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Fuel Cell Power System Conceptual Design for Unmanned Underwater Vehicles

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Abstract

Improving the subsea endurance and the power system efficiency of unmanned underwater vehicles (UUVs) has become more important in recent years as their demand grows for different applications. Integrated electric power systems are commonly applied in UUVs with different types of batteries as power sources. Utilizing fuel cells hybridized with batteries is one of the most efficient ways to increase the UUV's range and overall system efficiency. In this paper, a conceptual design is presented for a fuel cell/battery hybrid UUV. This design process includes a review of the UUV fuel cell stacks, the commercial fuel cell UUVs, the fuel and oxidant storage technologies, and the electrical energy storage subsystems. Also, analytical investigations were presented on the degree of hybridization (DOH) between fuel cells and batteries. The fuel cell/battery hybrid system design for a UUV and the technologies of its main components are proposed as the final step of the conceptual design process.

1. Introduction

Due to increasing concerns about consuming sources of energy, global pollution and warming, fuel cell vehicles (FCVs) have become more popular because of their energy efficiency and low pollution [1]. Researchers continue to propose more efficient sources, including fuel cells, hybrid engines, and battery storage systems, that would be an optimum choice

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for the present systems [2]. As an example, transportation leads to a large portion of fossil fuel usage in most countries. Burning fuel will lead to the emission of NO_2, CO, and CO_2. Using fuel cells instead is one of the solutions to this problem. Studies have shown that fuel cells will reduce CO and CO2 emissions up to 99.75%, which is 54% less than fossil fuels on average. Scientists are studying several types of fuel cells in transportation [3-6], but there remains a lack of knowledge and technology in hydrogenation; moreover, the cost of hydrogen fuel is high. One of the most important challenges of commercializing fuel cells is to increase efficiency and reduce hydrogen consumption by designing appropriate energy management strategies (EMSs) for the power systems [7]. As a new concept, the fuel cell has been proven to be a prominent source of power with little pollution and low operating temperature; however, since fuels cells are still new, the costs (although reducing) are still high resulting in many researchers trying to reduce the costs [2, 8-12]. Hydrogen fuel cells, with the benefits of no emissions, low noise, high efficiency, and high specific power, are a superior power source for systems and vehicles [6].

Many design requirements for an efficient system must be implemented to combine fuel cells with energy storage devices like batteries and supercapacitors, i.e., reducing hydrogen consumption, fuel cell size, and power system cost [13,14]. A battery can be employed as an additional power source in a hybrid power system to meet peak power requirements [15]. While there are various types of fuel cells [16], polymer electrolyte membranes (PEMs) are currently most commonly used in industrial and commercial applications, in particular vehicles [17]. PEMFCs are the most suitable form of fuel cell in terms of power supply requirements because they can operate at low temperatures while delivering high power densities. Prototypes of fuel cell-powered UUVs have successfully used this kind of FCs [21–23]. Other benefits of PEMFC over other FC types are low operating temperature, quick startup, high efficiency, quicker reaction and start-up times, and improved resilience to shocks and vibrations [18]. Therefore, PEMFCs are the superior option for designers in the current technological landscape, considering the above factors [19]. UUVs equipped with fuel cell were initially used for military usage; however, due to their cost, safety, low acoustic signature, and operational ranges, they have since been used in the civil industry to access depths inaccessible to scuba divers [20]. The key challenge is that higher battery and power source technologies are required to increase the range and endurance. Fuel cells typically use air as an oxidant, but the absence of air for UUVs poses a significant problem. Storing oxidants along with fuel is one of the solutions [19].

Currently, batteries are used by the majority of large UUVs [19], but by applying fuel cell systems, UUV endurance will rise [21–23]. Auxiliaries and the fuel cell can match applications' power requirements, but external storage media only meet energy requirements. Fuel cells can perform better than batteries in terms of energy density because the storage medium has a far higher energy density than batteries, but their weights and system sizes are what cause the problems [24]. According to recent studies, commercial UUVs employ batteries to store energy. Their level of difficulty is the biggest obstacle. For instance, battery-powered UUVs for extended range and endurance are much larger than standard ones, making them less useful and requiring more space [19, 25].

So fuel cells are used in the UUV industry. The properties of suitable fuel cell systems are:

- The size of fuel cell systems must be as small and as light as possible.
- The power output of fuel cell systems must be in the range of 1 kW-4 kW.
- Fuel cell systems should be removable, exchangeable, and replaceable.

The requirements and limitations of using fuel cells in UUVs have been investigated in studies. One difficult issue is how to store oxidants in UUVs along with the fuel. Since there are various ways to store O_2 and H_2, a mixture of these should be studied, and the best combination for both reactants should be chosen [19]. According to recent research, fuel cells are the better choice for UUV implementation because they have longer endurance and are smaller and lighter. However, the technology still requires further development, and the cost is prohibitively expensive. Nevertheless, according to studies, if we use both batteries and fuel cells, known as hybrid systems, the system efficiency will be higher, and the cost will be lower than if we only use fuel cell systems [16].

