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Review article

A review of the impact of ambient conditions and degradation in hybrid fuel cell powered unmanned aerial vehicles

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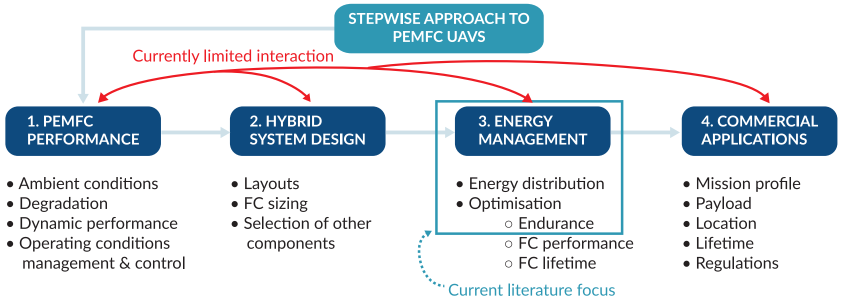
HIGHLIGHTS

- Commercial PEMFCs for UAVs employ simplified operating conditions management systems.
- Performance of these FCs may be more sensitive to ambient conditions and degrade faster.
- There is a lack of layout and dimensioning guidelines for PEMFC UAV hybrid systems.
- Recent works focus on energy management but oversimplify FC performance and lifespan.
- Future work should assess the feasibility of PEMFC UAVs in commercial applications.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrogen fuel cells (FCs) integrated into unmanned aerial vehicles (UAVs) are considered a sustainable technology enabling long-endurance missions using electric propulsion. This paper reviews the current state of the art in the energy system design of fixed-wing UAVs using FCs. The power profiles of UAVs are highly dynamic, and power surges are possible, requiring hybridisation. We review the commercially available PEMFCs specifically designed for UAVs. Moreover, we discuss the management of operating conditions and show that, due to mass considerations, PEMFCs for UAVs are supported by a simplified balance of plant. Therefore, PEMFC UAVs may experience lower performance and shorter lifetimes due to increased exposure to ambient conditions and higher degradation rates. This necessitates further research as it could limit the deployment of PEMFC-powered UAVs. In addition, it is advised to consider these effects when designing PEMFC UAVs hybrid systems. Besides taking durability into account, we identified clear knowledge gaps. They originate from a lack of guidelines focusing specifically on the selection and dimensioning of hybrid electric systems for PEMFC UAVs. A stepwise approach is proposed to assess the commercial feasibility of

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PEMFC UAVs for realistic missions, focussing on the applicability, performance, and lifetime to move beyond the demonstration phase.

Contents

1. Introduction

The aviation industry underwent an immense transformation in the last decade thanks to unmanned aerial vehicles (UAVs). Compared to manned aircraft, they offer unrivalled flexibility, ease of deployment, and cost-efficiency [1–3]. The applications and sectors in which they are deployed keep growing progressively [4], with an expected compound annual growth rate (CAGR) of 25.82% between 2023 and 2030 [5]. One typically distinguishes five main areas in which civil UAVs can be used, notably inspection tasks, surveillance, and logistics, including urban air mobility, wireless communication, and agriculture [6,7].

Electric-powered UAVs are becoming more popular than drones relying on combustion engines thanks to their higher efficiency, absence of pollutant emissions [8–10] and potential to decarbonise aviation [11]. Airbus, for example, invests significantly in the future electrification of its fleet [12]. In addition, electric powertrains are easier to control, emit less noise, and have a low thermal signature [9,13]. However, the downside of full electrification is the weight penalty it involves compared to the use of conventional powertrains with internal combustion engines burning hydrocarbon-based liquid fuels. The latter systems are characterised by gravimetric energy densities that outperform those of batteries [14]. Therefore, electric UAVs powered by batteries typically suffer from a lower endurance [2,15,16], but also from long charging times compared to drones using liquid carbon-based fuels [7,16]. In this regard, fuel cells become attractive.

Fuel cells (FCs) are electrochemical devices that generate electricity directly by converting a chemical energy carrier and an oxidising agent into reaction products. For drones in particular, one primarily considers hydrogen (reductant) and atmospheric oxygen (oxidant), which are transformed into water with heat as a byproduct. Compared to batteries, FCs have the potential to significantly increase the endurance and payload of electric UAVs thanks to a combination of high efficiency and a high gravimetric energy density of hydrogen [17–19]. Xiao et al. [10] reported a doubled flight time when using FCs instead of batteries. Another study indicated that battery-powered UAVs have a specific energy density of 150–250 Wh/kg, allowing the studied fixed-wing UAV to theoretically have a flight time ranging between 60–90 min [20]. They suggested that FCs have the potential to reach an energy density of 800–1000 Wh/kg when combined with compressed hydrogen stored in a tank with a gravimetric efficiency of 6%. A similar study determined the endurance of electric UAVs, where the flight performance is compared between drones with batteries on the one hand and FCs on the other [21]. They concluded that FC-powered drones outperform those powered with batteries in terms of endurance when the UAV energy demand goes beyond 4 MJ. UAVs with longer endurance could open up opportunities for broader applications and new markets [9,16].

Implementing FCs into UAVs can be complex due to their limited power density and slow dynamics [6,8,10,20,22]. Therefore, FCs tend to degrade faster when subjected to highly unsteady power profiles [23]. The available peak electric power determines the UAV's maximum flying speed, payload capacity, flying altitude and climb rate [24]. Since most of the mission profile of a fixed-wing drone requires less than maximum power, FCs are combined with other energy systems that exhibit better peak-power characteristics by forming a hybrid system [6,8,10,22]. In general, batteries are commonly used to support the FC [7,23,25], while other options include (super)capacitors and solar cells [6,22]. DC–DC converters then enable management strategies to regulate the different power sources and determine the hybrid system layout [20]. However, the required level of hybridisation depends greatly on the specific UAV use, which is associated with the power profile.

To the authors' knowledge, existing literature does not provide a comprehensive overview of dimensioning strategies for UAV FC hybrid systems. As a result, this review paper aims to offer a thorough perspective on various layout and dimensioning strategies for designing hybrid electric systems for PEMFC UAVs, with a primary focus on FCs. First, a review of various electrical energy systems that can be combined into a hybrid configuration is provided. Their operating principles are briefly described and compared. Second, commercially available FC systems for UAVs are presented and discussed in terms of operating conditions. The potential impact of different ambient conditions and the degradation of FCs is given particular attention. Considering these factors in the design of FC-based hybrid propulsion systems is expected to be vital for successfully adopting FC technology widely into UAVs and aircraft in general. Third, the different hybrid system architectures are discussed and linked to energy management. Lastly, the paper concludes with suggestions for future research.

2. Energy systems for FC UAVs

A Ragone plot, as shown in Fig. 1, is frequently used to compare the gravimetric energy density and power density of energy conversion and storage systems [26]. These parameters are critical for UAVs as they have a substantial impact on the design and flight performance [22]. Fig. 1 clearly shows that FCs are an excellent option if the design objective is to obtain a UAV with high endurance since minimising mass is always a concern in aircraft design. This is indeed equivalent to choosing energy systems characterised by a high gravimetric energy density. For FCs, this parameter is affected by the FC efficiency, the amount of stored hydrogen, storage methodology, such as compressed gas or liquid, and the storage efficiency of the tank [3,20]. However, the exclusive use of FCs also implies a limitation in power density. Dimensioning the fuel cell relying on the gravimetric power density to provide the UAV with the maximum required power is obviously not a reasonable approach. The maximum required power is generally only required during limited flight phases in the mission profile, such as take-off, climbing and manoeuvring under high load factors. This would result in an overly heavy propulsion system and, thus, in excessive fuel consumption. Therefore, hybridisation of the propulsion system is essential for UAVs using FCs. The following subsections review, besides the FC, two energy systems that are eligible to be used in a hybrid configuration with a FC. These include different types of batteries and supercapacitors. The operating principles, advantages and disadvantages of their implementation in a hybrid system are discussed concisely. Note that some works have been found in the literature that describe the potential benefit of the use of solar panels (PV) as part of the hybrid propulsion system to improve the endurance of UAVs [10,22,27,28]. However, commercial UAVs are typically required to fly in all weather conditions. This makes relying on solar energy difficult due to its intermittency [27]. Therefore, this review paper will not further elaborate on PV technology.

2.1. Fuel cells (FCs)

Like batteries, FCs are electrochemical devices that convert chemical energy into electricity [19,30]. The chemical energy in batteries is stored in the active material using intercalation [31,32]. FCs, on the other hand, extract the energy from fuel, usually in the form of pure hydrogen. Despite the benefit of fast refuelling, pure hydrogen storage and handling in any state of manner introduces extra complexities. Moreover, the current lack of hydrogen infrastructure and thus availability is also a disadvantage related to using hydrogen [11,32]. A potential solution is the use of FC types that accept fuels other than pure hydrogen, such as methanol [7]. In literature, Solid Oxide Fuel Cells (SOFCs), Polymer Electrolyte Membrane Fuel Cells (PEMFCs), and Direct Methanol Fuel Cells (DMFCs) are cited to be eligible for use in UAVs [6,20,22]. A brief examination of these FC types in terms of their modes of functioning, advantages, and limitations follows next. The key characteristics of these devices are reflected in Table 1.

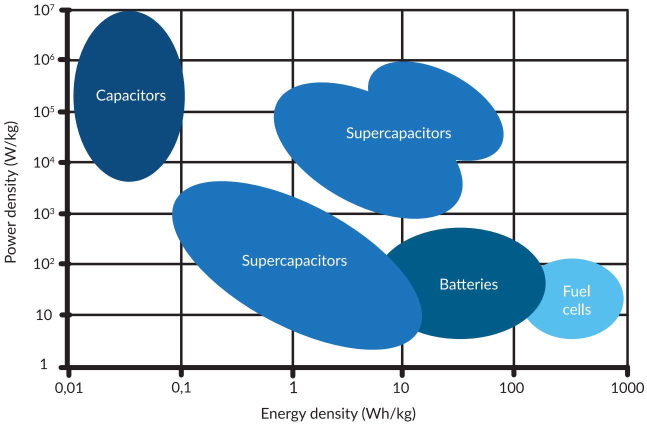

Fig. 1. The Ragone Plot presents the power and energy density of various energy systems categorised by type. Based on [29].

SOFCs belong to the category of high-temperature FCs. They typically operate within a temperature range of 600 to 1000 °C. As a result, less expensive catalysts can be used, and it is possible to feed the FC with not only hydrogen, but also hydrocarbon fuels [33,34]. The latter fuels are currently more cost-effective than pure hydrogen and easier to store and handle. However, the use of hydrocarbons (HCs) in SOFCs will still emit greenhouse gasses [22]. High-temperature FCs have long warm-up times and exhibit slow transient response resulting in poor load-following abilities [35,36]. Due to high temperatures, issues related to thermal and mechanical compatibility may arise in SOFCs. These issues include cracking, delamination, and corrosion, which arise from differences in material parameters and thermal stresses, as well as chemical changes at the interfaces of the materials [34]. According to Giacoppo et al. [37], there is a lack of literature available on the thermal and mechanical issues associated with SOFC implementation in UAVs. Research is still focusing on developing better materials to enhance thermal, chemical, and mechanical compatibility [34]. Besides, SOFCs are mainly used in stationary systems [38] exhibiting high efficiencies, i.e. between 60%–70% [6,39]. Unfortunately, smaller systems have approximately a 10% lower efficiency due to higher thermal losses [20]. Therefore, relevant studies [6,20,22] conclude that the current SOFC technology is not the best option to power UAVs. Nevertheless, SOFCs are still considered to decarbonise aviation by, for example, incorporating SOFCs in high-temperature applications, such as in a jet engine [40].

In PEMFCs, pure hydrogen is electrochemically oxidised at the anode, producing protons and electrons (a more elaborate discussion follows in Section 3). The protons migrate through the electrolyte to the cathode, while the electrons travel through an external circuit to the cathode, where they recombine with oxygen to form water [18,19]. Pure hydrogen introduces extra complexity regarding handling, storage and size of the storage system [41]. However, PEMFCs offer a relatively high power density compared to other FC types, and they respond better to dynamic loads [42]. In addition, their efficiency is high [18,19] and the operating temperature range of 30–80 °C is better suited for use in UAVs due to quicker startup times [10], improved safety,

Table 1
Comparison of fuel cell types for UAVs.

Type	Fuel	Efficiency [%]	Temperature [°C]	Stack specific power [W kg^{-1}]	System specific power [W kg^{-1}]
SOFC	Hydrocarbons	60–70	500–1000	>800	>100
PEMFC	Hydrogen	40–60	30–80	>500	>150
DMFC	Methanol	20–30	20–90	>70	>50

and higher reliability in terms of mechanical, thermal, and chemical compatibility [22].

