrogen and FC technologies are still in the early stages of commercialization due to high costs. Therefore, this research identified the feasibility to utilize three types of HFCs, PEMFC, MCFC and SOFC, from the economic point of view.

In order to investigate the economic aspects of HFCs, a case by the use of short sea shipping services was conducted. The case study referred to the replacement of a conventional auxiliary unit from fuel cells accompanied with an appropriate energy storage system. During this analysis, three alternative scenarios were developed and examined. Their common line was the establishment of a hybrid synergy including Fuel Cell technology and a Lithium-Ion battery while their differences relied on the type of Fuel Cells that was introduced and the marine fuel that powered them (with their relating alterations in each scenario). Conclusively, all three proposed scenarios exhibited economic weaknesses when compared to the conventional system (3 Diesel Generators) due to high Capital and Operational Costs (especially in the case of PEMFC which are LH_2-fueled). In contrast, the environmental impact of their operation is negligible and in accordance with every strict legislation. Therefore, FC technology propose a solid but expensive solution for Emission Control Areas that has a long way to go before it becomes economically competitive against conventional topologies (as proved in Chapter 7 within the scope of current thesis' sensitivity analysis).

Recommendations for Future Research

This diploma thesis had to face one great opponent for scientific research purposes; the lack of a well-constructed basis on which someone can rely. It was indeed, quite a task to find valid information about this topic as the level of knowledge and commercialization of FCs is low. However, this diploma thesis managed to fill this gap and create a basis for future diploma theses. Since fuel cells and hydrogen economy traverse a period of research resurgence, it is my duty to make some proposals for future projects. These recommendations include:

- **The overall design of a newbuilding vessel oriented to be equipped with fuel cell technology**

  This diploma thesis would cope with the problems associated with the embarkation of fuel cells on commercial vessels. Having in mind the commands of Class Societies, among others, it will pinpoint FCs practical difficulties, suggest possible topologies and determine potential onboard positions for LH2 or LNG fuel tanks. As an additional part, for deeper analysis purposes, someone can also calculate the hydrostatic stability of the proposed design and assess its integrity (taken into consideration the effects of FC weights, volumes and positioning).

- **A Feasibility analysis regarding the construction of a hydrogen infrastructure in Ports**

  This diploma thesis main target would be the calculation of the total cost for the completion of hydrogen facilities in Ports. Piping networks, fuel tanks, safety issues should be included. The Port of Piraeus could offer a breeding ground for case studies.

- **The Thermodynamic Analysis of a FC type (PEMFC, MCFC, SOFC)**

  This diploma thesis penetrates FC's interim structure to conduct the necessary energetic calculations. The research should include topics such as the calculation of FC's efficiency, lifespan, ability to serve transient phenomena and possibly dimensioning FC's electrolyte and overall capacity for a particular operational profile scenario.

- **A Feasibility Analysis of a SOFC or MCFC technology with combined-cycle power generation systems**

  It has been noted that a well-modified SOFC or MCFC plant combined with a power generation system can offer an overall efficiency of 75% and more. The main target of this diploma thesis would be the design optimization of an integrated high-temperature fuel cell system for marine applications, considering heat recovery options for additional power production

- **Analysis of a Supercapacitor/Battery & Fuel Cell Hybrid Power System**

  This paper will introduce a hybrid power system that combines a Fuel Cell power module (for the generation of direct electric current) with two different energy storage systems (ESSs) [lithium-ion batteries (LIBs) and supercapacitors (SC) focused on port operations and maneuvering phases of ships]. To verify the proposed system a target ship will be selected, and each size (capacity) of LIB and SC is therefore determined based on assumed power demands. Finally, the proposed system is compared to a conventional one in terms of environmental and economic aspects.

- **A Research about safety topics regarding to FCs' operation and Hydrogen bunkering, storage & conditioning**

  FC's are sensitive to vibrations, which occur relentlessly in a shipping environment, while hydrogen is very flammable and quite explosive. Following the steps of the Classification Societies which has already produced LNG Guideline material, this diploma thesis would specify all the safety issues relating to FC's operation and hydrogen and suggest possible practices for their safe establishment on-board.

