

# Chapter 10

## Fuel Cells as Naval Prime Movers: Feasibility, Advances and Implications



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### 1 Introduction

Traditionally, the guidelines for the selection of naval prime movers focused on the demands for greater speed, better shock absorption, low noise generation and low infrared signature; but modern warships require a more versatile package which should be flexible enough for broadly varying operational requirements. Modern propulsion systems are expected to operate in a greater range of speed with longer durations of deployment and cleaner emissions [1] while aiming to operate with a numerically inferior manpower compliment than ever before.

Fuel cells inherently offer reduced maintenance costs, emissions and infrared signatures, acoustic signatures, radar cross-section and increased ship survivability due to distributed power reduction and greater flexibility of design and operation due to their modular nature [2]. Fuel cells produce such low levels of noise that the fuel cell cabin on board a ship is expected to have noise levels similar to that of any regular office [3]. Thus, they promise to be a more promising approach towards a clean and efficient power solution as compared to other power sources or prime movers in both stationary and mobile applications. However, their foray into naval propulsion systems is relatively new and is still in its infancy in both maturity and deployment.

The first fuel cells to enter production for naval propulsion as prime movers are Siemens' PEM fuel cells employed by German-Italian Type 212A submarines along with its export derivative: the Type 214 as a part of their Air Independent Propulsion mechanism. These boats are in service with various navies across the globe including the German, Italian, Hellenic (Greek), Portuguese and South Korean navies.

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Furthermore, on the economic front, the U.S. Navy estimated that if a ship service fuel cell plant, having an efficiency of 37–52%, replaces the existing gas turbines on board a DDG 51 Arleigh Burke class destroyer, then, considering a 3,000-h time window, it would consume only a paltry 33% of the fuel relative to what would have otherwise been consumed by the warship. This, the U.S. Navy estimated, could save them more than \$1 million per ship per year in the form of ship service fuel costs [2].

Despite the proliferation of fuel cell-powered Air Independent Propulsion equipped submarines around the world in the last few years, the technology has not gained much turf in the realm of surface vessels: especially naval. In [4], Jing Sun, et al. note that there is a lack of published studies focusing on larger vessels with greater power requirements. They propose a notional Solid Oxide Fuel Cell module and analyse the fuel saving and machinery arrangements by using a hybrid SOFC-gas turbine module for a U.S. Navy Sealift vessel. They concluded the same benefits of employing fuel cell prime movers but also noted that large technology gaps exist and such power density levels, as they have considered in their study, have not been yet achieved by modern state-of-the-art fuel cell technologies.

However, there have been many attempts to construct viable fuel cell modules; the developments and deployments of which are discussed further in this paper.

## 2 Naval Fuel Cell Technologies

### 2.1 The Notional 5 MW SOFC Unit

Fuel cell technology has been making rapid strides with the worldwide effort to develop cleaner and more efficient power sources. A study conducted by Jing Sung, et al. identified the baseline desirable parameters of a marine fuel cell prime mover. Four such notional fuel cell units were coupled with a gas turbine to obtain a total output power of 24 MWe [4]. Principal parameters of this hybrid SOFC-GT system are listed in Tables 1 and 2.

Using this system, a mission endurance analysis was performed on a U.S. Sealift Command's Roll on–Roll off (Ro-Ro) cargo vessel, and the mission endurance was determined by the amount of distance travelled by the ship with 90% of the full fuel capacity at the peak speed of 24 knots [4].

**Table 1** Principal SOFC parameters of the hybrid SOFC-GT system [4]

SOFC Parameter	Magnitude
Output Power (MW <sub>e</sub> )	5
Efficiency (%)	50
Fuel Utilisation (%)	85
Air Utilisation (%)	25
Air/fuel inlet temperature (°C)	600

**Table 2** Principal GT parameters of the hybrid SOFC-GT system [4]

GT Parameter	Magnitude
Compressor Efficiency (%)	5
Turbine Efficiency (%)	50
Pressure Ratio	85
Generator Power (MW <sub>e</sub> )	25

In this analysis, the fuel cell-powered ship was found to have an endurance advantage of 25% over diesel systems and 57% over gas turbine systems while consuming 20% and 50% less fuel than the said prime movers, respectively. Furthermore, amongst all the conditions evaluated, the power output of the combined system never fluctuated by more than 2% which indicated a reliable design and arrangement [4].