DMFCs are very similar to PEMFCs in terms of operating principles and composition [43] but allow the use of methanol as a fuel. This results in a higher volumetric energy density compared to hydrogen while also making handling and storage more convenient [44]. However, a less hydrogen-dense fuel, which contains a lower amount of hydrogen per unit volume compared to pure hydrogen, typically leads to lower efficiency due to low anode kinetics. In addition, the crossing of methanol through the membrane without undergoing any reactions is also a significant issue that reduces efficiency [45]. The low specific power also suggests that PEMFCs are a better option for UAV applications [6,20,22,39].

Considering the above, it is not surprising that literature currently presents PEMFC technology as the most promising to power UAVs [6, 20,22,24,46]. Section 3 will elaborate on this technology, discussing its configuration and operating conditions, and focus specifically on FC systems designed for UAVs. There, the challenges related to the hybrid system dimensioning will be highlighted when degradation and ambient conditions must be taken into account, as these are often ignored in the literature.

To conclude, it is important to highlight some of the major disadvantages related to FCs. They have relatively low power densities and slow response rates compared to other energy systems such as batteries and supercapacitors [7,24,32]. This can be a disadvantage for certain UAV applications and specific missions that require rapid responses, such as evasive manoeuvres, sudden altitude changes, and strong winds. The slow dynamics are mainly caused by the electrochemical reaction characteristics and lag related to the balance of plant (BoP) [20,22]. The BoP is the assembly of all supporting systems around the FC, such as the FC cooling system, reactant supply systems, and the hydrogen storage system. The BoP must ensure that the FC operating conditions remain in the desired operating range [32]. Therefore, it plays a crucial role in the impact of ambient conditions and is discussed in detail in Section 3.3.

2.2. Batteries

At present, electric UAVs mainly rely on batteries as their primary power source [6,10,47,48]. The battery technology is mostly lithium-based, which can either be Li-ion- or Li-polymer-type batteries [6,8]. Battery electrochemistry relies on lithium ions, which are kept in the electrode's active material, consisting of a layered structure [49]. During battery discharging, electrons are separated from their source at the anode and flow through an external circuit. At the same time, protons and electrons combine at the counter electrode, a process known as intercalation, which is a crucial step in the energy storage process [50,51]. The general half-reactions occurring at the cathode and anode in a lithium battery are given below. Lithium ions are absorbed during discharging at the cathode [52]. When the battery is being charged, this process is reversed, completing a cycle that can be repeated [53]. Li-based batteries are already widely studied in combination with FCs in hybrid systems for UAVs [22]. Compared to other rechargeable battery types, lithium-based batteries have a higher power density, handle dynamic power profiles better, possess a longer life cycle, and self-discharge slower [8,10,51].

$$\textbf{Cathode}: \mathrm{LiCoO_2} \longleftrightarrow \mathrm{Li_{1-x}CoO_2} + \mathrm{xLi^+} + \mathrm{xe^-} \qquad \text{(reduction)}$$

$$\textbf{Anode}: \mathrm{xLi^+} + \mathrm{xe^-} + 6\,\mathrm{C} \longleftrightarrow \mathrm{Li_xC_6} \qquad \text{(oxidation)}$$

Batteries fulfil four main functions in hybrid FC systems for UAVs. First, batteries can provide a relatively constant output voltage for the propulsion system [6]. In FCs, the cell voltage depends strongly on the load current, as shown by the polarisation curve discussed further in Section 3.1 [18]. For batteries, the State of Charge (SoC) has a less pronounced influence on Li-ion battery voltage, although the C-rate can play a significant role [51]. Besides batteries, DC–DC converters can also be used to achieve a constant output voltage [54,55]. However, adding extra components to the hybrid system can lead to an increased mass and cost, a larger system complexity, and a lower efficiency [6, 56]. Additionally, this potentially reduces the dependability of UAVs by introducing a new failure mechanism [23]. Section 4 discusses the relationship between hybrid systems and DC–DC converters in more detail.

Second, a battery can provide buffer power during highly demanding flight phases, for example, during take-off [10]. As mentioned, FCs are characterised by a low power density, resulting in a heavy and over-dimensioned system if only FCs are used to power UAVs [20]. In addition, FCs delivering high power exhibit a lower efficiency due to concentration losses [19]. Frequent operation in these high-power regions can also reduce FC lifetime due to local dehydration, membrane flooding and reactant starvation as described in Section 3.5.3. Batteries can support FCs in delivering a higher power output during highly demanding flight phases. Furthermore, the FC can recharge the battery during lower power demand phases, such as the cruise phase [57].

Third, the FC power demand can be stabilised using batteries [21]. A highly dynamic and noisy power profile, common for UAVs, is unsuited for FCs due to the limited dynamic response and causes accelerated FC degradation. In addition, operating the FC at low power outputs corresponding to the low-efficiency region can be avoided using batteries, which can also increase the FC lifetime. These degradation mechanisms are also detailed in Section 3.5.3.

Fourth, previous studies suggested using batteries to provide emergency power in case of a FC failure [24]. According to Xiao et al. [10], the capacity required for emergencies should be considered when sizing the battery in UAVs.

To conclude, the literature suggests that batteries are crucial components in FC UAV hybrid systems, fulfilling various roles depending on the application. Choosing the right combination of batteries and fuel cells for UAVs is a complicated process, considering factors such as capacity, open circuit voltage, C-rate, mass and size. The load profile of the UAV application also plays a significant role. This topic will be explored further in Section 4. In this section, we provide a literature overview of various hybrid systems and link them to dimensioning strategies. This will help to assess the role and necessity of using batteries in PEMFC hybrid systems.

2.3. Supercapacitors

Supercapacitors are a promising technology that can complement FCs in hybrid systems for UAVs. They offer high power density and reliability, which makes them an attractive choice [8]. Compared to batteries, they operate within a wider temperature range, have lower internal resistance leading to faster response times, can handle overcharge, and have longer lifetimes [6,20]. This is thanks to their construction based on two electrodes separated by an electrolyte. Supercapacitors combine the specific capacity of electrochemical capacitors with the high working voltage of an electrolytic capacitor [8]. This results in various types of supercapacitors, explaining the multiple and large regions in Fig. 1 [29]. In a hybrid system, supercapacitors can furthermore provide peak power during high-demanding flight phases, reduce voltage fluctuations when combined with a FC and a battery and provide emergency power [10,58]. However, since the electric charge determines the operating voltage of the supercapacitor, which may vary substantially, the technology is considered more challenging in supporting the FC to achieve a constant load voltage independently of the current demand. Therefore, it is advised to use supercapacitors only in a hybrid FC-battery setup combined with the use of DC–DC converters [22].

Gong et al. [59] claim to be the first to analyse the performance of a hybrid system consisting of a supercapacitor, FC, and battery for UAVs during flight. They concluded that the supercapacitors showed the expected load smoothing of the FC. In a similar study by Gong et al. [60], the authors conducted a hardware-in-the-loop analysis of a FC-battery-supercapacitor hybrid system. They demonstrated load smoothing and improved performance under gusty flight conditions. Wang et al. [22] mentioned the idea of using supercapacitors to provide emergency power in case of a failure. Nevertheless, while implementing supercapacitors in FC hybrid systems for UAVs shows to be promising, it still needs further study and development [8,9].

3. Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

This section focuses on commercially available PEMFC stacks designed explicitly and solely for UAVs. Hereby, a market survey is performed, giving specific attention to the various operation conditions management strategies employed involving heat, water and gas management. The potential impact of ambient conditions relevant to UAVs on the PEMFC performance and degradation mechanisms will be explored.

3.1. Working principles and layout

In PEMFCs, hydrogen is fed at the anode and oxidised electrochemically, delivering protons and electrons [18,19]. The basic operating principle, composition and chemical reactions for one cell are shown in Fig. 2. The anode electrode basically consists of a porous gas diffusion layer, a conductive layer and a catalyst, usually platinum nanoparticles supported on carbon [17]. The cathode electrode has a similar layout. Anode and cathode are adhered to a polymer(-based) electrolyte membrane (PEM) such as Nafion$^{\text{TM}}$. The membrane electrode assembly (MEA) is defined as the combination of the anode, the PEM and the cathode. It is considered the most essential component of a FC [18,19]. The PEM only allows protons to pass through it. During operation, the protons and electrons obtained from hydrogen move from the anode to the cathode to react with oxygen and form water. The electrons, however, must pass through an external circuit, whilst the protons can migrate directly through the membrane. This way, the PEMFC generates a direct current (DC). Note that the oxygen consumed in the FC is typically taken from ambient air.

The polarisation curve gives the performance characteristics of the PEMFC. An increase in current density results in a lower voltage, with a typical operating range of 1 V to 0.5 V per cell. An example of a typical single-cell PEMFC polarisation curve and the corresponding power curve is also provided in Fig. 2. To achieve a higher power output while also improving output voltage compatibility and efficiency, multiple cells must be combined to form a PEMFC stack [61].

3.2. Commercial PEMFC stacks for UAVs

There are several commercially available PEMFC stacks that are specifically designed to power UAVs. Table 2 provides an overview of these stacks and their respective power ranges, as well as the type of heat, gas, and water management strategy used by each manufacturer. Mass is not included in the comparison table as some manufacturers include controllers, batteries, and fuel tanks, making it difficult to compare. H3 Dynamics, Intelligent Energy, and Spectronik are the most commonly mentioned options in literature. Honeywell and Plug Power also manufacture PEMFCs for UAVs, but there is less information publicly available. Table 2 clearly exposes the similarity of employed management strategies by the different manufacturers, which are discussed in detail in the sections below. Fig. 3 illustrates a typical open cathode PEMFC configuration for UAV applications. It shows the front, back, and side views, along with the airflow direction of a 2021 H3 Dynamics A250.

3.3. Operating conditions management for open cathode systems

The operating conditions are defined as the conditions under which a system is expected to function effectively [66]. These have a significant impact on the FC performance [67,68]. Therefore, a balance of plant (BoP) system is usually employed and built around the FC stack to manage these conditions to improve performance [69]. In this section, the different options regarding PEMFC BoP composition are discussed and compared in terms of performance. Subsequently, heat, water, and gas management are discussed and summarised in Fig. 4. This section focuses on the relevant operating conditions associated with the most common configurations for PEMFC UAVs, as outlined in Table 2. It is important to note that the configurations for operating conditions management differ between PEMFC systems used in different mobile applications. For instance, the layout for PEMFCs used in UAVs is different from those used in other applications such as automotive vehicles. Fig. 5 illustrates this comparison schematically, showing examples of a typical BoP layout for PEMFCs used in UAVs and for other applications.

3.3.1. Heat management

Heat management is one of the most critical parameters influencing PEMFC performance. It affects cell performance in terms of efficiency [70,71], safety [71] and even dynamic operation [72]. However, it is often disregarded in performance discussions as these tend to focus on maximising the electric power output only [73]. The efficiency of PEMFCs typically lies between 40%–60%, which means that about half of the energy contained in hydrogen is converted into heat [74,75]. Therefore, adequate heat management is essential.

Different phenomena are observed in FCs due to changes in the stack operating temperature. Meyer et al. [73] focused on the influence of temperature on PEMFC performance. Electrochemical Impedance Spectroscopy (EIS) at different operating temperatures and currents was used to link these parameters to the FC resistance. They stated that temperature influences the FC electrochemistry, thermodynamics, electro-kinetics, transport processes and membrane water distribution. In general, PEMFC performance improves with an increasing operating temperature due to higher kinetics, resulting in lower activation losses, avoidance of flooding and improvement of proton conductivity [76–78].