Socially Oriented Recommendations

As it is obvious from the above analysis, fuel cell systems are able to bring a tremendous evolution in maritime transport industry. Abatement of GHGs - if not zero emission operation -, reduction in operational noise magnitude and high efficiency are only some of the promises that fuel cells can bring to life in the shipping sector. However, there is a lack of knowledge in the cababilities of fuel cell Systems and main principles of operation as well as major gaps in the current international legislation (bunkering, on-board storage, guidelines for the efficient and secure operation of fuel cell systems, safety issues for both the passengers and the ports, etc.). In order to overcome these barriers, the statutory authorities must act at once and develop stable, sufficient and detailed regulations. If this is the case, the scientific community will be more empowered and determined than ever before to invest time and energy in the development of fuel cell systems. Furthermore, the constitution of solid legislation is certain to reinforce the dynamics of fuel cell projects, increase their objective value and open new paths for the advance of eco-friendly hybrid propulsion systems. At this point, it is indeed possible, when using fuel cells on ships, that it has to be a tradeoff between economic benefits and GHG emission reduction but with continuing development, evolution will come as a logical outcome of the entire process. Pretty soon, hydrogen can be world’s main power source, fueling the majority of stationary and mobile transportations while fuel cells could be its driving force. After all, mankind`s most important duty should be to ensure an auspicious future for generations to come.

In this context, in order to secure a feasible future for the establishment of fuel cell technology in shipping industry, it is of a great importance to highlight the minimum required developments in the procedure of lawmaking with some pertinent recommendations.

These can be summarized in the following actions:

- ✓ **Develop specific rules for the type of approval of Hydrogen and Hydrogen Fuel Cells on vessels.**
- ✓ **Develop and share minimum requirements for the operation and maintenance of Hybrid Fuel Cell vessels**

Who are responsible:

- International Maritime Organization
- EMSA (European Maritime Safety Agency), The European Commission, CESNI (Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure) for inland navigation)
- National Maritime Authorities
- Classification Societies

✓ **Clarify and streamline applicable rules for the landing and bunkering of hydrogen.**

Who are responsible:

- National / Regional and Local authorities
- The European Commission, Class Societies
- Business assurance companies, Standards bodies and Organizations[26].

✓ **Provide specialized grant packages and sponsorships oriented for the application, testing, assessment and development of fuel cell technologies on-board.**

Who can be the main sponsors in a global basis:

- The European Commission, the International Maritime Organization and the International Energy Agency (IEA)

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[26]A **standards organization**, **standards body**, **standards developing organization** (**SDO**), or **standards setting organization** (**SSO**) is an organization whose primary activities are developing, coordinating, promulgating, revising, amending, reissuing, interpreting, or otherwise producing technical standards that are intended to address the needs of a group of affected adopters. Most standards are voluntary in the sense that they are offered for adoption by people or industry without being mandated in law. Some standards become mandatory when they are adopted by regulators as legal requirements in particular domains.

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Appendix

Flow Rates

The amount of hydrogen and oxygen consumed in a fuel cell stack are a function of the current obtained from said stack. We can use Faraday's law to derive the relation between required flow rates of reactants for a specified current, where:

$$\mathbf{I.t = n.z.F} \quad \text{(a.1)}$$

Where I, t, n, z and F are current in A, time in seconds, number of moles, number of electrons in the reaction, and Faraday`s constant, respectively. Based on the reactions at the anode the cathode for a hydrogen fuel cell and since *z will be equal to 2 in this case*, the molar flow rates of the reactants can be calculated as follows:

$$\dot{\mathbf{n}}_{\mathbf{hydrogen}} = \frac{\mathbf{I}}{\mathbf{2F}} \quad \text{(a.2)}$$

$$\dot{\mathbf{n}}_{\mathbf{oxygen}} = \frac{\mathbf{I}}{\mathbf{4F}} = \frac{\dot{\mathbf{n}}_{\mathbf{hydrogen}}}{\mathbf{2}} \quad \text{(a.3)}$$

Where $\dot{n}$ is the molar flow in mol s^{-1}.

Taking into account stoichiometric ratios, number of cells per stack, and the generalized case where the fuel and oxidant are not pure; we get the following more practical equations for the required molar flow rates of fuel and oxidant given a certain current output:

$$\dot{\mathbf{n}}_{\mathbf{fuel}} = \frac{\mathbf{I.S_{H_2}.N_{cell}}}{\mathbf{2F.r_{H_2}}} \quad \text{(a.4)}$$

$$\dot{\mathbf{n}}_{\mathbf{oxidant}} = \frac{\mathbf{I.S_{O_2}.N_{cell}}}{\mathbf{4F.r_{O_2}}} \quad \text{(a.5)}$$

where N_{cell} is the number of unit cells, S is the stoichiometric ratio, and r is the volume/molar fraction.

