AIP for Ocean Going Submarines: off-the-shelf or promise

Carel Prins, PhD, MSc, **Douwe Stapersma**, MSc, FIMarEST

Member of Dutch Underwater Knowledge Centre & Delft University of Technology, The Netherlands

Synopsis

Atmosphere Independent Power has been with us for more than 80 years but there is still an impressive amount of development work going on. The more so after nuclear propulsion set an unattainable goal that can therefore not be emulated by the most advanced concepts. Even so conventional AIP submarines, small and large, can profit from operational advantages depending on the specific system. Hence the question remains what to choose from a variety of options. This overview is intended to provide a background on what is available “off-the-shelf” and what can be expected from on-going development even if today’s naval architect has to wait for the promises to become true. The present paper provides an overview of the options and the impact they have on the submarine design under consideration. Apart from Closed Cycle Diesel and Stirling systems also Fuel Cell systems with stored or reformed H_2 are reviewed. In addition the performance of advanced batteries is included as an alternative to AIP

Keywords: Conventional submarines, Air independent Power generating concept, Fuel cells, Advanced batteries

1. Introduction

A submarine design shall meet the Navy’s established functional requirements and the corresponding Concept of Operations. These requirements differ in a great many ways, resulting in a variety of submarine designs. Whether the product is a small “coastal” or larger “ocean going” or even nuclear submarine, stealthy atmosphere independent operation in whatever form is a key factor. Many of the AIP systems that have been brought to light were developed to support the operations of the future user. For the design of a new class of submarines the naval architect is faced with question whether a specifically developed or an off-the-shelf AIP system is the best option.

The review is made with a conventional submarine of around 3000 ton in mind with ample internal space and adaptable to unknown future operations. In the submarine design the power generated by the diesel generators and AIP systems must be fine-tuned with the three ways of storing energy – F76, H_2 and LOX – on board. Of the two off-the-shelf AIP systems, the Stirling system and the PEMFC, the first only comes in 75 kW units and for a much higher power output the corresponding number of units need to be installed whereas the PEMFC system is much more scalable. The Closed Cycle Diesel system has been proven but is not presently operational.

The data provided in this paper were taken from open sources and cannot reflect on-going development work. When comparing systems and fuel- and oxidant storage systems it is only realistic to take system and compartment packing factors into account. When installing an energy conversion system in a submarine the space that the components occupy is larger then the bare volume of the components themselves, accounting for auxiliary subsystems, accessibility, mounting supports, etc. Acknowledging that these factors are specifically design dependent, realistic numbers have been adopted in this review. For the storage of H_2 and LOX a system packing factor (H_2 adsorbed in a Metal Hydride in a canister or LOX in a double wall vessel) is applied. Installing these

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Author's Biography

Carel Prins graduated in 1964 as mechanical engineer at Delft University of Technology and was awarded a PhD in nuclear power engineering 1972. He joined the Rotterdam Dockyard Company in 1971where he held various positions and was general manager for design and engineering at RDM Submarines in Rotterdam until 2000, when he retired from the company. He is cofounder of the Dutch Underwater Knowledge Centre (DUKC).

Douwe Stapersma graduated in 1973 as a mechanical engineer at Delft University of Technology in the field of gas turbines and then joined Nevesbu - the Dutch design bureau for naval ships - where he was involved in the design and engineering of the machinery installation of frigates and submarines, in particular the integration aspects, shock & noise and machinery control & automation. After that he was in charge of the design of submarines in a joint project organisation with RDM. In 1993 he became professor of Marine Engineering at the Royal Netherlands Naval College, now part of the Netherlands Defence Academy. In 2000 he was appointed a part-time professor of Marine Engineering and Marine Diesel Engines at Delft University of Technology. His main fields of interest are: energy generation and conversion on board ships, gas turbine and diesel exhaust emissions and ship propulsion and machinery dynamics. In 2013 he retired from NLDA but is still affiliated to TUD to supervise some PhD students.

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storage systems on-board a compartment packing factor shall have to be applied as well, that is different for in- or outboard location as applicable..