However, high operating temperatures can cause overheating, resulting in membrane dehydration and a drastic performance decline due to higher ohmic losses [79–83]. This was confirmed by Shen et al. [84], who compared the performance of two open cathode FC stacks with embedded thermocouples. They found that if the temperature rose above 60 °C, the performance suddenly dropped. Ling et al. [85] observed a reduction in power density of more than 50% caused by overheating when the temperature reached 57 °C. Before continuing the discussion on heat management, it is important to note

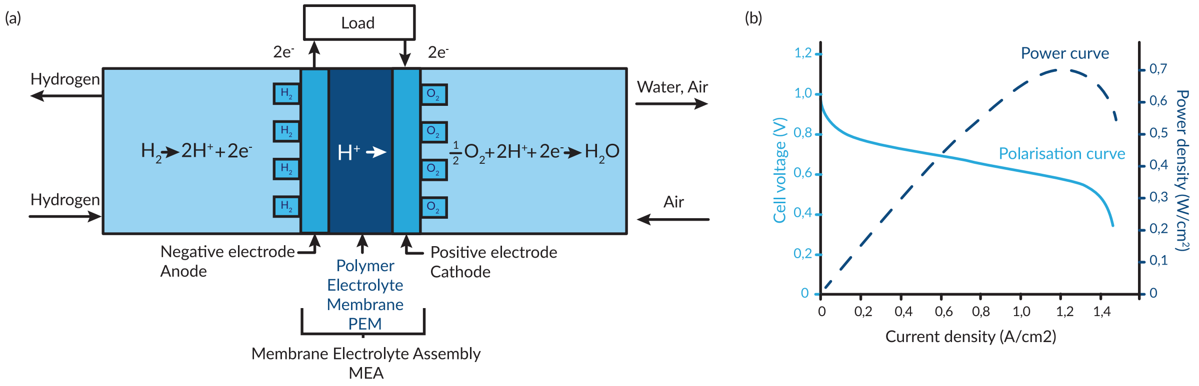

Fig. 2. (a) Simplified composition and operating principle of a single-cell PEMFC, (b) along with its corresponding typical polarisation and power curve under unspecified conditions for illustrative purposes based on [19].

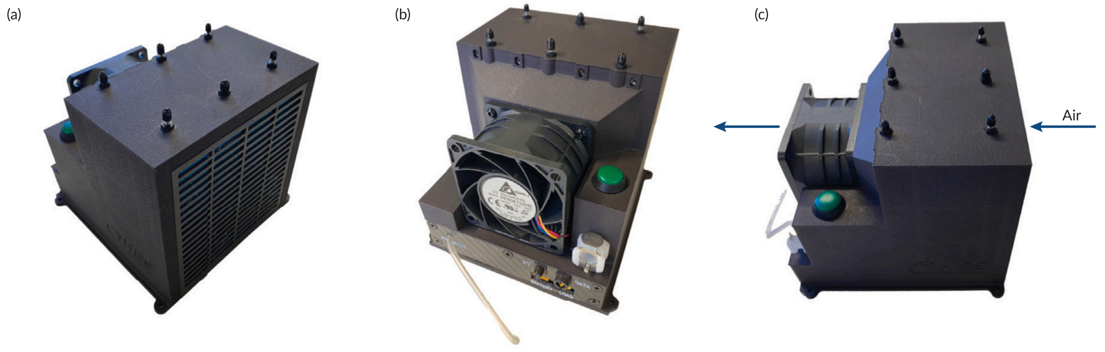

Fig. 3. Example of an open cathode PEMFC for UAV applications (H3 Dynamics A250 2021): (a) Front view, (b) Back view, and (c) Side view with airflow direction.

Table 2
Overview of commercially available PEMFC systems for UAVs.

Manufacturer	Rated power range [W]	Heat management	Water management	Anode gas management	Cathode gas management
H3 Dynamics [62]	250–4000	Air-cooled	Internal, short circuit	Dead-end purge	Open cathode
Honeywell [63]	600 & 1200	Liquid-cooled	No information	No information	Closed cathode
Intelligent Energy [64]	800–2400	Air-cooled	Internal	Dead-end purge	Open cathode
Spectronik [65]	25–2500	Air-cooled	Internal, short circuit	Dead-end purge	Open cathode but higher power can be closed cathode

that the effect of the operating temperature is strongly coupled with the water management in the FC. The latter is discussed in the next subsection (3.3.2). Both heat and water management impact the risk of flooding and dehydration in a FC [79].

The typical FC operating temperature ranges between 30–80 °C [86]. However, this range is significantly influenced by the heat dissipation characteristics and water discharge capacity of the stack [87], FC power [74,88] and type of cooling system [73]. Ideally, the cooling system maintains the FC operating temperature relatively constant within the optimal performance range. Liso et al. [80] found that variations in the operating temperature of PEMFCs cause degradation and concluded that control of stack temperature is paramount in dynamic applications.

Different types of cooling systems are available for PEMFCs, with liquid-cooled systems offering superior cooling performance and more flexible control [81,89]. However, these require additional components such as pumps, de-ionisers, and coolants, causing increased mass and BoP power consumption. This can make them less attractive for certain mobile applications [90] and explains why Table 2 showed that UAVs are usually equipped with simpler air-cooled PEMFCs.

Air-cooled systems generally rely on airflow over the cells, which can be linked to cathode gas management. Open cathode systems use a single inlet channel where air serves both as a coolant and oxidant [87,89,91]. In order to maintain proper cooling, a high mass flow rate of air is needed, which is often realised by an axial fan drawing in the air directly from the atmosphere [91–93]. This configuration is typically identified by the cells and bipolar plates of the FC stack being visible, hence the name open cathode. Closed cathode FCs, on the other hand, have separate air channels for the coolant and oxidant flows. Note that liquid-cooled systems are always considered as closed cathode, as they need only one air intake, which is only used to provide the cathode with oxygen [94]. Closed cathode FCs typically outperform the open cathode FCs by use of additional reactant air conditioning systems thanks to the installation of, for example, a compressor, humidifier, heating system and particle filters, which can be installed conveniently as there is no need for a high airflow rate [95]. Recent research suggests that adding extra systems for recovering heat from low-grade heat streams in PEMFCs could improve efficiencies [96]. Some examples of these systems include adsorption cooling, absorption cooling, and the use of turbines [96,97]. However, the economic assessment of these heat recovery systems for PEMFCs is still an open question [96]. In general, adding extra systems to improve the efficiency of closed cathode FCs comes at a mass penalty, which is not desired in UAVs.

Continuing the discussion on open cathode FCs, they can be further subdivided into air-breathing and forced air-cooled systems. Air-breathing FCs rely on free air convection for cooling without using a fan, which is only feasible for low-power systems [82,91] and thus

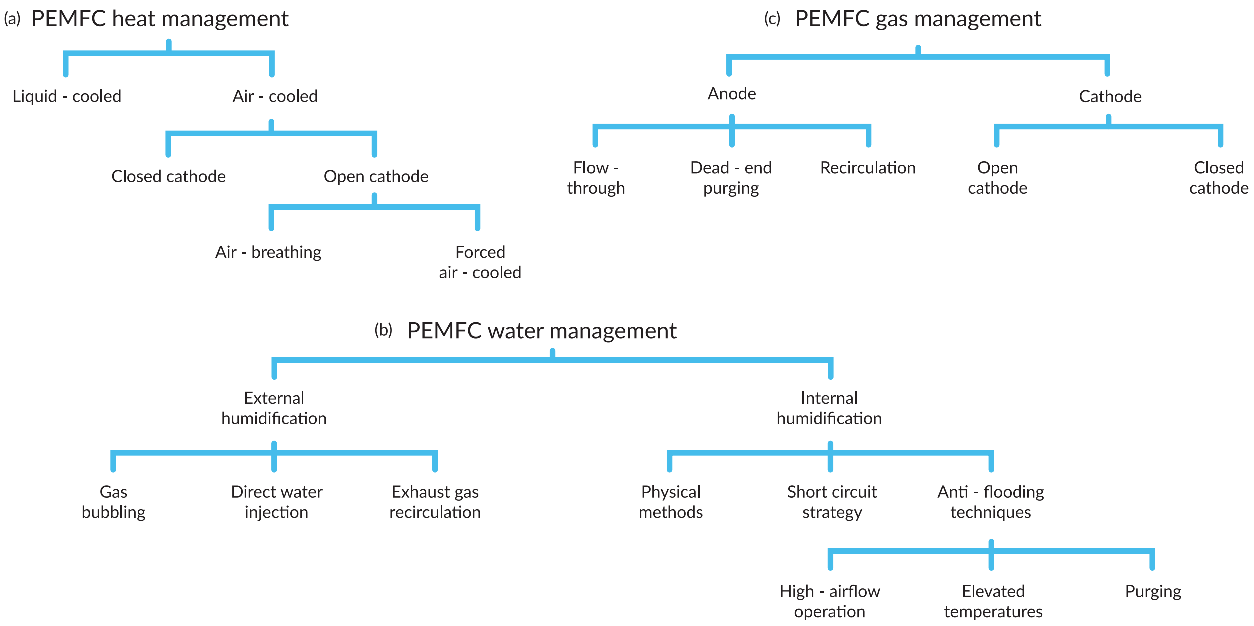

Fig. 4. Overview of the most common PEMFC (a) Heat management, (b) Water management, and (c) Gas management strategies.

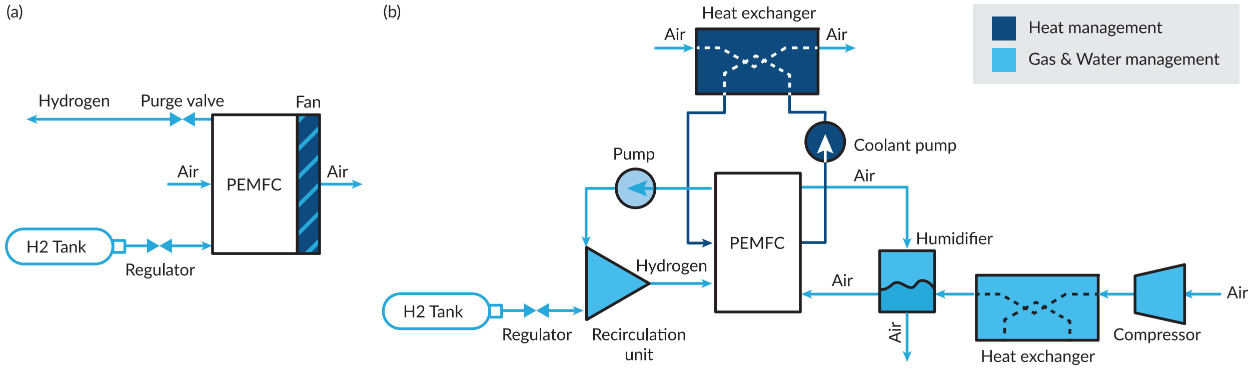

Fig. 5. Comparison of a typical balance of plant configuration in PEMFCs for (a) UAVs and (b) other applications.

considered less suitable for UAVs. However, Atkinson et al. [81] studied the implementation of air-breathing PEMFCs on the surface of UAVs cooled by the airflow around the UAV. They assessed the effect of operating conditions by testing a single-cell PEMFC with perforated and flexible current collectors in a wind tunnel. EIS was performed in different operating conditions and they concluded that integrating cells onto the surface of the UAV is promising.

Forced air-cooling uses a fan and is characterised by improved heat rejection, mass transport and water management, resulting in better performance and a broader operating range [81,82,91]. In a study conducted by Yan et al. [98], the performance of air-breathing PEMFCs was compared to that of forced air-cooling PEMFCs using simulation and characterisation techniques. They concluded that the forced-cooled FC performs about 20 times better than air-breathing cells. This was demonstrated by means of the polarisation curve, combined with the fact that the FC using forced air-cooling had a more stable and better temperature distribution. However, the maximum operating temperature of the stack is influenced by the dew point temperature in both cases [71]. This once again demonstrates a strong interconnection between heat and water management.

Forced air-cooling is usually obtained by installing a DC fan on the FC with a variable flow rate, which allows the temperature of the FC to be controlled [87,91]. Typically, fan-cooled FCs are in the power range of 100–2000 W [89,99]. Chen et al. [71] designed a 2 kW forced air-cooled PEMFC and studied the performance using EIS, proving it is a viable option. A higher airflow improves cooling performance and prevents overheating [82,92], but too much airflow can hinder performance by disrupting water management [84]. This was confirmed in a study conducted by Wang et al. [87], a single-cell open cathode PEMFC was analysed at various fan speeds using EIS. The results revealed that excessive airflow may lead to lower performance due to lower temperatures and excessive water removal, while insufficient airflow can cause overheating. Ling et al. [85] discovered that positioning the fan at the back of the stack and drawing air through it, instead of blowing air over it, leads to a 16% improvement in performance. This is due to a more uniform temperature distribution resulting from a more consistent velocity profile in the draw case.

It is also instructive to discuss the cooling performance of liquid-cooled systems in PEMFCs. Compared to air-cooled systems, the temperature is much more uniform throughout the stack [100,101]. Luo et al. [102] equipped an air-cooled PEMFC stack with 60 thermocouples distributed over five bipolar plates at different positions in the stack. They analysed temperature distribution in the stack and on the bipolar plates. Significant differences were found in both cases for increasing currents, resulting in a temperature difference of 5.2 to 12.9 °C on the outer surface of the stack. Noorkami et al. [103] performed similar work and observed a temperature variation higher than 12 °C across the active area of the stack. Chen et al. [71] mentioned that the maximum temperature difference throughout the stack for liquid-cooled systems is 4 °C.