However, this analysis was performed with an auxiliary vessel of the U.S. Sealift Command and, therefore, does not adequately reflect the demands of a frontline warship. Also, it was acknowledged by the authors that present technology does not allow us to field such systems, however, they predicted that they can be developed in the near future, i.e. within a span of 15–20 years [4].

## 2.2 Siemens SINAVY PEM Fuel Cells

Siemens offers two kinds of SINAVY Proton Exchange Membrane fuel cells: the FCM 34 and the FCM 120. The FCM 34, developed in 1984 at the request of the German Ministry of Defence, is employed by Type 212A submarines which are in service with the German and the Italian navies. The FCM 120, developed at a later date, is deployed in Type 214 submarines which are Type 212A's export variant currently in service with various navies across the globe including the Hellenic (Greek), Portuguese and South Korean navies [5]. Table 3 lists the technical specifications of FCM 34 and FCM 120 SINAVY fuel cells.

The voltage of SINAVY PEM Fuel Cells with respect to the operating time is quite stable. The degradation rate of the system is less than  $2 \mu V/h$  per cell for a FCM 34 module and significantly lower than the same for a FCM 120 module [5]. This property is particularly desirable as naval vessels have stringent operational requirements wherein all the deployed equipment is expected to adhere to their specifications for the duration of a reasonably long service life along with extended operating time durations.

These fuel cells are employed by the aforementioned submarines as a part of their Air Independent Propulsion system which allows them to stay submerged for relatively longer durations than what their diesel engines would have allowed for. However, under the fuel cells' power, the boats can only cruise at a speed of approximately 5 *knots* (submerged).

In comparison to this, the cruising speed of naval surface escort ships, which tend to be of significantly greater displacements and thus requiring greater power

**Table 3** Specifications of SINAVY FCM 34 and FCM 120 SINAVY fuel cell modules [5]

Technical data	FCM 34	FCM 120
Rated power (kW <sub>e</sub> )	Approximately 34	Approximately 120
Voltage range (V <sub>DC</sub> )	Approximately 54	Approximately 215
Efficiency at rated load (%)	>58	>53
Efficiency at 20% load (%)	Approximately 71	Approximately 68
Operating temperature (°C)	70–75	Approximately 70
H <sub>2</sub> pressure (bar)	2.3 (absolute)	2.4 (absolute)
O <sub>2</sub> pressure (bar)	2.6 (absolute)	2.7 (absolute)
Dimensions (cm)	H = 47 W = 47 L = 143	H = 50 W = 53 L = 176
Weight (kg) (without module electronics)	630	930
Maximum applied current in continuous operation (A)	650	560
Technical data	FCM 34	FCM 120

densities than their sub-surface counterparts, is about 10–15 *knots* while peak power allows them to achieve 25–30 *knots* conventionally in the open seas. These requirements pose a challenge for fuel cells as significant technology gaps exist which need bridging if such systems are to be successfully incorporated in surface vessels as prime movers.

However, due to inherent flexibilities offered by fuel cells, it is possible to refit operational submarines with SINAVY PEM fuel cell modules and, thus, extend AIP capabilities to those boats. Furthermore, as shipboard reformer technology advances suitably, fuel cell technology's field of application can be expanded and it may become the preferred prime mover for sub-surface and surface vessels [5].

### 2.3 Fuel Cell Energy Inc. Direct Carbonate Fuel Cell

In 1997, the Office of Naval Research of the United States sponsored a three-phase project to demonstrate the viability of commercial fuel cell technology in ship service applications on board its warships whose conceptual design criteria are listed in Table 4. By 2003, FuelCell Inc. completed the conceptual design and critical component testing of a 2.5 MW fuel cell module for future surface combatants. To achieve this, FuelCell Inc. used its Direct carbonate Fuel Cell (DFC) technology which provided thermal efficiencies in excess of 50% [6].