By hybridizing, the system takes the benefits of both systems. Furthermore, hybrid systems are more efficient, have lower emissions, and have extended operation compared to a single-source system. A sizing design methodology is required to achieve these advantages. For example, in the UUV design process for applying the energy storage technology, sizing it for the application and determining the fuel load/range limitations are prominent [26]. Scientists have focused on the mass, size, and energy balance of the system component to compare these hybrid systems. They showed that the mass and volume of the energy system are mostly related to H_2 and O_2 storage systems, compared to the fuel cell and battery. Using liquid O_2 is also recommended for oxidant storage, depending on the mission length requirement [27]. Recently, many scientists and companies like Teledyne have been working on fuel cells to achieve higher efficiency. Teledyne used this technology on a seabed supercharger called the Teledyne seabed supercharger (TSS)[28]. A review was done for several prototypes and conceptual designs for implementing fuel cells like DeepC, Urashima, IDEF, Ifremer, Seahorse, etc. [29].

The present study first discusses the main types of fuel cells and different methods for storing hydrogen and oxygen. Then the commercial fuel stacks for UUV applications are reviewed. Next, energy storage technologies, one of the main components of the fuel cell/battery hybrid power systems, are explained. The last section of the paper deals mainly with the conceptual design of a fuel cell/battery UUV power system. A general review and the conceptual design of fuel cell UUVs are the main contributions of this paper.

2. Fuel Cell/Battery Power Systems in UUV Applications

Fuel cell and battery-based systems and the corresponding technologies are discussed in this section. Fuel cells and energy storage systems as power sources are the two main components of these systems. In the following, their technologies and also related commercial products are introduced. Also, the power systems technologies of the fuel cell-powered UUVs are reviewed.

2.1. Fuel cell stacks

In this section, several recently introduced fuel cell stacks and hydrogen and oxygen storage systems are discussed. Each has its own characteristics, such as operating temperature, and is made of different materials. The appropriate fuel cell technology is chosen based on the application [30, 31]. The three main technologies for fuel cells are the polymer electrolyte membrane fuel cell (PEMFC), intermediate temperature solid oxide fuel cell (IT-SOFC), and alkaline fuel cell (AFC). Due to their low operating temperatures, PEMFCs are well-suited to transportation applications that require frequent on-and-off operations. Hybrid PEFC power systems have been applied to cars [32, 33, 34], buses [35], scooters [36], airplanes [37], and underwater vehicles [38]. They are also suitable for portable applications and intelligent uninterruptible power supply systems [39]. SOFCs are primarily applied to stationary applications where heat can be used. Recently, intermediate temperature SOFCs (IT-SOFCs) [40] hybridized with ZEBRA batteries have been considered for road vehicles' power sources [41, 42, 43] and hybridized with gas turbines for unmanned aerial vehicles [42]. Alkaline fuel cells have been tested in vehicular systems [44], including space missions.

Three main fuel cell stack technologies, PEMFC, SOFC, and AFC, are briefly introduced and compared in Table 1.

Table 1. Comparison of three cell technologies [26].

	PEMFC	IT-SOFC	AFC
Cell material	Electrode: Pt/C Electrolyte: polymer Membrane-GDL: carbon materials	Electrode: ceramic materials Electrolyte: ceramic membrane	Electrode: Pt/C- Electrolyte: KOH solution- Nickel mesh support
Fuel	Hydrogen (high purity, zero CO-emission)	-Hydrogen (with low CO) -Hydrocarbons	Hydrogen (high purity, free of CO_2)
Oxidant	Air or pure oxygen	Air or pure oxygen	Air or pure oxygen (free of CO_2)
Operating temperature	less than 80 ºc	500-800 ºc	60-100 ºc
Cooling	Water or air cooling	Air cooling	Circulating electrolyte
Advantages	-Well developed -Quick start-up	-Well developed -Wide choice of fuels	Low cost
Disadvantages	-Expensive -Water management can be a problem	-Long start-up time -Low volumetric power density	Severe problems with CO_2

There are several ways to store hydrogen as a fuel for the system. The main methods of storing hydrogen include [26]:

- Compressing
- Metal hydride
- NaAlH4
- Cryo-compressed
- Liquid cryogenic

More details about the methods are presented in Table 2. The gravimetric and volumetric densities in different storage methods directly affect the total volume and weight of the UUV system. Therefore, these values are among the key parameters in the UUV design process and are affected by the available hydrogen storage technology levels.

Table 2. Hydrogen storage methods [19].

		Gravimetric density		Volumetric density		Cost	
Methods	Conditions	kWh/kg H_2 system	g H_2/kg H_2 system	kWh/ L H_2 system	g H_2/ L H_2 system	\$/kWh	\$/kg H_2
Compressed	700 bar	1.48	44	0.84	25	17	571
Compressed	350 bar	1.81	54	0.59	17.7	13	437
Metal hydride	NaAlH4	4	12	0.38	11.4	42.9	1441
Cryo compressed	300 bar 57 K	1.65	49	1.01	30.2	14	470
Liquid cryogenic	1 bar 22K	1.85	55	1.34	30.4	12	400

A relative comparison of fuel cell/battery power systems with different methods of hydrogen storage for three different durations is presented in Figure 1a-c.