Table 2 shows that most of the commercially available PEMFCs for UAVs are open cathode systems. This is due to the absence of complex gas channels and manifolds, which results in a simpler structure [90]. In addition, open cathode systems have a lower mass and less parasitic power due to a significantly smaller BoP [91]. In most cases, a simple DC fan is used to supply air and cool the stack [90]. This results in variable coolant characteristics and influences performance and degradation [90,104]. Note that Honeywell offers liquid-cooled PEMFCs for UAVs. However, their 1200 W PEMFC has a mass of 4 kg, which is nearly twice the mass of the H3 Dynamics A 1200 with similar power output [62,63]. Therefore, discussing the potential influence of variable ambient conditions on the performance of open cathode FCs for UAVs will be important, as well as making decisions concerning the type of BoP to be used. This will be further elaborated in Section 3.4.

3.3.2. Water management

The discussion on heat management already highlighted the importance of water management for FC performance. Proper water management in a PEMFC is essential for good performance [105–109]. The following paragraphs explain the importance of the water balance in the FC, its impact on performance, and possible water management strategies.

As shown in Fig. 2, hydrogen is electrochemically oxidised at the anode, producing protons and electrons, which follow separate paths to the cathode. A membrane between the electrodes helps the transfer of hydrogen protons from the anode to the cathode. The membrane plays a dominant role in the ohmic losses of the FC. Protons are more difficult to transport than electrons due to differences in their fundamental nature, leading to different conduction mechanisms [19,110,111]. In general, proton conduction in the membrane occurs via hopping in charge sites, a process known as the Grotthuss mechanism, which is much less efficient than electron conduction [112,113]. However, it is facilitated by higher temperatures due to increased proton internal energy [114,115]. Special membrane materials are developed for low-temperature PEMFCs to enable sufficient hydrogen proton conduction. A synthetic polymer membrane backbone contains sulfonic acid groups acting as charge sites to support the Grotthuss mechanism [113,116]. The membrane structure can and must also hold significant amounts of water [116,117], as PEMFCs rely on the membrane water content to improve proton conductivity [107,118]. In addition to the Grotthuss mechanism, hydrogen protons can form hydronium complexes by temporarily binding to nearby water molecules. In PEMFCs, water molecules act as carriers to transport hydrogen protons from anode to cathode in a mechanism known as electro-osmosis [116,117,119]. Furthermore, FCs generate water at the cathode. The difference in water content between the anode and the cathode results in a concentration gradient. Consequently, water diffuses back to the anode, a process known as back diffusion. This back diffusion of water supports the electro-osmosis process by maintaining the necessary hydration levels of the membrane and compensating for electro-osmosis, ensuring efficient proton conduction [107,116].

Generally, a higher membrane water content results in better proton conductivity. However, too much water blocks the porous electrodes, resulting in flooding. This hinders the supply of reactants, causing reactant starvation [107,109,116,117], resulting in an important and sudden voltage drop [120]. Moreover, PEMFC operation under high operating temperatures under low humidity may cause membrane dehydration, leading to a substantial decrease in membrane conductivity [116,121]. Therefore, heat and water management are strongly related and are crucial for a PEMFC to work effectively. They must be managed appropriately to maintain efficient operation [105,107,109]. Several water management strategies exist for PEMFCs [106,122]. The most important ones are discussed below, note that a combination of these strategies is possible.

External humidification involves methods employing devices that control the water content in the membrane by regulating the humidity in the reactant flows only [123,124]. This is done by heating and moistening the air and hydrogen flows to a certain temperature and humidity level using a humidifier [121]. External humidification supports processes such as electro-osmosis and back diffusion [116,125]. Strategies for external humidification exist, such as gas bubbling humidification [109], direct water injection [126], and exhaust gas recirculation in a flow-through configuration [123]. However, these systems increase the overall FC mass and the parasitic power consumption and add complexity. In addition, high humidity reactant flows might also be more susceptible to flooding [122,127]. Considering these disadvantages, internal humidification methods may be preferred over external ones for mobile applications [122–124].

Internal humidification has the objective of maintaining membrane hydration without external devices, which makes it inherently less complex [122]. The rationale is that the water produced by the cell is absorbed adequately by the membrane to improve conductivity while avoiding flooding, which is also referred to as self-humidification [126]. Wang et al. [108] suggested membrane hydration through physical methods, such as optimising the cell components' structure and improving operating conditions like temperature. Kim et al. [128] focused explicitly on the humidification of PEMFC stacks for UAVs by applying a short-circuit strategy. Hereby, an overcurrent is generated, which improves MEA humidification. They evaluated various short circuit durations and intervals and were able to increase the PEMFC stack power by 16%. A hybrid system was developed where a battery supplies power during the period that the FC is short-circuited. However, internal humidification does not avoid flooding. Self-water removal techniques are necessary when operating at high current densities, as then the water production rate is high [109,129]. A commonly used practice is operating the FC at higher temperatures to improve membrane water evaporation [130,131]. A high air stoichiometry can also be used to remove the water formed at the cathode [120,131]. Ous and Arcoumanis [132] conducted a study on both methods by assessing the performance and flooding characteristics of a transparent PEMFC under different operating conditions. They concluded that operating the cell at 60 °C instead of 30 °C was sufficient to avoid flooding, while a high air stoichiometry also proved to prevent water accumulation. Yang et al. [133] found that an open cathode single-cell PEMFC can experience dehydration at low currents due to increased temperature and flow rate. Another self-water removal technique involves a short recurring purge of the reactants feeding circuits to discharge water and other impurities [134], further discussed in the next section (3.3.3) on gas management.

The method of internal humidification is unfortunately more challenging to control compared to external humidification, making it currently unsuitable for high-power systems that have to operate in various ambient conditions [109]. For instance, the water and heat management of air-cooled open cathode systems on drones are anticipated to be affected by ambient air temperature and humidity. This is due to the lack of air-conditioning systems and high-performing cooling systems, which can potentially result in non-steady FC operating conditions [133,135]. This might be something to take into account for PEMFCs for UAVs as Table 2 showed that all these systems rely on internal humidification where a combination of hydrogen purging, high air stoichiometry, elevated operating temperatures and stack short-circuiting are the most common methods. Therefore, this is further discussed in Section 3.4 to investigate the literature for the expected performance impact of ambient conditions on typical water management strategies for PEMFCs for UAVs.

3.3.3. Gas management

This section focuses on several reactant gas management configurations. The previous sections already revealed a strong interrelation between heat and water management, and gas management interweaves seamlessly with them as well. For example, the choice of cooling strategy can determine the gas management approach, as will be discussed later for the open cathode air-cooled systems.

According to Hwang [136], there are three strategies for managing the fluids at the anode, which majorly consist of hydrogen gas: flow-through configuration, dead-end anode, and recirculation mode. In some cases, a hybrid approach is used by combining different strategies, such as the recirculation mode with recurring purge to discharge nitrogen [137].

In the flow-through method, hydrogen flows continuously at fuel stoichiometric ratios above 1.2, indicating that there is an excess of hydrogen. Specifically, a stoichiometric ratio of 1.2 means that there is 20% more hydrogen than what is required for a perfect chemical reaction where all reactants are entirely consumed with no leftover reactants. The 20% excess of hydrogen ensures a complete reaction of the other components or achieves specific reaction conditions. As a result, only part of the fuel is consumed, whilst the other part is released into the environment [137,138]. This method improves FC performance as excess water and impurities are removed continuously [137]. However, discharging unused fuel into the environment reduces efficiency and may pose safety risks due to hydrogen accumulation [125,137]. It is worth noting that allowing excessive water to be discharged immediately can also lead to membrane dehydration [82]. Therefore, studies conclude that an open flow-through configuration at high stoichiometric ratios is impractical in most applications [125,136,137].

In the dead-end method, a closed anode outlet prevents unused hydrogen from leaving the FC. This results in almost complete fuel consumption at a stoichiometric ratio of approximately one [137]. A significant disadvantage is the accumulation of water and impurities such as carbon monoxide and sulfur compounds, which can lower performance and lifetime [136,139]. Therefore, the dead-end mode generally involves some purging to flush the anode intermittently [136,140–142]. Hereby, a purge valve opens briefly to remove water and impurities, which also results in a small discharge of unused fuel [137,139]. In order to minimise the loss, proper control of the valve is necessary regarding purge duration and interval [137,138]. After purging, the FC voltage typically rises slightly when the valve opens following a sudden drop and then stabilises again to the nominal level [84]. Liu et al. [143] found that optimising the purge management strategy by controlling the purge valve can result in hydrogen utilisation rates of over 99% while simultaneously preventing water accumulation and impurities.

The recirculation method relies on ancillaries such as separation units and pumps to recirculate unused hydrogen from the anode while removing water [136,137]. This allows for higher stoichiometric ratios, improving the FC performance while minimising fuel waste, which enhances efficiency [136]. In general, a purging strategy is also employed to remove impurities like nitrogen [137]. The recirculation mode with purging is considered the best method to maximise hydrogen consumption while avoiding flooding and the accumulation of impurities [143]. However, the required ancillaries for the recirculation method result in a higher overall system mass, parasitic power consumption, and cost [137,138,144]. Therefore, the recirculation mode is not considered to be very useful for mobile applications. This clearly explains why all commercially available FCs designed for UAVs, such as those presented in Table 2, employ the purging strategy. Hereby, high operating efficiencies are available while keeping the mass and parasitic power low.

With regard to the gas management on the cathode side, Blunier and Miraoui [145] conducted a review on air management in PEMFCs for automotive applications. They reported that the major functions of the air supply system included reactant feeding, filtering, pressurisation, and humidification. They concluded that the humidification and compression subsystems cannot function independently, indicating complex dependencies between these tasks. The cathode gas management generally includes an air compressor, back-pressure valve, and ducting. Additional systems for heat and water management conditioning may also be present [125]. However, gas management depends strongly on the selected cooling configuration, notably an open or a closed cathode system (3.3.1). Gas management in open cathode systems is straightforward and simpler because air is drawn directly from the environment at high flow rates to ensure sufficient cooling [121]. Usually, forced-air cooling is employed, resulting in a simple solution that reduces mass and parasitic power. However, as discussed in the previous sections, it adds extra complexities related to durability, thermal, and water management [91,146].

In contrast, closed cathode systems are more common for industrial or high-power applications and offer a cooling system decoupled from the cathode air supply. This eliminates the need for a large cathode airflow and enables cathode air conditioning. Hence, closed cathode systems typically use compressors or blowers to increase the cathode air pressure, which results in better oxygen concentrations and, thus, FC performance. Moreover, it allows for the installation of additional components like filters. Compared to open cathode systems, better control of the FC operating conditions can be obtained. However, as stated before, the use of ancillaries results in higher parasitic power consumption and an increase in mass [91,121,147].

With regard to the gas operating pressures, FCs typically benefit from a higher cathode air pressure. The impact of using a higher hydrogen pressure at the anode is, even though useful, less pronounced [82,87]. However, the pressure difference between the anode and cathode is restricted due to limitations of the allowable mechanical stress on the membrane [148]. This limits the hydrogen pressure in open cathode systems, as the cathode is, for this type of system, typically at ambient pressure [135]. Consequently, the anode pressure can only be slightly higher than the pressure on the cathode. This is still beneficial as nitrogen migration from cathode to anode is hereby reduced [147].

Finally, it is instructive to consider the different gas conditioning systems found on PEMFC for UAVs before discussing the impact of ambient conditions on performance. The literature argues that eliminating air conditioning makes the performance of open cathode FCs more sensitive to variable ambient conditions [90,104]. As a matter of fact, Table 2 shows that most commercially available PEMFCs for UAVs employ open cathode systems to save mass, reduce parasitic power consumption, and benefit from a relatively simple implementation. This causes the drone to perform better and be more reliable. However, Spectronik provides closed cathode systems for their high-power systems, starting at the 1000 W version [149]. In this configuration, the large airflow needed to cool the FC is separated from the reactant air supply. A small radial blower with a filter on the cathode is then used to try to enhance the performance of the system. Nevertheless, no heating or humidification systems are installed due to mass considerations. Therefore, the Spectronik high-power PEMFC may perform better than the open cathode version of competing companies, but the configurations remain very similar [65,149]. In general, closed cathode systems rely on more complex air supply systems with multiple conditioning systems, such as compressors and humidifiers used in automotive applications. Therefore, a more appropriate definition for open cathode PEMFCs could be associated with the lack of inlet air conditioning systems needed to maintain constant temperature and humidity. This is because the difference between open and closed cathode systems for UAVs is expected to be small. The simplified operating conditions management systems in PEMFCs for UAVs potentially increase the impact of ambient conditions on the system's performance. Therefore, the following section (3.4) reviews the potential effect of ambient conditions on PEMFCs.