Activation Polarization

Activation polarization is the main cause of voltage drop at low current densities and is caused by sluggish oxidation and/or reduction kinetics at the electrodes surface. **Initiating the electro- chemical reactions requires energy that is reflected in the activation voltage drop**. The activations losses at the anode and cathode could be isolated and expressed using **Tafel's equation:**

$$\mathbf{E_{a,a} = A_a \ln\left(\frac{i}{i_{0,a}}\right)} \quad \textbf{(a.6)}$$

$$\mathbf{E_{a,c} = A_c \ln\left(\frac{i}{i_{0,c}}\right)} \quad \textbf{(a.7)}$$

where i is the current density, i_0 is the exchange current density, and A is given from:

$$\mathbf{A = \frac{R.T}{n.a.F}} \quad \textbf{(a.8)}$$

where α is a constant known as the charge transfer coefficient which depends on the electrode's material, microstructure, and reaction mechanism.

The exchange current density i_0 is defined as the rate at which the simultaneous oxidation and reduction reactions occur under equilibrium conditions when the net current is zero. Thus, it is a measure of the electrode's activity and the higher its value, the easier it is for a charge to move from/to the electrode to/from the electrolyte and the greater the current density. The exchange current density is the determining factor in activation losses. Its value is best given using the following equation:

$$\mathbf{i_0 = i_0^{ref}.\varepsilon_c.P_r^{\gamma}.\exp\left(-\frac{E_c}{R.T}(1 - T_r)\right)} \quad \textbf{(a.9)}$$

Where i_0^{ref} is the exchange current density at arbitrary reference conditions, ε_c is the electrode reference (typically between 180 and 500), P_r is the ratio between the reactant partial pressure and the reactant reference pressure, γ is the pressure coefficient (typically between 0.5 and 1.0), E_c is the activation energy(equal to $66\ kJ\ mol^{-1}$ for oxygen reduction on platinum), and T_r is the ration between the temperature and the reference temperature.

Ohmic Polarization

The ionic and electric resistance of the stack's components to the flow of charge results in ohmic polarization. The electrolyte, catalyst layer, GDL (Gas Diffusion Layer), flow field plates, current collectors, interfacial contacts between the components, and the terminal connections all contribute to these ohmic voltage losses. The electric resistivity is due to the resistivity of the electrically-conductive cell components to the electrons flow while the ionic resistivity is due to the resistivity of the membrane to the ions flow. Most of the electric resistivity occurs due to the lack of proper contact between the GDL, bipolar plates, cooling plates, and other interconnects. However, usually, the ionic resistivity dominates ohmic voltage losses. This is because the number of charge carriers through an ionic conductor is much less than in an electronic conductor. In an electronic conductor, the valence electrons of the atoms become detached and can move freely, whereas in ionic conductors, the ions move through the vacancies in the crystallographic lattice. Thus, the electronic resistance is usually negligible in comparison to the ionic and contact resistances.

We can express the ohmic voltage losses due to ionic, contact, and electronic resistances according to Ohm's law as:

$$\mathbf{E_0} = \mathbf{i}.\left(\mathbf{R_{ele}} + \mathbf{R_{ion}} + \mathbf{R_{CR}}\right) \qquad \textbf{(a.10)}$$

where $\mathrm{R_{ele}}$, $\mathrm{R_{ion}}$, and $\mathrm{R_{CR}}$ are the area-specific electronic ,ionic, and contact resistances in Ω/cm^2.

Ohmic losses are dominant at the middle of the polarization curve and affect all types of fuel cells. Thus, in order to minimize the ohmic losses, it is important to design the stack from materials with high conductivities (i.e., low resistivities), components with minimum thicknesses, and interconnects with minimum contact resistances through the optimization of the stack's compression pressure. This is particularly important for the electrolyte due to its dominant ionic resistivity. This could be achieved by designing a chemically and mechanically stable electrolyte with the highest possible conductivity and the smallest possible thickness since the resistivity of the electrolyte is proportional to the ratio of its thickness over conductivity. Also, the electrolyte material and water content play a significant role in determining its resistivity and need to be carefully considered.