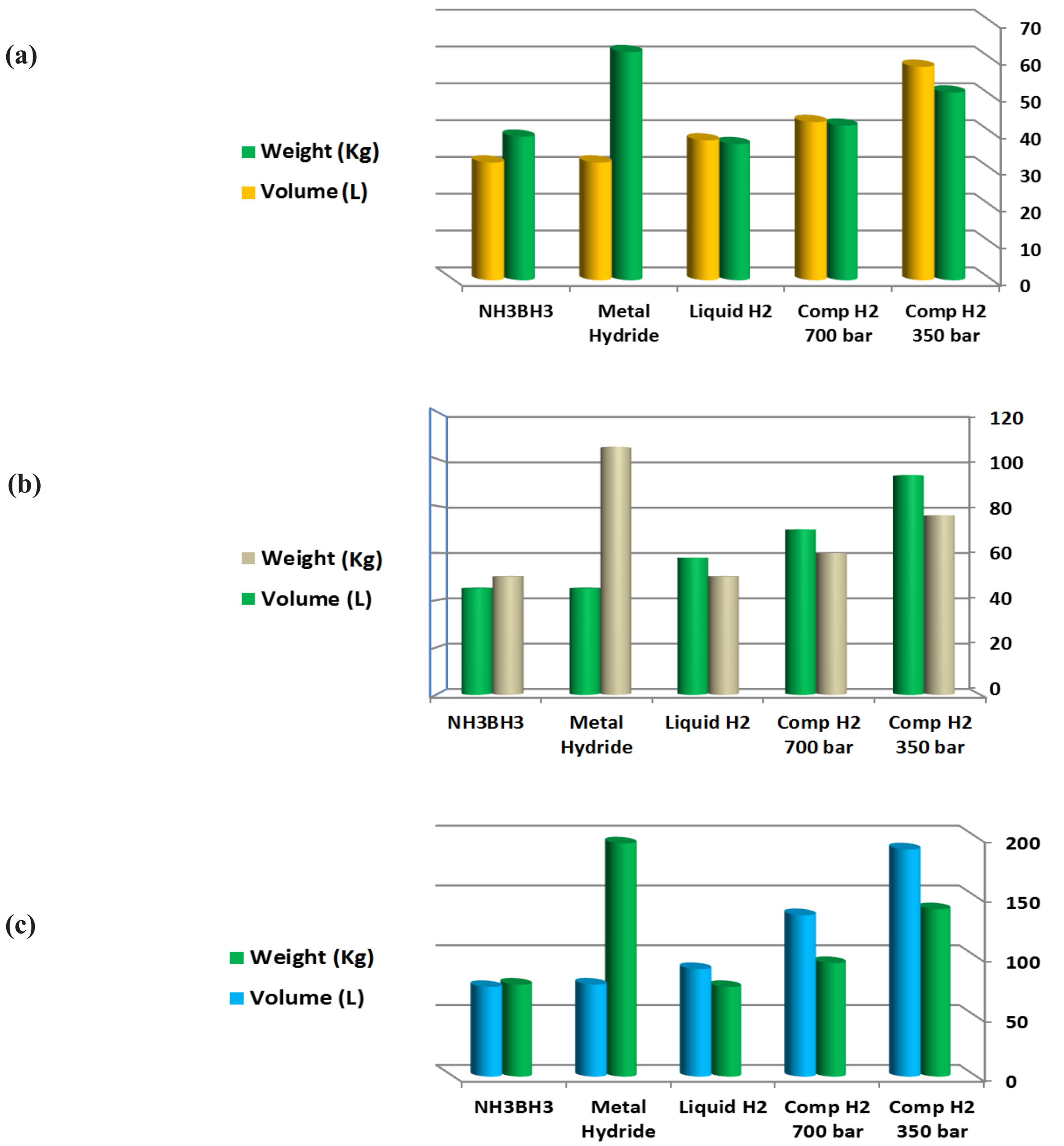

Fig. 1. Relative comparison of a fuel cell/battery power system with different methods of hydrogen storage for three durations, a: 20 h, b: 40 h, and c: 92.35 h [26].

Storing oxygen is generally done by one of the following methods [26]:

- Compressed oxygen
- Cryo-compressed
- Liquid cryogenic

The methods are described in Table 3. The differences in gravimetric and volumetric densities in different oxygen storage methods directly affect the UUV's size and weight. Therefore, one of the main items that should be considered in the UUV design process is selecting the oxygen storage method, which depends on available technology levels. Table 4 presents the comparison of different methods of storing oxygen.

Table 3.Three main oxygen storage methods [19].

		Gravimetric density		Volumetric density		Cost	
State type	Conditions	kWh/kg O_2 system	g O_2/kg O_2 system	kWh/L O_2 system	g O_2/L O_2 system	\$/kWh	\$/kg O_2
Compressed	700 bar	1.84	441	1.79	429	8	33
Compressed	350 bar	2.17	520	1.4	336	5.5	23
Cryo-compressed	300 bar 155 K	1.68	403	1.65	396	8.6	36
Liquid cryogenic	1 bar 90K	2.47	592	2.77	664	6.5	27

Table 4. Ranking of properties for different oxygen storage methods for UUVs 1-Excellent 2-Good 3-Fair 4-Poor [25].