3.4. Impact of ambient conditions on FCs for UAVs

Ambient conditions refer to the characteristics of the environment surrounding a system, which can affect its operating conditions [66]. Khan et al. [150] have stated that ambient conditions significantly impact PEMFCs. However, they mentioned that limited literature is available on procedures for analysing the influence of these conditions due to their expensive and time-consuming nature. Furthermore, the authors mentioned that the commonly used models are developed only for standard ambient conditions. Atkinson et al. [81] specifically noted that the absence of air preconditioning in open cathode PEMFCs makes the system more sensitive to changes in the surrounding environment. Therefore, assessing the feasibility of operating the system under the expected range of ambient conditions is necessary. This is confirmed by manufacturer Spectronik, mentioning that their closed cathode systems have an operating window of −10 to 45 °C, much wider than the open cathode version from 0 to 35 °C [149]. The Honeywell systems are designed to be liquid-cooled and are therefore considered closed-cathode systems. However, their temperature operating range from 5 to 45 °C is only slightly wider than the open cathode systems [63]. This is related to the systems used for air preconditioning. Santos et al. [151] evaluated a commercially available FC system designed specifically for UAVs and observed slight variations in performance, which they attributed to changes in ambient conditions. In addition to changes in the performance of open cathode PEMFCs caused by varying ambient conditions, Zhao et al. [152] also mentioned that the dynamic performance can also be influenced by pressure, temperature, humidity and even air quality.

In general, other works also highlight that changes in ambient conditions can impact the FC power output [91,153–156]. This, in turn, affects the performance of the hybrid electric systems and that of the UAVs in which they are installed. The effect of ambient conditions on FC performance is usually temporary and recovers when conditions improve [23], but it should not compromise the mission the UAV must perform. UAVs are often expected to operate under variable ambient conditions, which impact their performance characteristics, such as endurance and range. Selecting a FC with a closed cathode system, which is supported by a more extensive BoP, would reduce the influence of ambient conditions [157,158]. The UAV designer, however, prioritises mass reduction and usually selects FCs with a simple BoP. This decision is clearly echoed by the currently commercially available PEMFC systems relying on simplified operating conditions management systems (Table 2). Some ambient conditions can also accelerate degradation, as discussed later (3.5).

The following sections delve into the impact of ambient temperature, relative humidity (RH) and atmospheric pressure in greater detail, as these are considered the most crucial ambient conditions affecting UAV FC performance [22]. A summary is presented in Table 3, focusing on studies that investigated open cathode or similar PEMFC systems. The objective is to assess the importance of taking ambient conditions into account when dimensioning FC UAV hybrid systems. The literature primarily discusses closed cathode systems that rely on more complex operating conditions management systems due to their wider range of applications. This explains the limited amount of literature available on open cathode systems [159]. Furthermore, experiments that investigate the impact of ambient conditions on fuel cells can be expensive due to the necessary test benches and FC systems. Therefore, a recommended approach is to combine data-driven and physics-based models, as suggested by Vichard et al. [23].

3.4.1. Ambient temperature

The operating temperature of a FC affects its performance substantially, as discussed in Section 3.3.1. The thermal management of air-cooled FCs is affected by the temperature of the incoming air, airflow cooling rate [91] and humidity [71]. It is essential to have a cooling system that can perform well in a wide range of ambient conditions [121,161]. An increased airflow can enhance the performance of FCs by reducing the stack temperature due to an improvement in the membrane water content. However, this increase in air flow rate leads to higher fan power consumption, which is the main source of parasitic power for air-cooled PEMFCs [92]. In addition, Fluckinger et al. [162] used models to examine the cooling system of FCs and found that the cooling efficiency decreases beyond a certain flow rate due to a convergence of the temperature difference between the bipolar plates and cooling air. This finding is a fundamental aspect of heat transfer, highlighting the importance of optimising flow rates to maintain efficient cooling [163]. Meyer et al. [92] confirmed this by studying a 5-cell PEMFC stack at 25 °C ambient temperature. Increasing the air-cooling flow rate above 5.2 $\times 10^{-3}$ m^3 s^{-1} had diminishing results, reaching a stack temperature of 55 °C. Jung et al. [83] assessed how varying airflow rates in open cathode PEMFCs affect dynamic performance. They concluded that increased airflow can lead to a more stable and rapid response to dynamic load changes.

As mentioned earlier, Meyer et al. [92] focused on a 5-cell open cathode PEMFC to establish an electro-thermal performance map. The study did not investigate the impact of varying ambient temperatures. However, it did demonstrate the importance of the cooling rate of airflow, which indicates the significance of air temperature because of their interconnection. When the airflow rate was increased from 1.9 to 5.2 $\times 10^{-3}$ m^3 s^{-1}, the gross electric stack power increased by approximately 25%. However, it is important to note that they also observed an exponential increase in the net parasitic power related to an increase in fan flow rate, which should be considered as it lowered the net stack power at flow rates above 5.2 $\times 10^{-3}$ m^3 s^{-1}.

In Berning and Knudsen Kær's study [164], a Ballard FC was modelled to evaluate how changes in ambient conditions and airflow rates affected performance. The manufacturer stated that performance loss is expected above 30 °C ambient temperature and will be significant above 40 °C. Their model showed that to achieve reasonable cell outlet temperatures in dry conditions around −20 °C, the flow rate should be low and well-controlled. In conditions of 40 °C and 100% humidity, high flow rates may require hardware adaptation for different climate zones. Finally, at 40 °C and 30% RH, the model demonstrated that the ambient relative humidity starts to play an important role. This is expected because of the correlation between water and heat management, as discussed in the section on operating conditions (3.3). For example, the rate of water removal also depends on the RH and temperature of the inlet air, preferably at near operating conditions. If the incoming air temperature is too low, it will rise within the stack and expel more water, potentially disrupting the water balance of the fuel cell [163].

Dudek et al. [3] designed a modular PEMFC stack for UAVs by combining different stacks in series or parallel configurations. Although the study did not specifically focus on the influence of ambient temperature, it did yield interesting results on this topic. When two 1000 W stacks are combined in a modular series configuration, the outlet air of module one becomes the inlet air of module two. After analysing both stacks individually, it was found that they offer nearly identical performance levels. Module two experienced a gross electric power loss of approximately 15% at the maximum power point when configured in series. The authors attributed the performance loss to the hotter and more humid air, which resulted in a temperature increase of around 10 °C in the stack. This statement emphasises the significance of ambient air temperature in relation to the performance of FCs. However, the depletion of oxygen potentially also played a role but was not mentioned.

Al-Zeyoudi et al. [90] conducted a computational analysis of an air-cooled open cathode PEMFC, specifically focusing on how monthly varying ambient conditions in the United Arab Emirates affect the system. The temperature changes from 12 °C in winter to 45 °C in summer while the humidity varies from 20% to 90%. This resulted in a fluctuation of stack power by 10% in winter and up to 40% in summer. If only temperature is considered, the simulations showed that operating at conventional voltages resulted in a power density difference of up to 15% between the maximum and minimum temperature case at the maximum humidity setting. Al-Anazi et al. [165] performed similar work for the climate of Saudi Arabia, where temperature ranges between 6–40 °C and RH between 10% to 50%. The results show that environmental conditions significantly impact stack performance, influencing both efficiency and the application. There was a 20%

Table 3
Literature overview of the effects of varying ambient conditions considering varying ambient temperature (temp), ambient relative humidity (RH) and ambient pressure (pres) focused on open cathode PEMFC systems.

Source	Effect	Test method	Range	Result
Jung et al. 2008 [83]	Varying temp	Open cathode PEMFC	25–35 °C at 55% RH	20% power density increase at 35 °C at the maximum power point
Al-Zeyoudi et al. 2015 [90]	Varying temp	Simulations	12 °C vs. 45 °C	Maximum 15% power density increase for 45 °C at conventional voltages for the maximum humidity setting
Meyer et al. 2015 [92]	Varying temp	Open cathode PEMFC	High vs. low airflow	25% gross stack power increase at high airflow
Dudek et al. 2021 [3]	Varying temp	Open cathode PEMFC	Higher temp air	15% power loss at higher temp at the maximum power point
Jung et al. 2008 [83]	Varying RH	Open cathode PEMFC	70% vs. 55% RH at 25 °C	Maximum 20% power loss at 55% RH in ohmic losses area
Al-Zeyoudi et al. 2015 [90]	Varying RH	Simulations	10% vs. 50% RH	Maximum 60% maximum power performance increase at conventional voltages for the maximum temperature setting
Gould et al. 2015 [104]	Varying RH	Open cathode PEMFC	22% vs. 90% RH at 25 °C	15% power density increase at the maximum power point at 90% RH
Chen et al. 2016 [71]	Varying RH	Open cathode PEMFC	Wet vs. dry air at 65 °C	90% ohmic resistance drop for wet air
Atkinson et al. 2017 [81]	Varying RH	Open cathode PEMFC	22% vs. 90% RH	25% power density increase at 90% RH for the maximum power point
Rottmayer et al. 2011 [160]	Varying pres	Simulations	Sea level vs. Kabul (1800 m)	30% higher energy density (Wh/kg) is needed to achieve the same endurance at 1800 m as at sea level due to lower power density.
Atkinson et al. 2017 [81]	Varying pres	Open cathode PEMFC	0 vs. 3239 m	17% maximum power decrease at 3239 m
González-Espasandín et al. 2019 [155]	Varying pres	Simulations	0 vs. 8500 m	65% lower maximum power output at 8500 m

performance variation in winter and a 35% increase in performance during summer.

Xing et al. [166] conducted a review of heat management for open cathode PEMFCs that are forced air-cooled. They concluded that it is essential to pay close attention to the performance variation under different ambient conditions. Chen et al. [154] conducted a study to examine the impact of ambient temperature on a 1 kW PEMFC stack within the range of 10–30 ° C. They also concluded that ambient temperature has a significant influence and even noted that this should be considered when designing hybrid systems. Kurnia et al. [91] reviewed open cathode PEMFCs and mentioned that they exhibited low performance at low ambient temperatures. The authors also mention that starting PEMFCs below 0 °C is challenging. In an experiment conducted by Jung et al. [83], it was also demonstrated that the temperature of the inlet air influences the performance of the system. They operated a 6-cell forced-air open cathode stack at 55% relative humidity and compared its performance via the polarisation curve at air inlet temperatures of 25 °C and 35 °C. The results indicate that the gross electric power increased by 20% at the maximum power setting when the air temperature was increased to 35 °C.

This section proves that it is challenging to determine the optimal airflow rate for open cathode systems. PEMFC manufacturer Spectronik confirms that open cathode PEMFCs for UAVs experience a 98% power derate at 55 °C compared to closed cathode PEMFC performance [149]. To conclude, ambient air temperature plays a significant role in the functioning of open cathode PEMFCs. When exposed to varying ambient temperatures, the power output of such a system can fluctuate significantly, which has the potential to impact the overall performance of the hybrid system, propelling the UAV.

3.4.2. Relative humidity

Due to the strong interconnection between heat and water management in the FC, air humidity fluctuations can significantly affect open cathode FCs' performance. In their review, Kurnia et al. [91] mention that a low ambient relative humidity can cause low performance. This is confirmed by Atkinson et al. [81], stating that a higher ambient relative humidity improves membrane water content, resulting in better proton conductivity. The power density at the maximum power point of the air-breathing PEM cell they characterised increased by around 25% as the relative humidity went from 22% to 90%. However, it is crucial to avoid flooding as it can hinder oxidant delivery.

Chen et al. [71] built a 40-cell open cathode stack and assessed the influence of humidity on ambient conditions using EIS. The performance was significantly affected by air temperature. However, RH also played a role as the centre cells suffered from dehydration and lower performance under dry gas conditions. Operating the stack at 65 °C and 50 A under wet gas conditions resulted in a more uniform ohmic resistance, which also dropped by more than 90%. According to the authors, preventing flooding during periods of high humidity is recommended.

Gould et al. [104] evaluated the impact of ambient conditions on an open cathode single-cell air-breathing PEMFC. They found that the performance was higher at an ambient air relative humidity (RH) of 70% compared to RH levels lower than 30%. This was due to the shift in the polarisation curve to the right, resulting in higher voltages for similar currents, thanks to lower losses. It also appeared that increasing the RH to 90% did not have as much impact as previous increases.