It is the aim of this paper to provide input for an initial analysis of the benefits of potential AIP systems as integrated into the submarine design. It may also stress the need to verify the packing factors pertaining to an actual submarine arrangement. The operational performance of the reference submarine of around 3000 ton fitted with and without these AIP systems is discussed in a parallel paper [Stapersma, 2020].

2. Options for Stealth

The options considered in the analysis are presented in figure 1. The systems are described by their individual characteristics

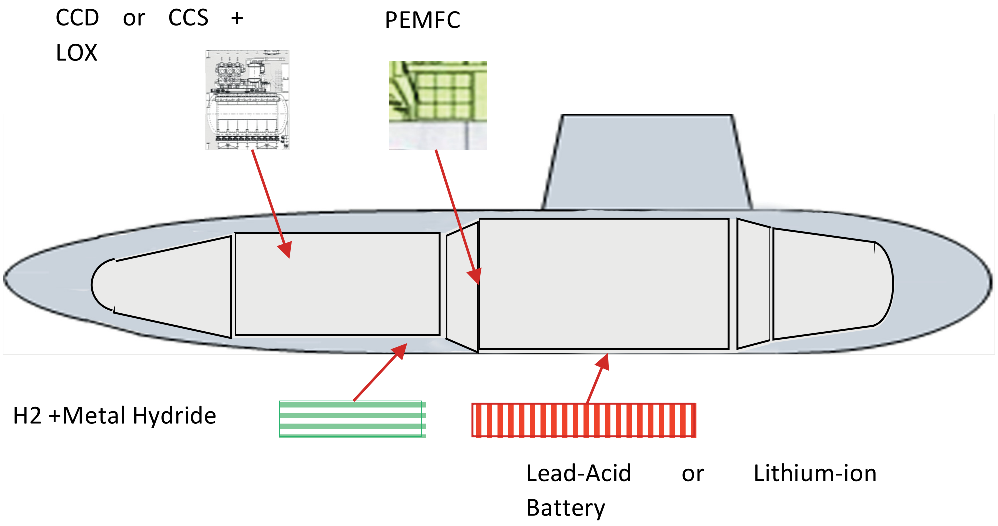

Fig. 1 Options of the AIP Submarine

2.1. Batteries

Lead-acid Battery

The energy density of submarine batteries differs from manufacturer to manufacturer and from specific submarine battery design to another. The volume usage of the battery compartment is not 100%, because there must always be space around the cells for access etc. So a compartment packing factor is assumed. The data used in this analysis are:

Lead-acid battery	Wh/l @ 5hrs 50% DOD	Cell volume [litre]	Compartment packing factor	Energy density compartment kWh/m3
	105	210	0,51	54
	Wh/kg @ 5hrs 50% DOD	Cell mass [kg]	Cell density [kg/m3]	Density compartment kg/m3
	38	575	2736	1396

Table 1 Data lead acid batteries

Lithium-ion Battery

The Lithium-ion battery has the potential to have a much higher energy density than the Lead-acid counterpart. It has been reported that the battery installed in the Japanese submarine Soryu has twice the energy density of the originally installed Lead-acid version. The same is mentioned for the new South-Korean SSKIII submarine. There are similar developments ongoing in Europe. The data for energy density of battery modules from the German[1]

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[1] EAS Marine High power (Battery 1)

and Japanese[2] makers of the Lithium-ion cells, that are supposedly involved in submarine application as quoted in their brochures, are not yet reflecting the values found in literature but these data are for commercial use as are the data of another manufacturer[3] that however is not involved in any submarine project. For these Li-ion batteries the packing factor was taken same as for Lead acid batteries although safety issues for the Li-ion battery may change this. The data are shown in Table 2 below.