	Gravimetric energy density	Volumetric energy density	Buoyancy	Buoyancy change during mission	Energy density at neutral buoyancy	System simplicity	Depth independence
Pressure tank of aluminum, 200 bar	4	4	3	2	4	1	2
Pressure tank of aluminum, 300 bar	3	3	1	2	3	2	3
Liquid oxygen, including thermal insulation and pressure hull	1	2	3	2	2	3	3
Hydrogen peroxide (50%)	3	3	3	2	3	3	1
Chlorate candles (e.g., $NaClO_3$)	3	2	4	3	3	4	3

The power system includes the fuel cell stacks, which produce power. UUVs are restricted by design due to their mass and volume. Special energy and energy density will be two crucial factors to take into account. Some common stacks, such as the Ballard 3 kW stack provided for the Perry PC-14 submarine, and the Ballard-Mark-V 35-cell 5 kW PEM stack, have been modified for use in UUVs [29]. Table 5 displays some fuel cell stacks used recently in various applications.

Table 5. Details of some implemented fuel cell stacks [29].

Manufacturer/Model	Fuel Cell Weight (kg)	Fuel Cell Dimensions L(mm)×W(mm)×H(mm)	Specific Power (W/kg)	Power Density (W/L)	Notes
UBZM Gmbh-BZ100 (1200W standard)	15	(180-520) ×145×125	78	127	Related o ZSW, manufacturer of DeepC PEMFC
Horizon AEROStACK A-1000 PEM FUEL CELL	1.75	275×135×120	571	224	With fan and casing, self-humidified
Horizon AEROStACK A-500 PEM FUEL CELL 500W	1.15	192×107×150	434	162	With fan and casing, self-humidified
Horizon AEROStACK A-200 PEM FUEL CELL 200W	0.5	120×80×75	400	278	With fan and casing, self-humidified
Ballard FCgen-1020ACS	11	(110-495) ×103×351	230	192	Air-cooled. Scalable. Self-humidifying membrane.
Horizon H-500XP	5.8	150×203×52	86	316	With blower, H2 supply and purge valve
Horizon H-1000XP	5.9	203×104×264	169	179	With blower, H2 supply and purge valve
Horizon H-300	2.79	118×262×94	108	103	With fan and casing, self-humidified, and blower
Horizon H-500	2.52	268 × 130 × 122.5	196	117	Blower, electronic valves, self-humidified, fan,
Horizon H-1000	4	268 × 219 × 122.5	250	139	Blower, electronic valves, self-humidified, fan,
Horizon H-2000	10	350 × 183 × 303	200	103	Blower, electronic valves, self-humidified, fan,
AREVA Helion 20 kW	160	690 × 470 × 335	125	182	-
Ned stack HP 2.0	15	217 × 194 × 288	133	18.4	-
Ned stack HP 5.0	22	353 × 194 × 288	227	254	-
Siemens BZM 34 kW	650	480 × 480 × 1450	52	102	Stack + balance of plant components
Siemens BZM 120 kW	900	500 × 530 × 1760	133	257	Stack + balance of plant components

2.2. Energy Storage

In this section, the energy storage units in the power systems are reviewed and shown in Tables 6 and 7. Table 6 provides the typical performance figures of electrochemical power sources in a generic UUV of a total volume of 1.2 m^3. The comparison of different energy storage technologies is presented in Table 7.

Table 6.Typical performance figures of electrochemical power [23].

Technology	Type	Energy density (Wh/dm^3)	Endurance (h)	Cost	Logistics/ maintenance
Lead-acid	Rechargeable	10-20	4-8	Low	Low
NiCd/NiMH	Rechargeable	10-30	4-12	Low	Low
Alkaline batteries (heated to +45 ºC)	Primary	10-30	4-12	Low/ high	Medium
Silver-zinc	Rechargeable	30-50	12-20	High	Medium
Lithium ion (D-cells)	Rechargeable	40-70	16-28	Medium	Low
Lithium polymer (poach)	Rechargeable	50-75	23-30	Medium	Low
Aluminum-oxygen	Semi fuel cell	80-90	32-36	Medium	High
Hydrogen-oxygen	Fuel cell	100+	40+	Medium	High
Lithium batteries	Primary	100-150	40-60	High	Low

Table 7. Comparison of different energy storage technologies [26].

	Lead-acid	Ni-Cd	NiMH	Li-ion	Zebra	Supercapacitor
Specific energy (Wh/kg)	35	45	65	100	120	1-10
Energy density (Wh/L)	120	110	135	115	140	N/A
Specific power (W/kg)	100	120	1000	1800	180	(1 10) 000
Self-discharge per month (%)	8	10	30	5	None	50
Nameplate cycle life	1000	1000	1000	>2000	2000	100,000
Efficiency (%)	70	80	80	85	90	95
Operation temperature (ºC)	-15-45	-40-70	-30-70	-20-60	275-350	-40-50
Cost ($kW/h)	105-175	200-300	250-350	250-1000	70-270	10,000

Comparing different electrical energy storage technologies, considering the energy density and power density in the form of the Ragone plot, as shown in Figure 2, would be useful [26].