Concentration Polarization

Concentration polarization is dominant at high current densities and occurs when the electrode reactions are hindered by reduced reactants availability (i.e., concentration) at reaction sites. This concentration reduction (which translates to a partial pressure reduction) could be due to limited hydrogen fuel supply, limited diffusion rate of the fuel and oxidant from flow field channels to the catalyst layer, poor air circulation at the cathode which leads to nitrogen (or any other non-participating inert gases for that matter) build-up, water accumulation and flooding at the cathode and anode(especially for PEMFCs),or impurities.

In order to describe the concentration voltage losses, we note that the maximum current density the fuel cell can produce occurs when the rate of reactant (i.e., the fuel or the oxidant) consump- tion is equal to the rate of reactant supply. Thus, at this maximum current density the concentration of the reactant (i.e., its partial pressure) at the surface of the catalyst would reach zero. Similarly, the maximum concentration of the reactant (i.e., its maximum partial pressure) occurs when the current density drawn is zero. Assuming we have a linear relationship between the partial pressure of the reactant and current density generated, we come up with the following simple linear equation that relates the two variables (applicable to fuel and oxidant):

$$\mathbf{P} = -\frac{\mathbf{P_{max}}}{\mathbf{i_{max}}}\,\mathbf{i} + \mathbf{P_{max}} \qquad \textbf{(a.11)}$$

Where P_{max} is the maximum partial pressure corresponding to the maximum concentration, i_{max} is the maximum current density, P is any pressure between zero and P_{max} and i is any current density between zero and i_{max}.

By rearranging we obtain:

$$\frac{\mathbf{P}}{\mathbf{P_{max}}} = \mathbf{1} - \frac{\mathbf{i}}{\mathbf{i_{max}}} \qquad \textbf{(a.12)}$$

Recall the relations we established based on Nernst voltage concept to describe the variation of a reactant partial pressure affects the voltage.

Based on these relations we establish the concentration voltage losses at the anode and cathode with hydrogen and oxygen flows as follows:

$$\mathbf{E_{c,a}} = -\frac{\mathbf{R.T}}{\mathbf{2F}}\mathbf{ln}\left(\mathbf{1} - \frac{\mathbf{i}}{\mathbf{i_{max,a}}}\right) \quad \textbf{(a.13)}$$

$$\mathbf{E_{c,c}} = -\frac{\mathbf{R.T}}{\mathbf{4F}}\mathbf{ln}\left(\mathbf{1} - \frac{\mathbf{i}}{\mathbf{i_{max,c}}}\right) \quad \textbf{(a.14)}$$

Notice the addition of the negative sign so that the outcome is a positive voltage loss value.

Synthesis

It is worth noting that as the constant difference between the thermoneutral voltage and the reversible cell voltage is due to the $T.\Delta S_f$ term. This constant difference represents the minimum amount of fuel input energy that must be converted into thermal energy under ideal fuel cell conditions. This is analogous to the Carnot efficiency concept in heat engines that represents the minimum amount of input energy that needs to be converted into thermal energy between a source a reservoir at known temperatures. The difference between the thermoneutral voltage and the actual cell voltage represents the actual amount of heat generation within the fuel cell. When the difference is multiplied by the current density, we get what is known as the heat generation density rate curve.

The polarization curve and equation represent a zero-dimensional steady-state model for a hydrogen fuel cell under the assumption that only a single gaseous phase is present. This is one of the simplest and most common tools for the evaluation of fuel cell performance. Nevertheless, more involved multi- dimensional and multi-phase models exist where numerical iterations and software packages are used.

If we use the expressions found in above equations the result is the following polarization equation for the Fuel Cell Operating Voltage:

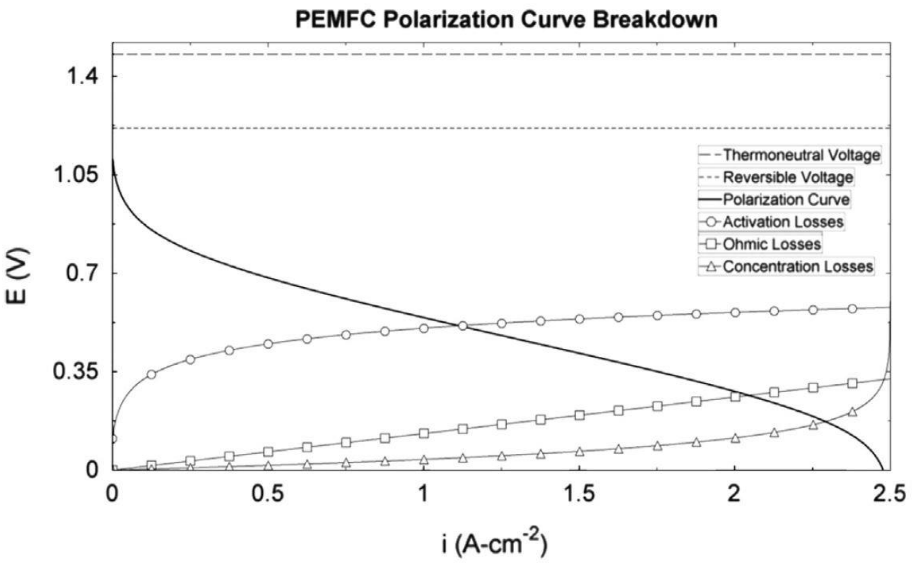
$$\mathbf{E} = \left[\mathbf{E^0_{rev}} + \frac{\mathbf{R.T}}{\mathbf{2F}}\mathbf{l\,n}\left(\frac{[\mathbf{H_2}][\mathbf{O_2}]^{\frac{1}{2}}}{[\mathbf{H_2 0}]}\right) - \right] - \left[\mathbf{A_a l\,n}\left(\frac{\mathbf{i}}{\mathbf{i_{0,a}}}\right)\right] - \left[\mathbf{A_c l\,n}\left(\frac{\mathbf{i}}{\mathbf{i_{0,c}}}\right)\right] - [\mathbf{i}.(\mathbf{R_{ele}} + \mathbf{R_{ion}} +$$

$$+\mathbf{R_{CR}})] - \left[\frac{\mathbf{R.T}}{\mathbf{2F}}\mathbf{ln}\left(\mathbf{1} - \frac{\mathbf{i}}{\mathbf{i_{max,a}}}\right)\right] - \left[\frac{\mathbf{R.T}}{\mathbf{2F}}\mathbf{ln}\left(\mathbf{1} - \frac{\mathbf{i}}{\mathbf{i_{max,c}}}\right)\right] \quad \textbf{(a.15)}$$

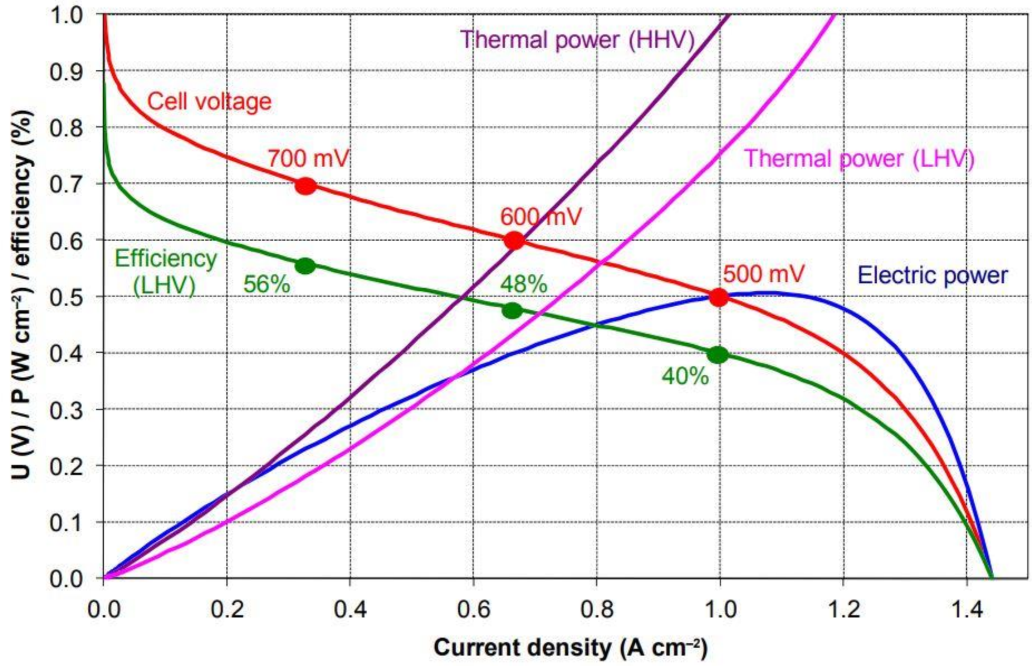
The parameters in this equation are listed in the following table for a typical hydrogen – air PEMFC. All the voltage loss terms within the square brackets in this equation are positive.