Battery 1	Wh/l @ 5 hrs 50% DOD	Volume [litre]	Compartment packing factor	Energy density compartment kWh/m3
Module	67	46	0.51	**34**
	Wh/kg	Mass [kg]	Density [kg/m3]	Density compartment kg/m3
Module	56	55	1189	606
Battery 2	Wh/l @ 5 hrs 50% DOD	Volume [litre]	Compartment packing factor	Energy density compartment kWh/m3
Module	128	17	0.51	**65**
	Wh/kg	Mass [kg]	Density [kg/m3]	Density compartment kg/m3
Module	82	27	1561	796
Battery 3	Wh/l @ 5 hrs 50% DOD	Volume [litre]	Compartment packing factor	Energy density compartment kWh/m3
Module	155	12	0.51	**79**
	Wh/kg	Mass [kg]	Density [kg/m3]	Density compartment kg/m3
Module	94	19.5	1647	840
Battery 4	Wh/l @ 5 hrs 50% DOD	Volume [litre]	(Compartment) packing factor	Energy density compartment kWh/m3
Module	241	34.8	0.58	
Rack of 20 modules	141	1192	0.51	**72**
	Wh/kg	Mass [kg]	Density [kg/m3]	Density compartment kg/m3
Module	140	60	1724	
Rack of 20 modules	140	1200	1007	514
Battery 5	Wh/l @ 5 hrs 50% DOD	Volume [litre]	(Compartment) packing factor	Energy density compartment kWh/m3
Module	250	44.8	0.70	
Rack of 17 modules	175	1086	0.44	**77**
	Wh/kg	Mass [kg]	Density [kg/m3]	Density compartment kg/m3
Module	165	68	1518	
Rack of 17 modules	173.5	1097	1009	444

Table 2 Data Li-ion commercially available Li-ion batteries

Data of another manufacturer[4] provides not only information of modules but also of racks. Although the energy density and specific energy of the modules seems better, the rack has a packing factor of its own such that with a compartment packing factor of 0.51 the overall figures are comparable to battery 2 and 3. Yet another

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[2] GS Yuasa LIM Series Industrial (Battery 2)

[3] Valence U-Charge XP (Battery 3)

[4] Samsung (Battery 4)

manufacturer[5] also delivers racks and provides to pack these in a 40 ft container with a compartment packing factor of 0.44, again resulting in an overall energy density comparable to the other manufacturers.

In the comparison with the conventional battery – based on equal volume – the advanced cell density gives hardly any improvement over lead acid. The ongoing developments promise much higher densities but are not yet available for submarines on the open market. In a study for a submarine with a battery as its sole power source [Los, 2018] quotes an article by [Gonzales, 2015] on Lithium-ion power for data storage and servers. This publication provides an overview of established technology with energy densities ranging from 300 to 700 Wh/l.

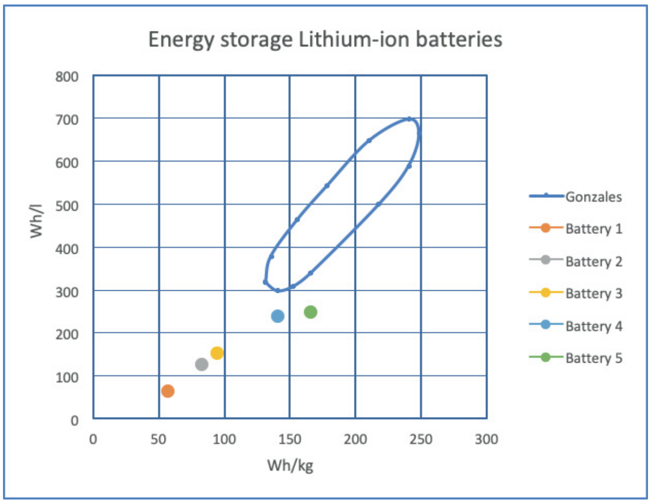

Fig. 2 Trend of Li-ion energy density

The value Los used is 315 Wh/l with a compartment packing factor of 0.625, the latter being denser than for Lead-acid. Figure 2 shows the Gonzales trend for Lithium-ion batteries. The data shown, cited as 'established technology' are clearly much higher than those of the five manufacturers mentioned above. The trend reflected by five data points is the same as for the Gonzales presentation, although their mass density tends to be lower. It is not evident whether such high energy densities as presented by Gonzales can also be achieved in high power batteries such as for traction or in submarines. It is not clear whether the density of batteries for data storage is higher than for power batteries by nature. It is clear that next to technology the overall packing factor, which is probably driven by heat production and safety issues, is most important for the performance potential of Li-ion batteries.