The device is fuelled by reforming methane and steam to produce carbon dioxide and hydrogen which is then fed to the anode of the cell. The power-producing anode reaction converts hydrogen to steam which allows reforming reaction to tend towards the product side at a relatively low temperature of 650 °C by continuously shifting the

**Table 4** Fuel cell energy Inc. direct carbonate fuel cell specifications [5]

Parameter	Magnitude
Power (MW <sub>e</sub> )	2.5
Voltage range (V <sub>AC</sub> )	450
Efficiency at 50% load (%)	40
Spatial allowance (m <sup>3</sup> /kW <sub>e</sub> )	0.057
Weight allowance (kg/kW <sub>e</sub> )	18
Production cost (\$/kW <sub>e</sub> )	1,500

reaction equilibrium to obtain the desired products. Such a commercial fuel cell stack typically comprises 350 individual cells arranged in a cuboidal fashion measuring 1.2 m × 0.6 m [6].

PEM fuel cells, in general, require storage of highly flammable and dangerous hydrogen gas which can be a potential safety concern on board any ship. An error, accident or battle damage (in case of warships) may result in uncontrolled discharge of the stored hydrogen gas which can be a significant health hazard on board any vessel. Therefore, internal reforming in the direct carbonate fuel cell at a relatively moderate temperature is a desirable capability on board naval vessels as it only requires the storage of relatively safer hydrocarbon fuels.

The efficiency, size and weight constraints, as indicated in Table 4, were determined by the U.S. Office of Naval Research so as to be comparable with marine diesel engines and offshore power generators. The production cost of the system was determined as such to be “somewhat” lesser than that of large diesel engines [7]. These parameters, therefore, indicate the absolute minimum respective magnitudes that ship bound fuel cell technology should attain to be operationally and economically feasible as compared to conventional diesel prime movers.

### 3 Integration

Conventionally, naval propulsion systems comprise internal combustion engines, viz. gas turbines and diesel engines. These systems are employed in a combination in the propulsion system with different prime movers often being employed for different purposes such as propulsion, services and auxiliary demands. The integration of notional fuel cells in such an arrangement is outlined in [4] and is illustrated in Fig. 1.

In modern propulsion systems, however, the concept of Integrated Full Electric Propulsion (IFEP) is gaining turf. IFEP is defined as the use of a common power system for both propulsion and ship’s services. In such an arrangement, efficient operation is obtained by the use of the minimum number of prime movers necessary to meet the load which all run at their optimum efficiency [8].

It is lucrative for applications in naval propulsion because of the inherent benefits that it carries. A lesser number of prime movers would imply lesser sources of noise

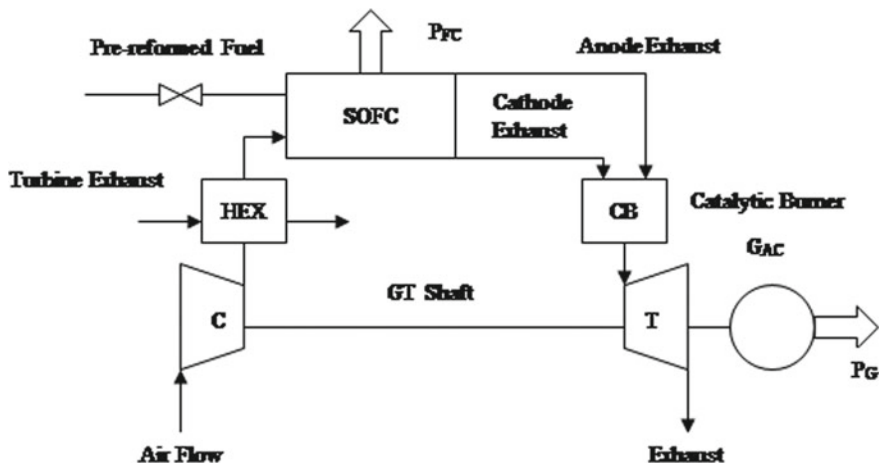


Fig. 1 Combined Fuel Cell and Gas Turbine arrangement for marine applications [4]

generation which is a very desirable outcome for any warship. Furthermore, such a system will be less maintenance intensive and would, thus, require a lesser manpower compliment which would result in reductions in life cycle costs [9]. The first warships to wield an Integrated Full Electric Propulsion system are the Royal Navy’s Type 45 air defence destroyers. Their IEP system is illustrated in Fig. 2 [9]. This concept is also known as that of an All Electric Ship (AES).