Al-Zeyoudi et al. [90] simulated the performance of PEMFCs in Saudi Arabia, considering the influence of ambient conditions such as relative humidity, ranging from 10% to 50%. This led to a maximum power performance increase of 60% at the maximum operating temperatures for conventional voltages, which is higher than the influence of temperature evaluated in this study.

Jung et al. [83] assessed the effect of varying air relative humidity on the performance of open cathode PEMFCs. They established the polarisation curve at an air relative humidity of 70% when the air temperature was 25 °C. In a subsequent test, the relative humidity was reduced to 55%, resulting in a 20% decrease in power performance observed in the polarisation curve, starting from the ohmic losses region. This was confirmed by a similar test conducted at an air inlet temperature of 35 °C. Reducing the relative humidity from 55% to 25% resulted in a decline of maximum power performance by 35%.

It can be concluded that a variation in the RH of the ambient air can significantly impact the performance of open cathode PEMFCs. Therefore, this parameter must be considered when selecting PEMFCs for a specific application, especially when varying ambient conditions are expected, which is the case for UAVs.

3.4.3. Atmospheric pressure

The atmospheric pressure is a crucial parameter for FCs for UAVs as a function of flying altitude. Therefore, the performance of the FC can be significantly affected depending on the UAV type and mission specifications. As discussed in Section 3.3.3, FC performance generally improves at higher cathode pressures. Pratt et al. [167] combined theory and experiments and proved that at higher altitudes, the performance decreases due to increased losses related to reaction kinetics. It was observed that the performance showed a significant decline when the pressure dropped to 23.3 kPa. Werner et al. [168] conducted a comparable study on a 12 kW PEMFC, utilising a low-pressure test facility and statistical experimentation. Operating the stack at low pressure (70–95 kPa) was found to reduce its performance and efficiency. In their review of FC propulsion for fixed-wing UAVs, Gong and Verstraete [20] pointed out that flying at higher altitudes presents additional challenges. These include complicated cooling due to thinner air and the risk of dehydration due to the lower boiling point of water. Their review mentions a performance loss of 15% to 35% at 1500 m and up to 60% at 10 000 m.

González-Espasandín et al. [155] investigated the impact of operating and environmental conditions on a single-cell PEMFC model, with a specific focus on UAVs. They incorporated an atmospheric model to examine the effect of varying cathode pressure at different altitudes. If the temperature is constant, at 8500 m, the maximum power point was 65% lower compared to sea level. At an altitude of 1000 m, the maximum power point decreased by 20%, and at 3000 to 5000 m, it decreased by as much as 40%. However, the difference in maximum power was less pronounced at different operating temperatures.

Atkinson et al. [81] placed an open cathode air-breathing single-cell PEMFC in an open wind tunnel and climate chamber. The maximum power decreased by 17% at an altitude of 3239 m above sea level. The polarisation curve indicated increased activation losses related to the cathode kinetics. However, it was impossible to maintain constant ambient relative humidity and temperature, so the authors could not attribute the complete performance loss to the change in altitude.

Rottmayer and Miller [160] also performed calculations considering only the influence of oxygen pressure on FC performance to achieve a certain endurance. According to their calculations, a FC with an energy density of 515 Wh/kg could achieve 8 h of endurance at sea level. The authors state that an energy density of 662 Wh/kg would be required to achieve this at 1800 m in Kabul.

In their study on how ambient conditions affect air-breathing open cathode FCs, Gould et al. [104] also evaluated the effect of altitude. They found that the performance of the single-cell significantly reduced when tested at an altitude of 300 m. The study concluded that altitude is the most important ambient condition that affects the performance of air-breathing open cathode FCs. However, the difference is expected to be less pronounced in open cathode forced air-cooled PEMFCs. Honeywell has reported that their liquid-cooled closed cathode 1200 W system experiences power derating at 1500 m, reaching 10% at 4500 m [63]. Although they have not provided any information about the cathode gas management strategy, it is expected that the power loss will be more severe for open cathode systems.

This section highlighted the complexity of challenges posed by altitude variation on the performance of open cathode PEMFCs. It emphasises the need for careful consideration and study in the design and operation of FC-powered UAVs linked to the UAV application.

3.5. Impact of other degradation mechanisms on open cathode systems

FC degradation is the irreversible reduction in power output at a given operating point [23]. FC durability is considered a significant challenge in commercialisation due to inevitable degradation linked to operating time [23,169,170]. However, exposure to various factors, such as contaminated environments or harsh operating conditions, can significantly increase the degradation rate, reducing FC lifespan [171]. Therefore, specific measures are taken to slow down the degradation rate of FCs [172].

As a result, various factors, such as location, flight time and timing, can affect the degradation of a FC UAV. It is beneficial to study the existing literature to determine whether it would be useful to consider the effect of degradation on open cathode PEMFCs while designing a hybrid system or for deployment in commercial applications. Therefore, this paper categorises different degradation mechanisms into chemical degradation, degradation associated with harsh operating or ambient conditions, and degradation associated with the power profile. This subdivision is illustrated in Fig. 6. A summary of the literature overview is presented in Table 4, focusing on studies that investigated open cathode or similar PEMFC systems. The objective is to assess the importance of taking ambient conditions into account when dimensioning FC UAV hybrid systems. It is important to note that this section does not provide a complete discussion of FC degradation related to each component and mechanism. This section focuses on reviewing the effects of degradation mechanisms on open cathode PEMFCs through in-situ testing. It might be essential to consider specific degradation mechanisms as they could severely impact the performance or lifespan of PEMFC UAVs. However, comparing the impact of degradation mechanisms via numerous studies is complex due to differences in cell components, materials, ambient conditions, operating conditions and operating points, which can all affect degradation rates [152,173].

3.5.1. Chemical degradation

Chemical degradation can occur due to metal poisoning, impurities in the fuel and air streams, and radical attacks, Cations arising from metal poisoning and fuel or air streams can occupy a significant number of active sites in the MEA. Radicals are highly reactive species formed during chemical reactions that can damage the MEA components [186]. Below, these are explicitly discussed, focusing on open cathode PEMFCs. In general, the impact of chemical degradation is also influenced by FC operating conditions and exposure duration [187,188]. Assessing the impact of contaminants on performance can be complex, as the degradation may be temporary and partially or fully recoverable [177]. First, metal poisoning can lower active sites and membrane conductivity, thus affecting PEMFC degradation [174,189]. FCs are prone to two primary sources of metal ions causing metal poisoning. One reason could be the FC and BoP elements like coolants, gaskets, bipolar plates, humidifiers, etc. Another potential source of metal ions could be the impurities found in the fuel streams [186,190]. The first source is a general concern for FCs, while the second source can significantly affect open cathode PEMFCs. Metal ion contaminants in the hydrogen stream, such as Ca^{2+} and Na^{+}, are linked to production from water and humidification and can be avoided by ensuring adequate water and hydrogen purification [191]. Avoiding impurities in the air that can cause metal poisoning can be more difficult, especially since it was shown that PEMFCs designed for UAVs usually do not have filters due to mass constraints. Typically, this problem is associated with the operation location. For instance, higher concentrations of Na^{+} and Cl^{-} in the air are present in regions near the sea [192]. Madhav and colleagues [193] used chemical degradation and physical analysis techniques to investigate the impact of saline environments on Nafion. They concluded that it accelerates degradation. They suggested the development of membranes that have a higher resistance to salty conditions. This is confirmed by a study conducted by Sasank et al. [174], who noted that marine environmental conditions are identified as a

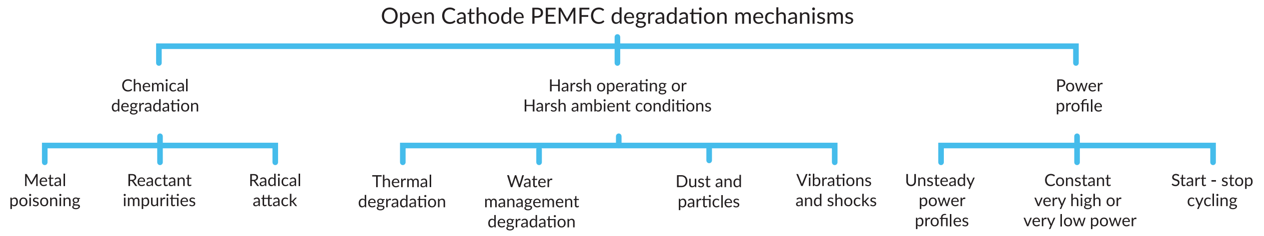

Fig. 6. Overview of the major degradation mechanisms of PEMFCs.

Table 4
Literature overview of the effects of degradation on open cathode PEMFC systems through in-situ testing.

Source	Degradation type	Method	Result
Sasanak et al. 2016 [174]	Chemical degradation	NaCl metal poisoning using salt water evaporation in inlet air on a 60 W 42-cell PEMFC stack	A power decrease of 50%–60% was observed after 48 h of exposure before stack washing.
Misz et al. 2016 [175]	Chemical degradation	Traffic-related reactant (air) contaminants on a single-cell 45 cm^2 PEMFC	SO_2 impact of 0.1 and 1 ppm was irreversible, resulting in an average current loss of 2% and 62%, respectively.
Talke et al. 2018 [176]	Chemical degradation	Traffic-related reactant (air) contaminants on 300 cm^2 PEMFC stacks under semi-dynamic tests	NO_x impact of 11.5 g/mol for 1110 h was irreversible, resulting in a voltage degradation of 10%. SO_2 impact of 3.7 g/mol for 572 h was irreversible, resulting in a voltage degradation of 19% NH_3 impact of 9.6 g/mol for 1110 h was irreversible, resulting in a voltage degradation of 7%
Moore et al. 2000 [177]	Chemical degradation	Realistic concentrations of battlefield pollutants as reactant (air) contaminants on an 11 cm^2 single-cell PEMFC	At least 50% voltage degradation for all battlefield pollutants after recovery with clean air
Frensch et al. 2019 [178]	Harsh conditions	Thermal degradation by subjecting membranes to temperatures over 80 °C	60% greater membrane thinning at 80 °C than at 60 °C, and double at 90 °C compared to 80 °C, thinning resulted in increased oxygen crossover
Lee et al. 2023 [179]	Harsh conditions	Water management degradation by exposing a 25 cm^2 single-cell PEMFC to various RH settings	After 200 h at 10% RH, the maximum power density was half that of the cells operated at 50% and 100% relative humidity.
Panha et al. 2012 [180]	Harsh conditions	Water management degradation by RH cycling on a 42 cm^2 single-cell PEMFC	30% higher voltage degradation rate when cycling between dry and 100% RH every 10 and 40 min
Rajalakshmi at al., 2019 [181]	Harsh conditions	Short-term vibration tests on a 30-cell 500 W PEMFC stack	No significant performance difference
Hou et al. 2016 [182]	Harsh conditions	Long-term vibration tests	Leading to lower gas tightness and higher stack AC impedance
Han et al. 2020 [183]	Power profile	NEDC electric load profile for 300 h on a short stack	Degradation was significant and increased with higher current density and was influenced by operating conditions
Meng et al. 2021 [184]	Power profile	Three different dynamic load cycles	Degradation rate is closely related to the number of load cycles and cyclic loading rate
Wahdame et al. 2007 [185]	Power profile	Comparison of the effect of current oscillations on two PEMFCs	The average current load significantly affects the ageing process

major contaminant affecting PEMFC performance. They tested an open cathode PEMFC stack by exposing it to a saltwater bath and infrared lamp to simulate air contamination. No measurements were taken to determine the actual concentration of salt in the incoming air. The overall power performance of the PEMFC stack decreased by 50%–60% after exposure to seawater. However, washing the stack improved power performance by 150%, but it was still 15% lower than the initial performance.

Second, in addition to metal ions in the fuel streams, other contaminants also affect PEMFC performance. For hydrogen, this is generally caused by impurities related to the production process. The presence of Ca^{2+} and Na^{+} in green hydrogen from water electrolysis was already discussed. Grey hydrogen produced from hydrocarbons [194] may contain impurities such as NH_3, H_2S, CO_x, traces of HCs and benzene [187, 195]. The primary impurities are CO, NH_3, and H_2S [186]. Their effect can be summarised as platinum catalyst poisoning, resulting in decreased performance [188,195]. However, membrane properties may also be impacted [186,187]. As for impurities related to water electrolysis, hydrogen purification is a common method to avoid performance degradation [187,195,196]. According to ISO 14687–2 specifications for FC hydrogen fuel, there are strict limits on the concentrations of fuel impurities. These limits can require special equipment and increase costs [190]. However, as discussed, this is generally easier to achieve than air filtering in commercially available open cathode PEMFCs for UAVs. Therefore, the possible impact of air impurities is discussed below.