Parameter	Value	Unit	Parameter description
ΔH_f	285,250	$J\ mol^{-1}$	Enthalpy of formation
E^0_{rev}	1.18	V	Reversible Nernst voltage at standard conditions
R	8.3145	$J\ mol^{-1}\ K^{-1}$	Gas constant
T	353	K	Operation temperature
n	2	–	Number of electrons involved
F	96,485	$C\ mol^{-1}$	Faraday's constant
P_{H_2}	100	kPa	Hydrogen partial pressure
P_{O_2}	21	kPa	Oxygen partial pressure
P_{H_2O}	45	kPa	Water partial pressure
α_a	0.5	–	Anode charge transfer coefficient
α_c	0.3	–	Cathode charge transfer coefficient
A_a	0.03042	V	Anode activation constant
A_c	0.05070	V	Cathode activation constant
$i_{0,a}$	0.15	$A\ cm^{-2}$	Anode exchange current density
$i_{0,c}$	1.5×10^{-4}	$A\ cm^{-2}$	Cathode exchange current density
i_{loss}	0.008	$A\ cm^{-2}$	Lost internal current density
R_{ele}	0.0	$\Omega\ cm^2$	Area-specific electronic resistance
R_{ion}	0.10	$\Omega\ cm^2$	Area-specific ionic resistance
R_{CR}	0.030	$\Omega\ cm^2$	Area-specific contact resistance
B_a	0.045	V	Anode empirical constant
B_c	0.045	V	Cathode empirical constant
$i_{max,a}$	15	$A\ cm^{-2}$	Anode maximum current density
$i_{max,c}$	2.5	$A\ cm^{-2}$	Cathode maximum current density

The following figure shows the polarization curve of the aforementioned PEMFC with voltage losses breakdown. In accordance with the previous discussion, it is cleat the activation losses dominate at low current densities. The ohmic losses linearly increase with increased current densities and dominate the intermediate range with the activation losses. While the concentration losses are very low until we reach the high current densities region where they dominate and are responsible for bringing the cell voltage to zero as a result of the current density reaching the maximum current density.



The following shows three out of four of the most important fuel cell performance evaluation curves (the fourth being the efficiency curve). The figure shows the opposed relation between the polarization and power density curves on the one hand and the density rate of heat generation curve on the other. The input fuel energy that is not being converted into useful electric energy is wasted as internal stack thermal energy. The power density curve shows a wide optimum range of current densities where power density is at is near-peak. This is an important observation for the stack designer and user.



Alkaline FCs (AFCs)

The alkaline fuel cell (AFC) is one of the earliest types of fuel cells, most famous for being used on NASA space shuttles. Also the first fuel cell driven passenger ship, The Hydra, was driven by a 5 kW AFC. The typical power output of an AFC is 1-5 kW, but recently report of test with 200 kW power output from stationary AFCs have been reported.

The AFC consists normally of a nickel anode, a silver cathode and an alkaline electrolyte. The electrolyte is an alkaline solution (eg. potassium hydroxide, KOH) which can be either mobilized or immobilized in a matrix. The fuel is hydrogen (H_2) and oxygen (O_2) and hydroxyl ions (OH-) are transported through the electrolyte from the cathode to the anode. The hydrogen and oxygen needs to be pure to avoid degradation of the AFC.

The AFC consumes hydrogen and oxygen and produces energy and water. In the NASA space shuttle, the AFC was also used as a source of water and heat.

The main reactions that are occurring are the following:

- Anode reaction:

$$\mathbf{2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-} \quad \textbf{(a.16)}$$

- Cathode reaction:

$$\mathbf{O_2 + 2H_2O + 4e^- \rightarrow 4OH^-} \quad \textbf{(a.17)}$$

- Total reaction:

$$\mathbf{2H_2 + O_2 \rightarrow 2H_2O} \quad \textbf{(a.18)}$$

Benefits and Challenges of AFCs

AFC is a low cost fuel cell, with low-cost catalysts and readily available electrolytes. It can operate at room temperature, which is beneficial from a safety perspective, but also ensures that the requirements for the material used are less stringent (and less expensive). The operation of the AFC is flexible, and cold start is possible. Water is the only by-product of the AFC, no other emissions. The AFC have a moderate efficiency, 50-60 %, and no need for reforming of fuels or heat recovery systems.