2.2. Closed Cycle Engines

Both the CCD and the CCSt will consume F76 as fuel. From a chemical point of view the combustion process using O_2 as oxidant is the same. The conversion efficiency is somewhat different from a thermodynamic point of view, and also because the Stirling system exhausts the excess oxygen to the outboard along with the flue gas. While the Stirling system is "off-the-shelf" the operational depth is presently limited to 200 m. The CCD is a truly closed cycle system where the excess oxygen is re-circulated back to the inlet of the diesel engine. This results in a better usage of LOX compared to the Stirling engine. Although proven the CCD is today "on-the-shelf". The heat of combustion of F76 is taken as 11.9 KWh/kg. From an equation of the moles involved in the oxidation of F76 the mass of oxygen is 3.4 times the mass of fuel consumed.

		Heat of combustion [kWh/kg]	Specific mass of consumables [kg/kWh]	Conversion efficiency	Specific consumable mass consumption [g/kWh]
	Fuel	11.9	0.084	0.40	210
CCD	LOX		0.288		720
	Fuel	11.9	0.084	0.30	280
CCSt	LOX		0.288		950

Table 3 Data CCD/CCSt energy conversion

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[5] LG Chem (Battery 5)

Closed Cycle Diesel (CCD)

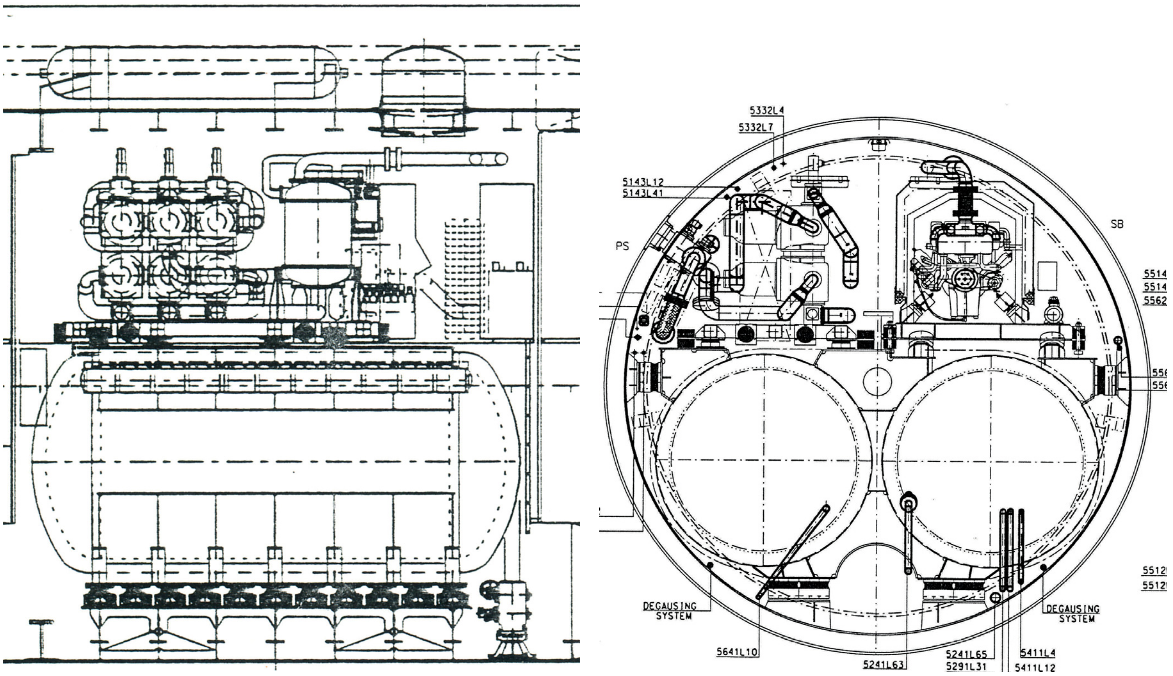

Fig. 3 Typical AIP section with CCD mounted on top of LOX storage tanks

Mass and volume of the CCD system is taken from the Moray1400-H design. The main components are a diesel generator set, a CO_2 absorber and water management system (WMS) to exhaust the flue gas (CO_2 and water vapor) overboard, plus auxiliary systems, piping and cabling. The O_2 is stored in cryogenic tanks, located inboard and shock- and also acoustically mounted as they act as an noise isolating mass for the in itself flexibly mounted CCD and WMS. The mass- and volume parameters of the system are:

	kW/kg	kW/m^3
DG set + auxiliary	0.034	25
WMS + Absorber	0.035	23

Table 4 Basic energy data CCD plant

The conversion efficiency for the CCD system is 40%. Because the CCD closed cycle operates at around 2 bar the efficiency can be somewhat above the average for the type and size of diesel engine. The CCD system is mounted on two racks parallel with the axis direction of the submarine. The total volume is about 25 m3. The space around the CCD system within the pressure hull is about 2.5 times the volume of the CCD system, resulting in a “compartment packing factor” of 0.4.

CCD plant	kW/m3 (system)	Compartment packing factor	kW/m3 (submarine hull)	kW/ton
	12	0.4	4.8	17

Table 5 Effective energy data CCD plant

Stirling Engines

The mass and volume of the special submarine Stirling generator sets are guesstimated values, as exact data are not found in open literature. The estimated mass and volume of the CCSt do not differ very much from the CCD dimensions [EPRI, 2002]. Almost the same data are used.

CCSt plant	kW/m3 (system)	Compartment packing factor	kW/m3 (submarine hull)	kW/ton
	12	0.4	4.8	15

Table 6 Effective energy data CCSt plant

2.3. Fuel Cells

PEMFC

The PEMFC considered here can either be fed with pure Hydrogen stored in metal hydride, an "off-the-shelf" AIP system, or produced through reforming a hydrocarbon fuel. With the (lower) heat of combustion value of 33.3 kWh/kg of hydrogen the amount of Oxygen is 0.24 kg/kWh. The conversion efficiency varies with the output power: the lower the load the higher the efficiency. An average conversion efficiency is taken to be 55 % [Han,2012].

	Energy content kWh/kg	Specific mass of consumables [kg/kWh]	Conversion efficiency	Specific consumable mass consumption [g/kWh]
Hydrogen	33.3	0.030	0.55	54.5
Oxygen		0.240		436

Table 7 Data fuel cell energy conversion

The dimensions of examples of fuel cell stacks to generate the power for submarine use are shown in the table below. The data are taken from [Mendez 2014]. The volume of the fuel cell system (stack + balance of plant) is compact, especially for the 120kW stacks. Because the complete system also encompasses switchboards and other electronic hardware the same usage coefficient as for the CCD is applied here.

PEMFC	Mass [kg]	Dimensions [mm]	W/kg	W/l (FC system)	Compartment packing factor	kW/m3 (submarine hull)
SIEMENS BZM 34 kW	650	480x530x1450	52	102	0.4	41
SIEMENS BZM 120 kW	900	500x530x1760	133	257	0.4	103

Table 8 Effective energy data Fuel Cell plant

Other fuel cell options

The low temperature PEM FC with external reformer is poisoned by any sulphur in the fuel and may need special fuels. Also the external reformer has a high volumetric impact [van Oosten, 2006]. High temperature fuel cells, e.g. SOFC, seem not well suited for submarine application. The start up time is very long and the installation must probably be started upon leaving the harbour and remain operational during the full mission. Also the ramp up to speed demands is slow, however in a submarine the battery could be used to cope with load variations. However disadvantaged the PEM FC with external reformer or SOFC with internal reforming may be, these systems have been included to mark the high energy source potential in comparison with other AIP systems.