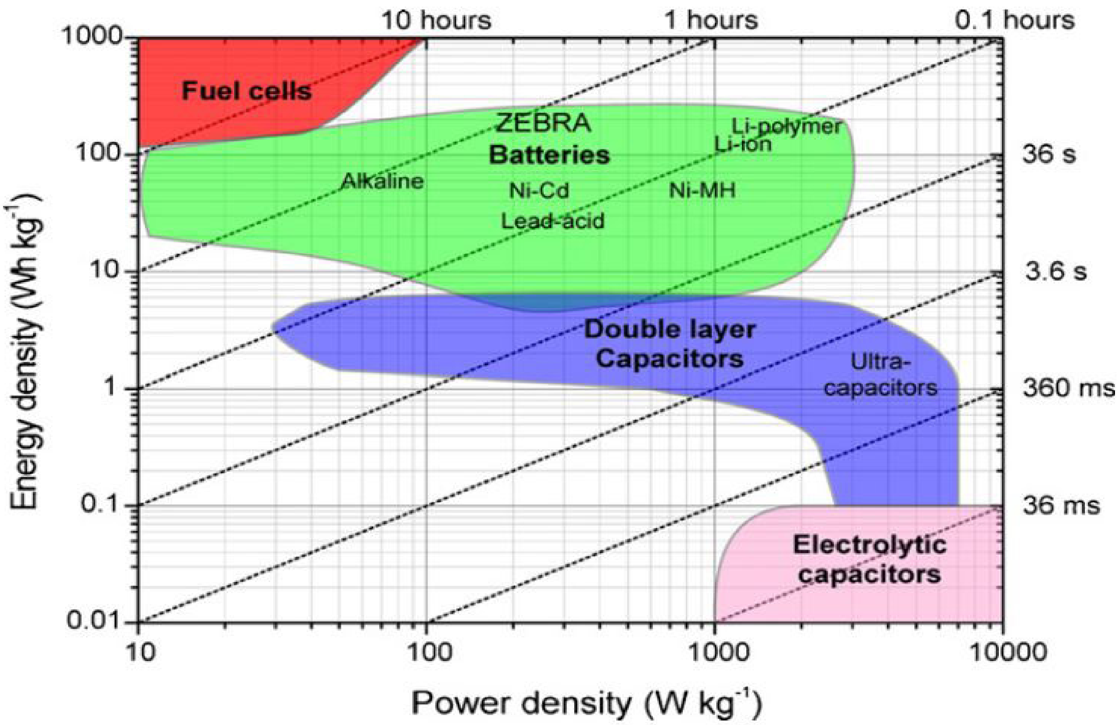

Fig. 2. The Ragone plot for electrical energy storage technologies [26].

The domains for each technology category are represented on the plot to demonstrate the locations of various technologies. Ragone plots are frequently revised due to the series' rapid technological improvements, particularly in lithium batteries.

From the top left-hand corner (high energy storage, low power density) to the bottom right-hand corner (low energy density, high discharge rate/power density), the technologies exhibit a spectrum of performance. The hybridization method can be considered the most critical factor in achieving extra-high power and energy densities [26].

2.3. Specifications of several models of fuel cell UUV

Information about certain fuel cell UUVs' features can be seen in Table 8. L is the length, D is the inner diameter, Δ is the mass displacement, h is the maximum depth, v is the maximum speed in knots, and then in m/s in the next column. E is the stored energy, T is endurance, and ŵ is the mean power output. Finally, the mean values for all UUVs are computed. More details on a famous UUV model. (HUGIN 3000) are shown in Table 9.

Table 8. Commercial UUVs components' data [19].