The major concern for the AFC is CO_2 poisoning. CO_2 in the fuel will react with the alkaline electrolyte, reducing the efficiency and eventually reading to precipitation and blocking of the cell by potassium carbonate.

$$\mathbf{2KOH + CO_2 \rightarrow K_2C0_3 + H_2O} \qquad \text{(a.19)}$$

Because of this the AFC requires pure oxygen and pure hydrogen to function in an optimal range over a prolonged time. If air is to be used, removing CO_2 is necessary and other fuels than hydrogen are not recommended as long as substantial purification is performed before injection to the AFC.

Further Development of ACFCs

Direct borohydride and metal-hydride fuel cells are subclasses of the AFC that are under development and do not have the same problems with CO_2 poisoning as the traditional AFC. These technologies are still too immature to be relevant for use in ships, but might be a future option.

Phosphoric Acid FCs(PAFCs)

Phosphoric acid fuel cell (PAFC) was the first fuel cell with higher temperature, operating at temperatures up to 200 ℃. The increased temperature means that the excess heat from the fuel cell is of such a quality that it can be utilized, increasing the overall efficiency of the fuel cell from around 40 % (electrical efficiency) up to 80 %.

PAFC has an electrolyte of phosphoric acid in a silicon carbide structure and electrodes made of platinum dispersed on carbon. The PAFC uses hydrogen as fuel under acidic conditions, the reactions that occur is therefore the same as in PEM fuel cells.

The main reactions in the PAFCs are:

- Anode reaction:

$$\mathbf{2H_2 \rightarrow 4H^+ + 4e^-} \tag{a.20}$$

- Cathode reaction:

$$\mathbf{O_2 + 4H^+ + 4e^- \rightarrow 4H_2O} \tag{a.21}$$

- Total reaction:

$$\mathbf{2H_2 + O_2 \rightarrow 2H_2O} \tag{a.22}$$

Due to the higher temperatures, other fuel sources than pure hydrogen can be used. This includes hydrocarbons like LNG and methanol. The hydrocarbons need to be reformed in a separate stage before the PAFC. A PAFC system for the use of LNG, methanol or other hydrocarbons would include both a reformer and a heat recovery system.

In a PAFC the heat recovery system will typically be a steam turbine. The reforming will be a steam reforming converting LNG (mainly methane, CH_4) to carbon monoxide and hydrogen. A subsequent water- gas-shift can also be used for further converting to CO_2 and more hydrogen. The steam reforming is a process that requires energy.

- Steam reforming:

$$\mathbf{CH_4 + H_2O \rightarrow CO + 3H_2} \qquad \textbf{(a.23)}$$

- Water-gas shift:

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2} \qquad \textbf{(a.24)}$$

Benefits and Challenges of PACFCs

The efficiency of the PAFC itself is relatively low, around 40 %, but including heat recovery the efficiency can be as high as 80 %. The higher temperature in the PAFC also makes it less sensitive to CO poisoning and other contaminants than other fuel cells using platinum catalyst.

The system has a low power density, and will thus be large and heavy. The moderate temperature makes start up slower than for low temperature fuel cell, but the PAFC is less prone to negative effects of cycling than the higher temperature fuel cells

DNV GL Fuel Cell Rules

What follows is a synoptic description of the rules and their enforcement methods. For the understanding of the concept DNV GL Rules “Fuel cell Installations” (Pt.6 Ch. 2 Sec. 3, edition October 2015[4]) will be used for providing an overview and exemplification of classification approach for fuel cell installations in shipping.

DNV GL Fuel Cell Rules cover aspects such as design principles, material requirements, arrangement and system design, fire safety, electrical systems, control monitoring and safety systems, manufacture, workmanship and testing.

A number of marine hydrogen fuel cell projects were approved based on a previous GL guideline (formally not rules) the most well-known being probably the Alsterwasser in Hamburg. The current DNV GL FC rules are developed with hydrogen fuel in mind, without however containing specific provisions for high pressure hydrogen storage technologies.

Safety Matters: Threats and Hazards

The primary safety issue to be addressed concerns the use of inflammable gas and/or fuel with low flashpoint (< 60°C). The main hazard to be prevented is the creation of explosive mixture pockets in case of gas release in any part of the system containing gas (leakage, accidental release). A second hazard to be considered is the impact of external fire on a part of the system containing gas (gas tank in particular).