2.3. LOX Storage

The LOX is stored cryogenically in two cylindrical double hull pressure vessels mounted side by side in a shock protection frame inside the pressure hull. With a density of 1140 kg/m3 about 40 ton of LOX can be stored in two vessels of 5.3 m length. The outer volume of the LOX tank is 1.6 to 1.8 times larger than the inner vessel. The compartment of the hull that includes the tanks, mounting frames, piping, etc again is 1.6 - 1.8 times the outer tank volume for a concept of two vessels in the lower half the hull (excluding the weight compensation tanks), i.e. a compartment packing factor of 0.56 - 0.63. That brings the storage density of LOX in the submarine to 350 - 450 kg/m^3. A value of 400 kg/m^3 for internal storage is assumed a good estimate. Assuming a pressure hull diameter in the engine room of 6.5 m and length of 13 m the available boat volume is 216 m3 in which an amount of 86 ton of LOX can be stored in 2 vessels installed side by side. When stored externally in the superstructure the compartment packing factor could be higher resulting and an overall 500 kg/m^3 would be realistic.

2.4. Hydrogen Fuel

Metal Hydrides

Hydrogen can be stored in a high-pressure gaseous form, cryogenically or adsorbed in a metal hydride. The last form is considered to be the "off-the-shelf" system. The percentage storage by weight for the various hydrides differs [Balosta, 2019] but a value of 1 to 2% is taken here. There are many different metal hydride compositions with a range of properties. The density of the hydrides varies too. Consistent data for submarine application is not widely available. A density of 4200 kg/m^3 is used [Busqué, 2017]. A practical set of dimensions for a canister would be a cylinder of 0.4 m diameter with a length of about 10 m, or 1.2 m^3. Such a canister would store 71 kg

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of hydrogen or 1.4 %. At 2.0 % it would be 101 kg. The weight of the hydrides however would be 5040 kg (exl the hydrogen). So hydrogen storage in spite of its own lightness is heavy, although when located low could function as ballast in a submarine, in particular when conventional batteries would be replaced by lighter Li-ion cells

There are carbon nano-structures that in future will show to have higher storage percentages [Man Mohan, 2019]. The performance varies with the type and treatment of the nano tubes. As an average the storage capacity is taken to be 5%. The density of the carbon nanotubes is 1400 kg/m^3. Of course these values could alter the scene drastically for storage of H$_2$ and thus for the PEM FC.

Reformers

Methanol, Ethanol and F76 reformers have been demonstrated, but no proven submarine application is as yet available today. Such reformers do add to the complexity of the submarine design and may demand longer reliable operational demonstration.

2.5. Energy Storage Density

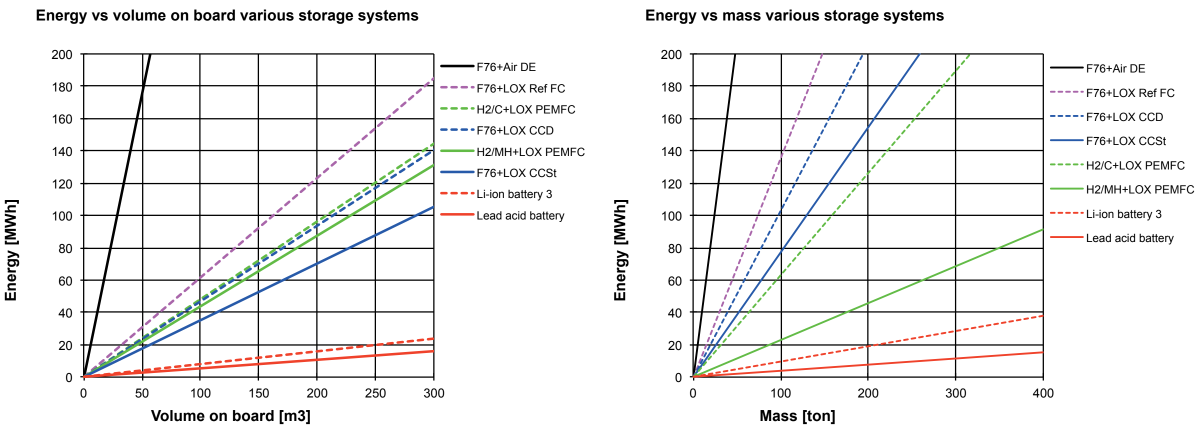
Batteries, CCD and CCSt systems and PEMFC systems represent a form of energy storage density. Table 9 gives an overview of values for fuel and oxidant assuming a packing factor for the storage itself (the "system") and for installation on board. Also the effective energy density on board for fuel and oxidant together is given. For operational purposes this is a point of interest for making the choice between systems.