The effect of metal cations present in the air on open cathode PEMFC performance, such as those found in marine environments, was shown to be potentially significant. Other impurities could also result in degradation depending on where the FC is operated, showing a similar effect to impurities in the hydrogen stream [186]. The major contaminants are NO_x, SO_x, CO_x, ozone and other organic chemical species such as benzene [177,190]. The concentration of these compounds is associated with areas with higher levels of automotive vehicle exhausts, industrial and manufacturing processes, and battlefield environments [188]. Operating a PEMFC in these areas can lead to performance degradation and damage to its MEA, as shown in the studies elaborated below. However, the literature tends to focus more on the impact of hydrogen impurities at the anode site [190].

Baturina et al. [197] have provided an overview of the performance degradation of PEMFCs linked to air pollutants. They focused on both organic and inorganic impurities such as salts, solvents, exhaust gases and combustion products. These impurities have been shown to have a negative impact on the cathode platinum catalysts, leading to lower performance even in minute concentrations of around 1 part per billion (ppb) of some contaminants. In certain instances, using highly pure air in the recovery process resulted in a performance recovery. However, the damage caused by some contaminants was irreversible. In conclusion, the authors suggest that for FCs to be a viable option as an energy source outside of the lab, solutions that focus on materials and operations need to be implemented. This includes efficient air filtering or other solutions, such as developing more resistant catalysts.

Misz et al. [175] focused explicitly on the impact of traffic-related air contaminants and how this relates to the operating temperature, potential and possible regeneration. A single-cell test bench of 45 cm^2 was used to inject the contaminants precisely. All tested pollutants, except ethane, negatively impacted performance, including NO, NO_2, SO_2, NH_3, and toluene. The impact of SO_2 proved irreversible and caused an average current loss of 2% and 62% at concentrations of 0.1 and 1.0 parts per million (ppm), respectively. In addition, an unexpected difference was observed between the impact of NO and NO_2 at concentrations of 1 ppm, resulting in 30% and 3% average performance loss, respectively. The authors also observed a strong influence of the operating conditions on the effect of impurities and regeneration.

A testbench was employed to evaluate the impact of realistic traffic-related air pollutant concentrations on 300 cm^2 automobile stacks operating at two different power profiles by Talke et al. [176]. It was concluded that NO_x will cause a 5%–10% performance loss in FC vehicles in Germany. The other tested contaminants, SO_2 and NH_3, also significantly negatively impacted the performance. They recommend conducting additional research to design appropriate filters and investigate the correlation between contaminant degradation and operational conditions.

Moore et al. [177] compared the effects of battlefield pollutants, such as sarin, sulfur mustard and hydrogen cyanide, on an air-breathing PEMFC with the effect of common air impurities such as SO_2, NO_2, CO, propane, and benzene. They used realistic concentrations based on the literature and subjected the single-cell 11 cm^2 MEA to contaminated ambient air. On the one hand, they concluded that short-term exposure to the common air impurities generally only temporarily affected performance, except for benzene. On the other hand, the impact of battlefield pollutants was found to be much higher, resulting in a performance decline of at least 50% even after recovery. The authors suggested the need for special filters or other mitigation strategies to ensure performance in battlefield environments.

Third, the most disastrous chemical degradation mechanism for PEMFC performance is considered to be a radical attack, which affects membrane conductivity and mechanical strength [193]. Oxygen permeation to the anode can cause the formation of a highly reactive species called H_2O_2. Combined with trace metal ions such as Fe^{2+} and Cu^{2+}, OH and OOH, radicals can be formed. These radicals can lead to irreversible damage to the membrane, creating pinholes and cracks [186]. The deleterious impacts of radical attack can be minimised by utilising more tolerant membranes and avoiding the formation of radicals through the prevention of oxygen crossover, eliminating trace metal ions and beneficial operating conditions [198].

To conclude, chemical degradation can significantly impact the performance of PEMFCs. However, degradation mechanisms associated with the hydrogen stream and FC components are thought to be less critical for PEMFCs used in UAVs. Filtered hydrogen can be used, and component degradation is a general FC degradation mechanism. Nevertheless, open cathode PEMFCs used in UAVs that sacrifice elaborate filtering systems combined with high air flows are expected to be significantly affected by air impurities. Therefore, when designing PEMFCs for UAV applications, it is important to consider the trade-off between a longer FC lifetime and a lighter, less complex BoP resulting in longer endurance.

3.5.2. Degradation linked to harsh operating or ambient conditions

The mass considerations for UAVs in PEMFCs result in minimising the amount of BoP components, which brings operating and ambient conditions closer. As discussed in Section 3.4, ambient conditions may significantly affect the performance of open cathode systems. This effect is typically temporary, but research also indicates that harsh operating or ambient conditions may accelerate irreversible degradation, ultimately shortening the lifespan of PEMFCs [23]. This section examines the link between harsh conditions and degradation acceleration, particularly concerning degradation caused by thermal and water management, temperature and RH cycling, dust and particles, and vibrations and shocks.

Thermal degradation is a crucial mechanism for PEMFCs that are closely associated with the properties of the PEM. As shown, the membrane water content is a critical factor that supports proton conductivity, which determines the operating temperature range of the PEMFC, typically between 40–80 °C. If the operating temperature of a membrane rises above 80 °C, it might result in membrane decomposition such as thinning [152,179,186]. Frensch et al. [178] conducted simulations and in-situ experiments, demonstrating that membrane thinning increased by 60% when operating at 80 °C, compared to 60 °C. Furthermore, operating at 90 °C resulted in twice as much thinning as at 80 °C, leading to higher oxygen crossover and reduced performance. Cooling systems are employed in PEMFCs to prevent this. However, as discussed, the unconditioned air intake of open cathode PEMFCs renders them more vulnerable to ambient conditions. This can lead to overheating in high ambient temperatures. It is important to note that the complete PEM cell overheating can cause thermal degradation damage, but also hot spots accelerate degradation [186]. Vichard et al. [159] confirmed that ambient temperatures significantly impact the short- and long-term performance degradation of an open cathode PEMFC. They conducted a 5000-h durability test under varying ambient conditions and used EIS to assess degradation. They concluded that low ambient temperatures can significantly reduce the degradation rate due to improved humidification.

Subzero storage and operation can cause the water in the membrane to transform to ice, thereby increasing its volume, which can lead to stress, causing microcrack growth and deformations [169,186]. A similar effect is observed when subjecting a PEMFC to freeze-thaw cycles [199]. Ous and Acroumanis [120] performed a review specifically focusing on degradation related to water formation and transport in PEMFCs. According to them, water accumulation has a detrimental impact at sub-zero temperatures.

Effective water management is also crucial in preventing membrane drying and consequential MEA damage linked to thermal degradation [23]. Low humidity operation can lead to dry membranes, which may result in pinholes and membrane thinning [179,200–202]. As discussed, this can affect mechanical stability and increase gas crossover. In contrast, high humidity operation can reduce performance by inducing flooding and increasing the degradation rate due to damage to the catalyst support and corrosion acceleration of components [203]. Lee et al. [179] conducted a study to compare the performance of a single-cell PEMFC under different RH levels. The PEMFC was operated at RH values of 10%, 50% and 100% for 200 h. The study found that during the first 100 h of operation, there was no significant difference in performance among the cells under different RH levels. However, after 200 h, the 10% RH single-cell showed a substantial deterioration in performance compared to the other cells, indicating that low humidity levels can cause significant degradation over time. Furthermore, the cycling of temperature and relative humidity, either independently or in tandem, can also significantly impact degradation rates. This latter process, known as hygrothermal cycling, can induce additional stresses on the PEMFCs [204]. Rong et al. [205,206] performed modelling and suggested that thermal and RH cycling may damage the catalyst layers in the form of cracks and delamination, reducing cell durability. Panha et al. [180] confirmed that reactant RH cycling on a single-cell

PEMFC of 42 cm^2 caused membrane damage and pinhole formation. They conducted an accelerated stress test at a low current density of 10 mA cm^{-2} where the RH changed from dry to 100% every 10 and 40 min. A comparison with a steady state run under high humidity idle conditions showed that the voltage degradation rate was around 30% higher. As a result, the PEMFC under RH cycling failed around 460 h of operation due to high crossover currents, whereas the steady-state run continued to operate for 700 h. In general, proper water management is crucial for ensuring the lifetime of a PEMFC [120,203]. Temperature cycling tests conducted in situ are likely to impact the degradation rate of PEMFCs, as they also affect the humidity of the membrane, as discussed in the water management section. However, there is a lack of research in the literature that focuses on this matter [152,186]. In-situ tests can be inconclusive when studying thermal and water management degradation and cycling, or hygrothermal cycling, making it a challenging topic to investigate [207].

Dust and particles are also associated with harsh operating conditions and are known to exacerbate degradation rates. Santa Rosa et al. [82] suggest using filters to keep the oxidant stream dust-free to avoid blocking and MEA contamination. According to Spectronik [149], a manufacturer of PEMFCs for UAVs, cathode protection from dust and particles is necessary for PEMFCs. However, in open cathode systems, this can be a challenging task as the filter area is quite large. In addition, filters increase flow resistance, which can increase fan power consumption by 10%–15% in hot ambient conditions.

Vibrations and shocks are also considered degradation mechanisms for PEMFCs. However, they are inadequately investigated, as noted in a review by Zhao and Li in 2019 [152]. Rajalakshmi at al. [181] conducted vibration tests on a 30-cell 500 W PEM stack by shaking the stack from 30 to 150 Hz at a constant acceleration of 3 g for 90 min at each axis. They found that the stack had good mechanical integrity and showed no significant difference in the electrochemical performance of the individual cells. To maintain the compression force, they recommend using padding or a spring suspension. Hou et al. [182] researched the effects of long-term vibration tests on the performance of a PEMFC. They examined gas tightness, voltage degradation, AC impedance, the polarisation curve, and characteristic parameters before, during, and after the tests, which lasted a maximum of 250 h. The study found that the gas tightness decreased significantly, and the steady-state performance decreased as well. Additionally, AC impedance rose, leading to the conclusion that vibration has a considerable impact on PEMFC performance degradation. Further research is needed to understand this phenomenon fully.

Harsh operating or ambient conditions can significantly affect the performance of PEMFC, especially in open cathode systems. If the FC UAV is expected to operate in such conditions, it is advisable to consider these effects. This can help assess the FC UAV's lifetime and evaluate the added value of certain measures to mitigate these, such as a more elaborate BoP.

3.5.3. Degradation linked to power profile

As previously stated, FCs are often integrated into hybrid systems alongside batteries to provide faster responses to changes in the load profile. However, certain load profile characteristics may accelerate the degradation of FCs, which is the main subject of this section. Dudek et al. [3] examined PEMFC stacks as power sources for UAVs. They mentioned that varying power profiles can cause undesirable phenomena such as local dehydration, flooding, and reactant starvation, discussed in the operating conditions Section 3.3. These phenomena can ultimately result in a decrease in the lifetime of the FC. Pei and Chen [203] focused on the main factors that affect PEMFC lifetime. They specifically discussed load cycling and its link to catalyst active area reduction, electrode thickness decrease, and ionomer layer decay, all of which can lead to a reduction in the FC performance over time. A different study by Pei et al. [208] focused on the FC lifetime and the link with certain operating conditions. Based on their experiments, the main factors were load cycling and start-stop cycling, while high and very low power operation also played a role.

Han et al. [183] conducted an experimental analysis on a short closed cathode stack with three cells to measure the performance degradation under dynamic load cycles. During the test, they continuously applied the New European Driving Cycle (NEDC) electric load profile for 100 h, after which they measured the polarisation curve and performed a recovery procedure. They repeated the process three times, resulting in a total test duration of 300 h. The authors observed a significant voltage degradation after 300 h using very low current densities. The voltage degradation rate was determined to be between 100–200 μV/h at 55 °C and 200–650 μV/h at 75 °C after 300 h of operation. Higher current densities resulted in higher degradation rates. However, they did not compare this to a steady load profile. In addition, they identified a link between the operating conditions and degradation and recovery rates, with the degradation and recovery rate being higher at 75 °C than at 55 °C. This shows the complex interconnection between the operating conditions, degradation, and ambient conditions, making the analysis and comparison of open cathode PEMFC degradation mechanisms challenging.

Ramirez-Cruzado [209] also conducted an experimental analysis of load cycling on a single-cell 50 cm^2 PEMFC. They used an adapted NEDC electric load profile version, and each cycle lasted around 21 min. The entire process was repeated five times. The study revealed that the PEMFC did not show any voltage degradation over the five cycles. However, further research is necessary to determine the impact of multiple cycles.