The secondary safety issue concerns the gas storage, each type of storage presenting its specific hazards:

- **Compressed gas storage:** the main hazard to be considered is gas tank failure. This can result from internal overpressure (e.g. error during refuelling, pressure rise due to external temperature rise in case of external fire) or from tank fatigue (e.g. effect of fatigue, embrittlement in case of hydrogen). The primary consequences of such a failure are a gas release with possibility of fire or explosion in presence of an ignition source, and the blast of (possibly ruptured) tank parts. Pressure vessels are already used onboard but they are made of steel. Due to its lower energy volume density, the storage of compressed hydrogen requires very high pressure levels for obtaining sufficient energy storage capacity, for which composite tanks are required. The long term behavior of such tanks in a marine environment is not very well known today and therefore requires special attention;

- **Liquid gas storage:** the safety issues are similar to the ones encountered with cryogenic natural gas storage, but more severe in the case of liquid hydrogen due to its lower boiling point and due to the embrittlement phenomenon if a metallic containment is used. In case of liquid gas spill, the main hazards are ship steel structure embrittlement and cold burn to personnel.

The above hazards are also relevant to the parts of the fuel cell power system which contain gas. **In addition, specific hazards should be considered when relevant:**

- Presence of hot surfaces and/or hot fluids (e.g. in hot fuel cells and in reformer), which may represent an ignition source in case of gas release, and a source of burning for personnel;

Presence of high electrical intensity or voltage, which may again represent a source of ignition and give a risk of electrocution of personnel.

Additionally, the presence of toxic substances may need to be addressed, either as primary fuel (e.g. methanol), or as by product/intermediate product (carbon monoxide created in fuel processing).

If the fuel cell installation is used to power an essential service of the ship (e.g. main propulsion), then the consequence of a failure of the installation needs to be considered as well.

In this context, other relevant rules include:

- Storage of compressed flammable gases as natural gas and hydrogen (above 10 bar) below deck will normally not be accepted, but the rules open for storage of compressed gas below deck on a case by case basis. Above deck storage will be less challenging. Storage of natural gas or LFL/hydrogen in enclosed spaces leads to requirements with respect to ventilation, ex-equipment etc. Double walled piping for low flashpoint fuels (methanol and ethanol) are covered by Rules for Low Flashpoint Liquid Fueled Engines **(DNV GL Pt.6 Ch.2 Sec.6).**

- In addition to prescriptive design requirements, **DNV GL rules require a Failure Mode and Effect Analysis** (FMEA) and a test program based on IEC standard 62282-3-1 "Stationary fuel cell power Systems-Safety" for the fuel cell.

- **DNV GL Pt.6 Ch.2 Sec.6 Low Flashpoint Liquid Fueled Engines,** covering methyl alcohol and ethyl alcohol (methanol and ethanol as fuel). Vessels built in accordance with these requirements may be assigned the class notation LFL. There are no international requirements existing for these fuels.

- **DNV GL Pt.6 Ch.2 Sec.5 Gas Fueled Ship Applications**, where gas is defined as a fluid having a vapor pressure exceeding 2.8 bar absolute at a temperature of 37.8 ° C fuel. Vessels built in accordance with these requirements may be assigned the class notation Gas Fueled.

Class rules applicable for battery fuel cell hybrid installations

To exemplify, the following is based **on DNV GL battery Rules Pt.6 Ch.2 Sec.1**. The scope for additional class notations Battery(Power) and Battery(Safety) cover safety related to battery installations in vessels.

The rules in this section are considered to satisfy the requirements for specific types of battery installation and certification, in accordance with the following list:

- battery systems used as main source of power
- battery systems used as additional source of power
- battery systems used for miscellaneous services
- Safety requirements for batteries other than Lead Acid and NiCd. **Lead Acid and NiCd** batteries are covered by another part of the rule set **(Pt.4 Ch.8)**
- requirements for certification of the batteries.

DNV GL Battery rules, with the class notations Battery(Power) and Battery(Safety) will be applicable for hybrid installations combining batteries and fuel cells. The choice of notation depends on how the batteries are used in combination with other power sources for the function in the ship. The class notation Battery(Power) is mandatory for vessels where battery power is used as propulsion power during normal operation, or when the battery is used as a redundant source of power.

The notation Battery (Safety) is mandatory when the battery installation is used as an additional source of power for battery capacities exceeding 50 kWh. Battery(Safety) can also be selected (not mandatory) for battery systems with less than 50 kWh capacity.

Hybrid solutions using battery power to supplement fuel cells for peak energy demands and for load levelling are potentially attractive to ensure smooth operation of fuel cells.

It may also result in a smaller fuel cell installation, and this can have a positive effect on system life expectancy and system costs.