The energy storage density for the AIP systems shows the CCD system to be the densest in energy storage, unless the storage of H$_2$ in carbon based nano structures becomes available or the reformer cell promises become true. Note that for all options using LOX it is stored internally with the exception of the PEM FC where the LOX as well as the hydrogen is stored externally. The values include some spreading because of the estimations, but are significantly higher than the lead-acid and Lithium-ion batteries.

Component		Fuel energy kWh/kg	Conversion efficiency	Output energy kWh/kg	Basic Storage density [kg/m^3]	Output energy incl carrier kWh/kg	Storage density system [kg/m^3]	Energy density system [kWh/m^3]	Storage desnity on board kg/m3	Energy density on board [kWh/m3]
Lead acid battery		-	-	-		0.038	2736	104	1395	53
Litium-ion battery 3		-	-	-		0.094	1647	155	840	79
PEM FC Metal Hydride	H2	33.3	0.55	18.3	1.014*4200	0.25	4052	1026	2800	709
	O2			2.29	1140	2.29	722	1653	500	1142
	H2+O2					**0.23**				**438**
PEM FC Carbon NT	H2	33.3	0.55	18.3	1.050*1400	0.87	1375	1200	950	830
	O2			2.29	1140	2.29	722	1653	500	1142
	H2+O2					**0.63**				**481**
CCD	F76	11.9	0.40 x 0.95	4.54	840	4.54	840	3813	840	3813
	O2			1.31	1140	1.33	722	963	400	535
	F76+O2					**1.03**				**469**
CCSt	F76	11.9	0.30 x 0.95	3.40	840	3.40	840	2860	840	2860
	O2			1.00	1140	1.00	722	722	400	401
	F76+O2					**0.77**				**352**
Reformer FC	F76	11.9	0.50 (?)	5.97	840	5.97	840	5017	840	5017
	O2			1.76	1140	1.76	722	1267	400	703
	F76+O2					**1.36**				**617**
DE	F76	11.9	0.37 x 0.95	4.20	840	**4.20**	840	3527	840	**3527**

Table 9 Overview energy storage density

Taking the energy density values of the systems in table 9, an estimate is presented in Fig. 4(a) of the space usage in a submarine. This assumes a linear relation of the energy density with the space occupied. The graph shows that for the proven AIP systems potentially the CCD system provides the highest volumetric capacity for energy storage, The reformer fuel cell would come out higher but there are doubts about the volume of the plant itself, which is not yet included in these data that are for storage only. When looking at mass in Fig. 4(b) the PEM FC has lowest specific energy due to the heavy storage of hydrogen even if carbon based storage would become available, although the gap then is closing.



(a) (b)

Fig. 4 Energy storage vs volume (a) and mass (b) for various systems based on submarine volume usage and mass of fuel (+ carrier) + oxidant

It should be noted that the linear relationship, in particular for the energy (volumetric) density is to be validated in a real design where interfaces between the various spaces on board will influence the actual outcome. The result is also strongly dependent on the packing factors employed here. These may vary from submarine design to submarine design resulting in deviations from this outcome. On the other hand it is a reminder that packing factors are to be contemplated because only considering the net dimensions of components and subsystems will not provide correct performance numbers.

In both graphs it is clear that air dependent propulsion on F76 is most dense and light and that the lead acid battery lies at the other end of the scale. AIP systems are in between, with the exception of the mass of the metal hydride hydrogen storage for the PEM FC. Also Li-ion cells do not yet come close to the AIP systems and as long as that remains so, there is a case for AIP systems.