UUV	L (m)	D (m)	Δ (kg)	h (m)	v (knot)	v (m/s)	E (kWh)	T (h)	ŵ (kW)	L/D	Battery type
HUGIN 3000	5.7	0.75	1200	4500	6	3.1	48	24	2	7.6	Li-Po
MUNIN	3	0.34	300	1500	4.5	2.3	5	12	0.42	8.8	Li-ion
REMUS 100	1.7	0.19	32	100	5	2.6	1.5	12	0.13	8.9	Li-ion
REMUS 600	3.25	0.32	240	600	4	2.1	5.2	24	0.22	10.2	Li-ion
REMUS 6000	3.99	0.66	240	6000	4.5	2.3	11	16	0.69	6	Li-ion
SeaCat	2.75	0.32	180	600	6	3.1	Not given	10	Not given	8.6	Ni-Cd
SeaOtter	3.65	0.48	1200	600	7	3.6	Not given	20	Not given	7.6	Ni-MH
Bluefin-9	1.75	0.24	60.5	200	5	2.6	1.5	12 (3kn)	0.13	7.3	Li-ion
Bluefin-9M	2.5	0.24	70	600	5	2.6	1.5	10 (3kn)	0.15	10.4	Li-Po
Bluefin-12S	3.77	0.32	213	200	5	2.6	4.5	26 (3kn)	0.17	11.8	Li-Po
Bluefin-12D	4.32	0.32	260	1500	5	2.6	7.5	30 (3kn)	0.25	13.5	Li-ion
Bluefin-21	4.93	0.53	750	4500	4.5	2.3	13.5	25 (3kn)	0.54	9.3	Li-Po
Teledyne Gavia	1.8	0.2	49	1000	5.5	2.8	1.2	7	0.17	9	Li-ion
A9-E	2.5	0.23	100	200	5	2.6	4.2	20	0.21	10.9	Not given
A18-E	3.8	0.47	370	300	6	3.1	11	24	0.46	8.1	Li-ion
A18D	5.5	0.5	690	3000	6	3.1	14.4	24	0.6	11.7	Li-ion
A18TD	4.7	1.8	1200	3000	6	3.1	22	24	0.92	2.6	Li-ion
A27-E	4.5	0.73	850	300	6	3.1	32.2	30	1.04	6.2	Not given
ALIStAR 3000	5.8	1.68	3000	3000	4	2.1	22	12	1.83	3.5	Li-ion
Solus-LR	8.5	1	3700	3000	4	2.1	Not given	360 (3kn)	Not given	8.5	Li-ion
Average of the report-ed values	3.9	0.57	735	1735	5.2	2.7	12.12	36	0.58	8.5	-

Table 9. HUGIN 3000 UUV information [23].

Displacement (m^3)	2.4
Dry weight (kg)	1400
Length (m)	5.35
diameter (m)	1
Maximum operation depth (m)	3000
Endurance	60 h at 4 knots, all sensors operating
Battery weight (kg)	472
Nominal system voltage (V)	30
Nominal system energy (clear electrolyte) (kWh)	50
Maximum continuous system power (kW)	1.2

2.4. Fuel Cell Power System UUVs

Investigating UUV power system commercial products and prototypes can be useful for fuel cell UUV conceptual design. Some fuel cell UUV prototypes and their brief descriptions are shown in Table 10.

Table 8. Several fuel cell UUV prototypes [29].

UUV	Country	Company	Year	Description
Urashima	Japan	JAMStEC & Mitsubishi Heavy Industries	1998-2005	PEMFC and lithium-ion cells Weighs 10 tons, 10 m length, and 1.4 m diameter Its fuel cell power has two 2 kW fuel stacks at 120 V Also has a 30 Ah lithium battery
Second Generation Long cruising UUV	Japan	JAMStEC & Mitsubishi Heavy Industries	2009-2013	A desktop PEMFC prototype for a fuel cell system called HEML (high-efficiency multi-less) Its fuel cell power has two 150 W fuel stacks at 120 V Can generate 600 h continuous electric power
DeepC	Germany	StN ATLAS Electronic funded by German Federal Ministry for Education	2003-2004	A hybrid battery-PEM fuel cell system consisting of two 30-cell stacks with a total output of 3.6 kW They are located in a gas chamber with a pressure relief valve for safety A total electrical energy of 140 kWh obtained
IDEF Ifremer	France	HELION firm (a subsidiary of the Areva group)	2009	It weighs 1.6 tons and has a 6 m length The PEM fuel cell is composed of 63 cells and produces 1.5 kW A total electrical energy of 36 kWh
Underwater Glider Dragon	China	Tianjin University	2018	PEMFC volume of 6500 cm^3 Weigh about 70 kg, 2.3 m length, 22 cm diameter Using a stack that has a 12 V voltage and 100W power
Seahorse	USA	Pennsylvania State University ARL	1999-2008	Worked on a 400 W PEM fuel cell

3. Conceptual Design and Analysis

A typical block diagram of the fuel cell power system of UUVs is shown in Figure 3. A control system manages the processes in the different subsytems.