In [10], the authors consider that in an AES, power can be provided by the means of diesel generator motors through transformers or by battery banks connected to the motors and evaluate three “options” of integrating hydrogen-oxygen fuel cells on board ships. The outcome of the analysis of these 3 arrangements, as determined by the authors, is presented in Table 5.

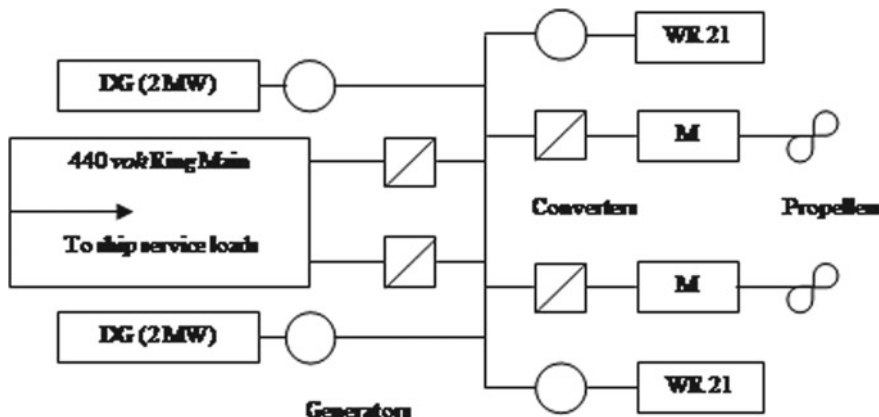


Fig. 2 Electric Propulsion System of Type 45 destroyers [9]

**Table 5** Comparison of options for fuel cell integration on board ships [10]

Parameter	Option 1	Option 2	Option 3
Advantage(s)	Less dependence on fuel cells	Without batteries or battery charge system	Power system totally operated with renewable energies
Disadvantage(s)	Fuel cells in parallel with batteries; the diesel generator is still in the system	The diesel generator is still in the system	Requires 8 fuel cell modules and a 12 V DC-DC converter
Complexity of the control system	High	Low	Low
Space	Not sufficient	Not sufficient	Adequate
Emissions	High	High	Low
Harmonic distortions	High	Low	Low

It is noted that diesel generators pose the problem of limited energy production and are sensitive to harmonic current consumption. Furthermore, the batteries have the disadvantage of relatively longer charging time as compared to the subsequent duration of operation. Also, the impedance of the diesel generator in combination with the non-sinusoidal current feedback of the battery chargers produces voltage distortion that limits the functionality of the power system [10].

Option 1 comprised of an arrangement in which fuel cells are arranged in parallel with batteries. This arrangement adversely affected the system's response time due to the different sources. Currently, fuel cells are not directly controlled causing disarrangement between the fuel cell and battery impedances, which makes it difficult to implement power systems that have fuel cells in parallel with the batteries [10].

Furthermore, an elaborate control system would be required to match the fuel cell's voltage, which varies from 440 to 800 V, to that of the batteries. However, the space that would be gained by eliminating a series of batteries to house the fuel cell modules and power conditioning system would be insufficient for the said task [10].

In option 2, the batteries and the continuous current charge mechanism were completely eliminated from the system. This option benefits by the removal of the limited use time and the presence of harmonic distortions due to these eliminations. Also, an increase in the overall power density of the system is thus achieved. However, the space constraints still do not allow for the accommodation of the fuel cells and their fuel and cooling systems in the space created by the elimination of battery stacks [10].

In option 3, the entire power system of the vessel is replaced by fuel cells and a DC-DC converter. Such an arrangement will be able to run completely on renewable energy and would operate below 80 °C making it "highly reliable". Furthermore, such an arrangement would be highly efficient with low emissions and would also be able to avoid the problem of harmonic distortions [10].

For such an arrangement to succeed, fuel cell modules would need to be connected in parallel with each other to satisfy the system's needs. However, upon connecting the fuel cells to a bus in parallel, a high possibility exists that the current flows back into the fuel cell modules which can reduce their useful life and service efficiency [10]. All of these analyses are summarised in Table 5.