There is a marked difference between the two battery types and the fuel consuming AIP systems. The Lithium-ion battery cited is only marginally denser than the Lead-acid battery. It should be noted that the space usage factor for the latter can be determined rather well. The extra volume is required for access for maintenance, cables, ventilation etc. Here it is assumed that the same usage factor applies to the Lithium-ion battery, while there is scarce information of the packing density of the modules of these type of batteries, the space for cooling, accessibility, and run away mitigation. Also the energy density of this type of battery is expected to improve greatly in the future, as is shown in Fig. 2

3. Restrictions

The diesel-electric submarine with AIP is no emulation of a nuclear propelled submarine. While the unlimited range of the nuclear boat would suit the expeditionary mission of the present design it would – by size and stealth – not be ideal for littoral waters. The choice of AIP or battery is determined by the desired agility of the boat. [Stapersma, 2020] And that is the solution to the problem of covertness – indeed the submerged undetected operation – in range and the speed required for that mission.

To choose between the various options, range or endurance and speed are the opposing quantities that determine the outcome. Is it more important to cover the maximum range in theatre for the maximum time or is the speed, to optimise the chance to intercept the COI, the driving factor. And whether the intercept manoeuvre has to be executed covertly or only for the very last moment when detection in busy sea lanes is negligent. That determines the required energy storage for AIP.

The availability of a forward supply base determines whether LOX, Hydrogen or Methanol- and Ethanol fuel can be replenished and hence if the autonomy would be endangered. It must also be remembered that reformers produce CO_2 that has to be exhausted. For these reasons the preference would be for advanced batteries if available. The large amount of F76 diesel fuel allows for the recharging of the battery at some distance of the operational theatre.

The need to limit the boat in size because of the manoeuvrability in shallow waters limits the space on board for the storage of energy and power conversion systems. While a well-balanced submarine design is subject to critically observed weight and volume balances as well as a series of appropriate design rules the present analysis is limited to more general considerations. There is a need therefore to set some space limitations for the systems contemplated to fulfil the submarine's functional requirements.

The development of more energy dense batteries is ongoing. The improvement over lead-acid batteries is growing and there are many maritime applications. The state of the art is not yet fully reported in open literature. A hazard of Lithium-ion batteries is the occurrence of thermal run away [DNV]. For maritime applications a possible fire is mitigated by isolating the particular cell or module and exhausting the combustion gases to the open air as to prevent the fire from spreading in the ship. A present restriction is the risk of fire when considering a Lithium-ion battery for submarine use where exhausting combustion gases outboard is not (yet) possible.

4. Conclusion

The two off-the-shelf AIP systems are presently operational at relatively moderate power levels. When considering applying such a system it cannot be evaluated without taking the energy storage capacity into account. The review shows that from the latter point of view the two systems, the CCD and the PEMFC with metal hydride storage, based on volumetric energy density are not far apart. Comparing on a mass basis however the PEMFC clearly lags far behind. The CCD might still come out first before both the off-the-shelf systems, had it been operational today.

The data found on Lithium-ion batteries differs rather much from the promises made by several designer-builders of submarines in the Far-East. When these batteries become off-the-shelf products they will indeed become game changers.

High temperature fuel cells such as the SOFC are characteristically not suited for rapid load changes, but if available with internal reforming of F76 fuel, they are very interesting regarding their low volume and weight footprint in the submarine design, although they still require disposal of CO_2. Their inflexibility may be compensated by an appropriately dimensioned battery. But if the promise of carbon based nano structures could reliably replace the present metal hydride storage of H_2 the scene could swing towards the PEM FC.

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Glossary of Terms

AIP	Air Independent Propulsion (various systems)
AUV	Autonomous Underwater Vehicle
CCD	Closed Cycle Diesel
CCSt	Closed Cycle Stirling
COI	Contact of Interest
ISR	Intelligence, Surveillance and Reconnaissance
F76	Nato designation of Marine Diesel Fuel
LOX	Liquid Oxygen
PEMFC	Proton Exchange Fuel Cell
SF	Special Forces
SOFC	Solid Oxide Fuel Cell
UUV	Umbilical Underwater Vehicle
WMS	Water Management System