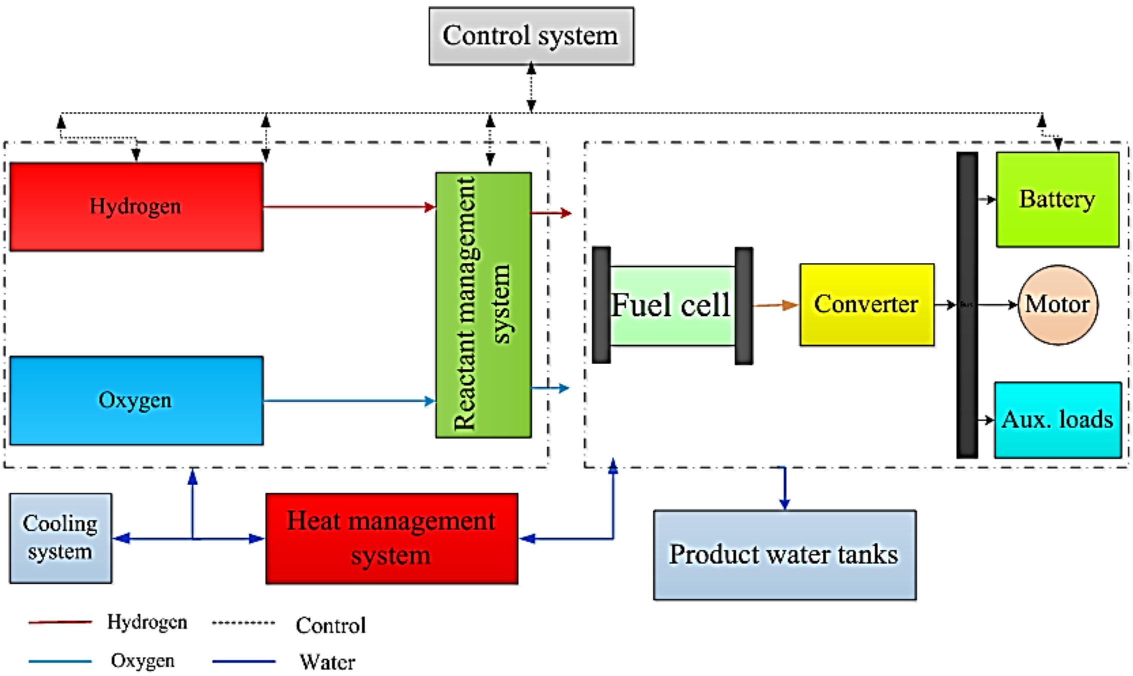

Fig.3. System architecture of the hybrid fuel cell/battery power system for UUVs.

3.1. DOH (Degree of Hybridization)

The power system requirements determine the specifications of the fuel cell hybridization with other electrical energy storage units. It is useful to define a variable called the degree of hybridization (DOH) as follows [26]:

$$DOH = \frac{\max power - fuelcellpower}{\max power} \qquad (1)$$

A high DOH number denotes a relatively high power output from the energy storage unit, while a low DOH value signifies a relatively low power output from the energy storage unit compared to the fuel cell.
Equation (1) can be expressed as equation (2) when the battery serves as the energy storage device [26]:

$$DOH = \frac{batterypower}{batterypower + fuelcellpower} \qquad (2)$$

A general power profile is shown in Figure 4. The fuel cell and battery have been combined so that the fuel cell will provide the constant average power, and the battery will provide the peak power during cyclic times of high and low power demand, both of which have variable duration.
The energy storage device is charged when the power given to the load falls below the average power. We define T as the ratio of the discharge time t_1 to the charge time t_2, as written in Equation (3), and F as the ratio of the peak power P_1 to the base power P_2, as

written in Equation (4). The average power ($P_{average}$) is determined by Equation (5). Therefore, DOH can be calculated by Equation (6) [26].

$$T = \frac{t_1}{t_2} \tag{3}$$

$$F = \frac{p_1}{p_2} \quad p_1 \geq p_2 \Rightarrow F \geq 1 \tag{4}$$

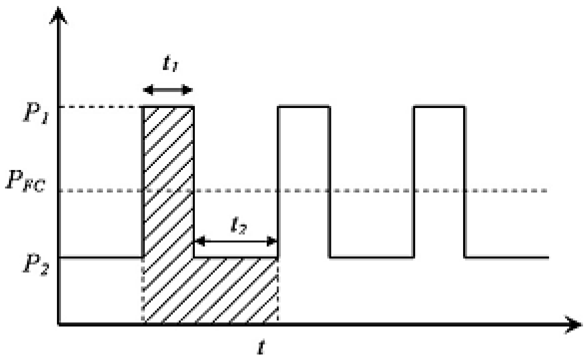

Fig. 4. A generic power profile [26].

$$P_{average} = \frac{p_1 t_1 + p_2 t_2}{t_1 + t_2} \tag{5}$$

$$DOH = \frac{p_1 - p_{average}}{p_1} \tag{6}$$

The energy discharged from the energy storage unit for a power profile like that in Figure .4 can be calculated by equation (7) [26]:

$$E_s = n(p_1 - p_{average})t_1 \tag{7}$$

And the energy from the fuel cell is

$$E_{FC} = p_{FC}(t_1 + t_2) = p_{FC} t_{total} \tag{8}$$

Where n is the total number of cycles in the operating time. If the fuel cell is the only source to supply the average power, as shown in Figure. 4, P_{FC} would be equal to $P_{average}$. P_{FC} generally equals $P_{average}$ plus the power required by the auxiliary units, such as pumps and fans, if the fuel cell system is to supply the average power as well as the power required from the balance-of-plant auxiliaries. In any case, charging the energy storage unit is directly tied to the average power. The parameters E_S and E_{FC} are used to determine the specifications of the energy storage unit and the fuel cell system needed for a particular application. [26]

3.2. Charge/discharge limitation (characteristic time)

The charge or discharge process will be the fastest processes, depending on the nature of the power profile. It is crucial to figure out which is fastest to identify the storage technology capable of attaining the required charge/discharge rate and how efficient the process is at that rate [26]. The system is within the charge limit if:

$$p_{average} < p_2 + \frac{1}{2}(p_1 - p_2) \tag{9}$$

$$p_{average} > p_2 + \frac{1}{2}(p_1 - p_2) \tag{10}$$

And the system is within the discharge limit, if:

It can be proved that for a given T and F, the system is in the charge limit if the DOH value satisfies Equation (11), and is in the discharge limit if the DOH satisfies Equation (12) [26].

$$DOH < \frac{2T(F-1)}{F(T+1)^2} \tag{11}$$

$$DOH > \frac{2T(F-1)}{F(T+1)^2} \tag{12}$$

The boundary between the two domains is written as Equation (13):

$$DOH = \frac{2T\,(F-1)}{F\,(T+1)^2} \qquad (13)$$

In Figure 5, the DOH-F profile for different values of T is shown in a logarithm scale. In Figure 6, the DOH-T profile for different values of F is given.

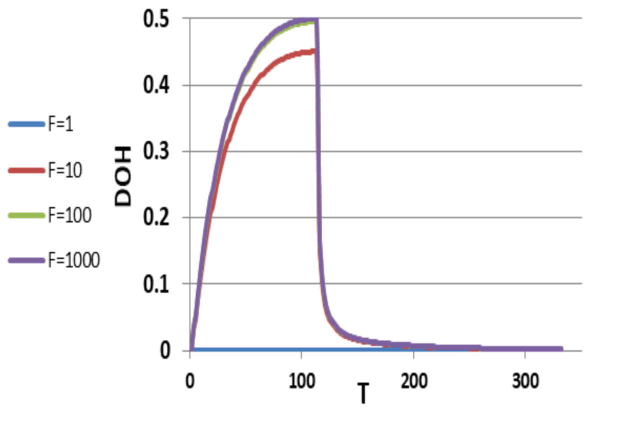

Fig. 6. The DOH-T profile for different values of F.

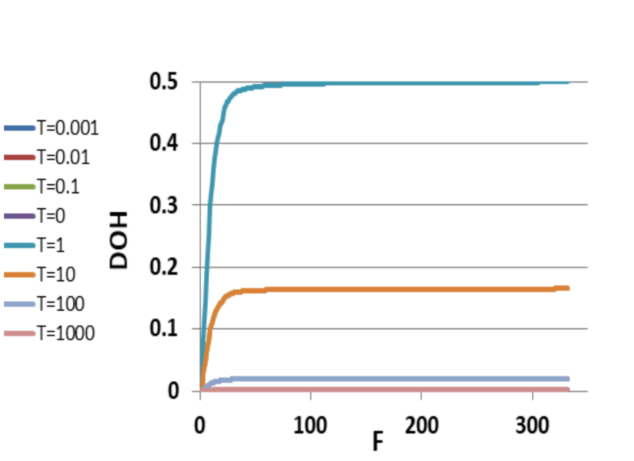

Fig.5. The DOH-F profile for different values of T.

3.3. Components of a Fuel Cell UUV Hybrid System: Proposed Technologies

The proposed technologies for fuel cell/battery hybrid systems from a survey of recent UUVs with tonnages varying from 1-10 tons are summarized in Table 9.

Table 9.The proposed technologies for hybrid fuel cell/battery system UUV.

Parameter		Type/Value	Unit/Considerations
	Tonnage	1-10	ton
	Type of Fuel cell	PEM FC	Low Temperature
	Oxidant	Pure Oxygen	Purity>99.5%
Hydrogen Storage	**Type**	High pressure vessel	-
	Pressure	> 350	bar
Oxygen Storage	**Type**	High pressure vessel	-
	Pressure	> 350	bar
	Fuel Cell Power	1-4	kW
	Type of Battery	Li-ion	-
	Endurance	20	hours
	Length	3.5	m
	Diameter	0.5	m
	Length/ Diameter	7	-
	Maximum Depth	1700	m
	Maximum Speed	5	knot

4. Conclusion

Utilizing fuel cells can be considered a key technology to achieve a new generation of UUVs with more endurance and efficiency. The selection of fuel cell type, hydrogen and oxygen storage methods, energy storage technology, and the range of DOH (Degree of Hybridization) are the main challenges in fuel cell/battery hybrid UUV design. The main fuel cell types and different method for storing hydrogen and oxygen were discussed in this paper. Also, the commercial fuel cell stacks for UUV applications were reviewed and the energy storage technologies were discussed. The conceptual design of a fuel cell/battery UUV power system, including the system block diagram and DOH range estimation, was also presented. The technologies for the main components of the hybrid UUV power system, with tonnages varying from 1-10 tons, were also proposed. The results primarily indicated that the low temperature PEM fuel cell with pure oxygen as the oxidant is superior to other fuel cell types in UUV applications. The proposed fuel cell power system's specifics were in the 1-4 kW range depending on the UUV demands with the hydrogen and oxygen stored in high pressure vessels (more than 350 bar). Li-ion battery was proposed as the energy storage unit of the hybrid system, giving the UUV an average endurance, length, and diameter of 20 hours, 3.5 m, and 0.5 m, respectively. The maximum depth and speed of the UUV were proposed as 1700 m and 5 knot, respectively.

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