## 4 Fuel

Like the prime movers, it has the potential to replace, fuel cells also have the ability to utilise hydrocarbon fuels, amongst other kinds of fuels. However, since the production of consumable energy, in the form of heat and electricity, only takes place through electrochemical reactions, and not through combustion, as opposed to the internal combustion engines in widespread use, emissions from fuel cells are mostly negligible in nature. Table 6 summarises the various compounds which may be used by a particular kind of cell with a potential for naval application as a fuel, and those which may act as a poison for them beyond certain concentrations.

Alkaline fuel cells as in contrast to the listed kinds of cells, they necessarily require pure hydrogen as a fuel for their operation and cannot operate on a reformed fuel as noted in [12], which was a study conducted by Arctic Energies Ltd. for the feasibility analysis of replacing the diesel-electric propulsion of a U.S. Coast Guard ship which later resulted into the development of the (Molten Carbonate) Direct Fuel Cell technology (2.3).

On board reforming of fuel is desirable for fuel cell operations as it avoids the shipboard storage of hydrogen which is dangerously flammable. The same influenced the Russian Navy's AIP choices and, in the light of the records of frequent fires on-board its ships, it chose not to develop fuel cells similar to the ones employed by German submarines (2.2) for its new Lada class diesel-electric boats, but instead went forward with developing technology that would "convert diesel fuel into hydrogen for power" [13], i.e. reform it.

**Table 6** Various gaseous compounds as fuel and poison for various kinds of fuel cells for potential naval applications [11]

Gas	Phosphoric Acid Fuel Cells	Molten Carbonate Fuel Cells	Solid Oxide Fuel Cells	Proton Exchange Membrane Fuel Cells
H <sub>2</sub>	Fuel	Fuel	Fuel	Poison (>10 ppm)
CO	Poison (>0.5%)	Fuel	Fuel	Diluent
CH <sub>4</sub>	Diluent	Diluent	Fuel	Diluent
CO <sub>2</sub> & H <sub>2</sub> O	Diluent	Diluent	Diluent	Diluent
S as H <sub>2</sub> S & COS	Poison (>50 ppm)	Poison (>0.5 ppm)	Poison (>1.0 ppm)	No studies



In [3], the authors conduct a thermodynamic analysis of a 120 kW<sub>e</sub> diesel-fuelled SOFC system and conceive it as an auxiliary engine while comparing it with a diesel-electric generator set for surface ships. They report a reformer efficiency of 85%, fuel cell efficiency of 68.47% and, thus, a net efficiency of 55.28% while using the NATO F-76 marine diesel fuel.

Also, the higher operating temperatures of MCFCs and SOFCs, in conjunction with their ability to use reformed fuels, can be particularly beneficial for warships which have limited power supply as the waste heat from the said cell stacks can be utilised for fuel reforming which also requires high temperatures to occur.

## 5 Conclusion

We discussed various aspects of deploying fuel cells as naval prime movers covering the assessment of their feasibility, review of the recent advances and understanding of their implications. Furthermore, their fuelling and integration within the existing marine propulsion systems were discussed.

We conclude that fuel cells offer a promising option for the future of naval propulsion with numerous environmental, economic and combat benefits. However, it is notable that no fuel cell systems are presently deployed as naval prime movers with the notable exception of the German-Italian Type 212 submarines with their Air Independent Propulsion systems. However, a significant number of studies and attempts have been consistently made around the world which were discussed in the review.

It was observed that the principal hurdle in the path of realising fuel cells as naval prime movers is their poor spatial efficiency and weight-to-power ratios (specific power). Furthermore, certain types of fuel cells, such as the SOFC and MCFC, which are gaining the turf for naval applications, operate at very high temperatures.

All the fuel cells discussed in this study prefer hydrogen as fuel which requires its on-board storage. This poses significant risks in a marine environment due to the dangerously flammable nature of hydrogen. It is, therefore, safer and cheaper to employ shipboard fuel reforming technologies to produce the necessary fuel for the fuel cells on board in real time from the regular marine diesel fuel which would save considerable monetary resources in the terms of on board and off board storage, handling, transportation and processing. With the notable exception of alkaline fuel cells, most other fuel cells can comfortably operate on reformed fuels with both SOFCs and MCFCs benefitting particularly from this arrangement.

Further innovations in the area, therefore, need to be directed towards improving the spatial efficiency, the specific power and the reforming techniques for fuel cells so that their numerous benefits, especially environmental, can be suitably exploited for the better.

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