A study by Meng et al. [184] has shown that the degradation characteristics of single-cell hydrogen-oxygen PEMFCs are influenced by dynamic current cycles. The researchers subjected the PEMFC to three different dynamic load cycles and evaluated its performance using the polarisation curve, cyclic voltammetry (CV), and EIS after every 100 cycles. They continued this process until the performance degraded by 10%. The study concluded that the rate of performance degradation is closely related to the number of loading cycles and the cyclic loading rate. The authors attributed this to the short-term unavailability of reactants, which leads to starvation and irreversible damage.

Wahdame et al. [185] examined the effect of current oscillations on a PEMFC by comparing it to a constant current profile. Two 100 W PEMFC stacks were tested, one with a stationary regime for 1000 h and the other with a standardised dynamic load profile for 700 h. Surprisingly, the results indicated that the voltage degradation rate was higher for the constant load. The authors attributed this to the average current levels of 12.5 A and 50 A for the first and second tests, respectively. Therefore, the study concluded that the average value of the load current significantly impacts the ageing process.

In a literature review conducted by Yu et al. [210], the causes, consequences, and mitigation strategies of PEMFCs during startup and shutdown processes are discussed in detail. The authors provide an overview of relevant works and conclude that startup and shutdown cycles play a crucial role in the durability and lifetime of PEMFCs. The main cause of degradation is thought to be a high cathode potential occurring during the cycles. In 2018, Zhang et al. [211] conducted a similar literature review that specifically examined the degradation caused by start-stop operation in automotive applications. The review confirmed that frequent startup and shutdown cycles limit FC lifetime. The main degradation mechanism was also attributed to the high cathode potential that occurs at the anode hydrogen-air interface due to the startup and shutdown processes.

3.6. Conclusion

This section focused on PEMFCs designed for use in UAVs. PEMFCs for UAVs were found to differ greatly from those used in other applications. They incorporate simpler systems for heat, water, and gas management, mainly driven by mass considerations. Therefore, it is expected that the performance of open cathode PEMFCs is significantly impacted by ambient conditions, leading to higher degradation rates due to chemical degradation and harsh operating or ambient conditions. It is also important to note that PEMFC UAVs deployed for commercial applications are expected to fly at any time of the year and in various flight conditions. Considering these factors in the design of the hybrid system is expected to enhance FC performance and longevity. In addition, the hybrid system should minimise the FC degradation linked to the power profile to improve lifetime. However, when it comes to UAVs, the aim of enhancing lifespan needs to be weighed against the added mass and complexity of a sophisticated hybrid system. The following section will present an overview of different hybrid system layouts and dimensioning strategies from the literature. The objective is to examine whether ambient conditions and degradation issues, which were previously discussed, have already been taken into account.

4. Energy system layouts and dimensioning in a FC UAV propulsion system

For UAVs, it is important to have a propulsion system that offers high specific power and energy densities. These two factors affect the flying characteristics, such as the flight endurance of the UAV [6,9,20,21]. Previous research indicates that hybridisation is necessary to achieve this goal, although it highly depends on the specific UAV application. The role of major energy systems for hybridisation in FC UAVs is discussed in Section 2. The purpose of this section is to evaluate different configurations of energy systems for UAVs in order to combine their unique benefits. First, the UAV propulsion system consisting of a FC only is discussed. Subsequently, hybrid systems are examined, which can be further subdivided into direct and indirect hybrid systems. Next, a literature review of various hybrid system layouts used in UAVs propelled with FC is given, with specific attention to the employed dimensioning methodology.

4.1. Fuel cell only

Bradley et al. [212] developed a FC demonstrator UAV using a self-designed 500 W liquid-cooled stack with an air compressor. The mission lasted approximately 110 s, reaching a maximum altitude of around 30 m. They conducted experimental characterisation and concluded it is a very promising technology for use in UAVs. The flight was only for demonstration purposes, and the climb phase was shortened by limiting the flying altitude. However, as already mentioned before, relying on a FC only to power a UAV is not recommended due to the limited power density, slow dynamic response, and possible accelerated degradation when subjected to unsteady power profiles [6,27,213]. According to a review by Gong and Verstraete [20], a hybrid system can successfully protect the FC. Furthermore, they mentioned that dimensioning a fuel cell on the maximum power segment of the flight profile is not desired as the FC will be over-dimensioned and thus too heavy for cruise operation. In another study, Gong et al. [214] conducted simulated UAV missions using a fuel-cell-only power profile. They found that the climb phase took 60% longer and significantly reduced the aircraft's utility. They still included a battery in the hybrid system for the internal short related to the water management strategy to provide power during these events. Therefore, further research is recommended to determine if a FC only layout can effectively power UAVs. Current literature has not sufficiently explored this possibility due to the focus on hybridisation. While hybridisation may improve power density and lower degradation rates, it also adds more mass and complexity, which may not be useful for certain types of UAVs.

4.2. Direct or passive FC hybrid systems

In a direct hybrid configuration, various energy systems are combined without using DC–DC converters [215,216]. This option is relatively simple, lightweight, cost-effective and exhibits low power loss. However, it does not allow for independent power regulation of the different systems, thus failing to optimise the operating points of the energy systems [22]. The load allocation is therefore not controlled but determined by voltage matching [20,215]. This requires extra components, such as a diode, to prevent backward voltages or a reverse current for the FC [10]. Another important aspect is that the bus voltage can vary, which could cause problems for the propulsion system [22]. Fig. 7 shows two options for the direct hybrid construction.

Nishizawa et al. [55] conducted a study on the feasibility of a direct hybrid system, which involved a 400 W FC stack and Li-ion battery packs, for use in UAVs. Their static test revealed that when the FC voltage dropped below the battery voltage due to an increase in current, the battery started delivering power. The direct hybrid system was highly efficient, with only a 4% power loss at its maximum power of 1000 W. During a dynamic test, various higher current variation rates were introduced using different current ramps and steps. During the load variations, the system was able to deliver the requested power. The battery again only provided power when the FC voltage dropped below the battery voltage, which happened during the highest current draws and during quick step changes to compensate for the FC time constant of around two seconds. The researchers also implemented a circuit using a MOSFET that recharges the battery using the FC after high-demanding flight phases. They concluded that the direct hybrid system is a simple and highly efficient way to power UAVs. The study did not provide information on the unsteady power profile that the FC potentially experiences in a direct hybrid configuration. However, they did demonstrate that the direct hybrid system was capable of following a cycle operation at a frequency of 2.5 Hz. This experiment did show quick and large FC current spikes. This could accelerate degradation, as discussed in Section 3.5.3. The following section discusses how indirect hybrid systems can be used to solve this.

4.3. Indirect or active FC hybrid systems

The indirect hybrid construction technique uses DC–DC converters to align the voltage of energy sources, creating a hybrid system without potential conflicts or issues that can occur when different energy sources or components interact directly. This could be due to variations in voltage levels, power delivery characteristics, or other electrical properties [217]. Unidirectional or bi-directional converters can be used depending on the type of energy source. Energy management systems can control and optimise the power distribution through DC–DC converters. Indirect hybrid systems can improve performance, energy system lifetime, and fuel consumption [6,10,22]. Moreover, they allow for the combination of energy sources with varying voltages [218] and provide a more stable output voltage in comparison to direct hybrid systems [219]. However, using DC–DC converters increases mass, volume, complexity, conversion losses and cost [10]. Furthermore, adding DC–DC converters also introduces an extra point of failure. In fact, according to a literature review by Vichard et al. [23], the failure of DC–DC converters is one of the most significant reasons for the failure of FC-based systems. Therefore, there are different indirect hybrid constructions that are linked to the number of sources that can be actively controlled via the use of DC–DC converters. The fully-active and semi-active configurations are discussed below. Fig. 8 illustrates an example of all the indirect hybrid systems discussed.

Several energy management strategies are available to regulate energy systems with a DC–DC converter in indirect hybrid systems. Zhang et al. [6] have provided a comprehensive overview of these strategies for FC UAV hybrid systems. They have grouped the strategy according to the control approach into three categories: rule-based,

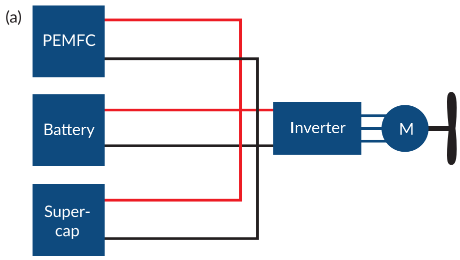

Fig. 7. Overview of direct hybrid systems: (a) direct FC/battery/supercapacitor hybrid system, (b) direct FC/battery hybrid system.

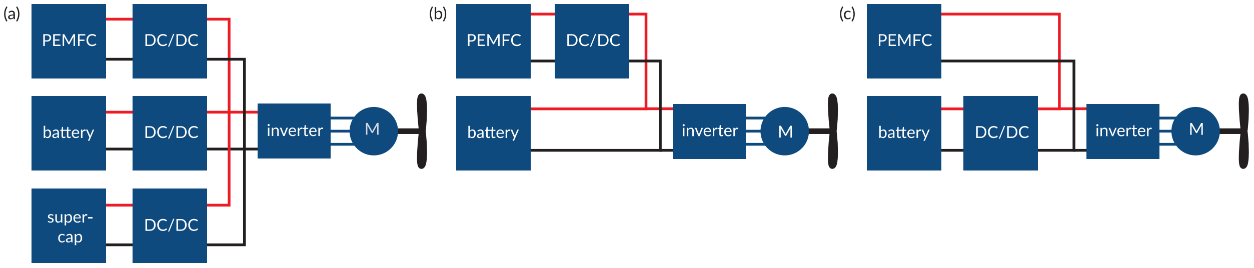

Fig. 8. Overview of indirect hybrid systems: (a) fully active hybrid system, (b) semi-active hybrid system with active FC, (c) semi-active hybrid system with active battery.

optimisation-based, and data-based energy management strategies. Xu et al. [27] used the same categories. In contrast, the review paper focuses more on the FC and various hybrid system layouts and relates them to dimensioning strategies.

4.3.1. Fully-active configuration

In a fully active configuration, DC–DC converters are used to control all power sources actively. All systems are isolated from the DC bus voltage. This configuration allows for the highest level of control. However, as discussed, this comes with increased complexity, resulting in higher mass, cost, and conversion losses [10,22].

4.3.2. Semi-active configuration

To simplify and reduce the cost and mass of a hybrid system, it may be advantageous to use fewer DC–DC converters. This can be achieved through the use of the semi-active construction, where at least one power source in the system is managed passively without a DC–DC converter. The other energy sources are considered active and can be controlled via energy management strategies. Combining direct and indirect systems can lead to reduced controllability and efficiency for hybrid systems. However, the reduction in mass, volume, and cost makes this approach a viable option [6,10,22]. Choosing the active source based on where a DC–DC converter is employed results in different configurations, as shown in Fig. 8, and elaborated below.

1. *Active fuel cell*
   The FC is actively managed by a unidirectional DC–DC converter, enabling active FC regulation to choose, for example, the optimal operating point. The battery voltage determines the DC bus voltage, and it can be used to supply or absorb additional power [220]. This configuration is considered promising as the FC is protected from power fluctuations, which can reduce degradation, as discussed in Section 3.5.3.
2. *Active battery*
   In this case, a bidirectional DC–DC converter is utilised for the battery to allow for load-sharing control and management of charging and discharging. The battery only provides power and, therefore, determines the load voltage when the FC cannot meet the demand. During periods of low power, the FC operates in load-following mode and can recharge the battery as needed [218]. A diode is needed for the FC to protect it from reverse currents, as for direct hybrid systems, or energy management can be used. However, this setup is not ideal for the durability of the FC as it may be affected by a fluctuating power profile.

4.4. Dimensioning strategies

Appropriate design is required to compose a hybrid system that combines the benefits of good dynamic response and sufficient power density for high-demanding flight phases with appropriate volume, mass, energy consumption, and energy requirements [220]. The optimisation of the energy management strategy is becoming a popular trend in recent literature, as highlighted by recent works [6,27,221]. However, the sizing of the hybrid system is considered more important as a first step in optimising FC hybrid systems for UAVs. Therefore, this section will discuss and provide an overview of various strategies that have been used in the literature and is summarised in Table 5.

Cai et al. [231] developed a sizing methodology for hybrid FC power systems for unmanned underwater vehicles. They focused on a simple power profile composed of discrete, cyclically repeated power levels. Their first step was to calculate the average power demand and use this to dimension the FC, reasoning that this would increase the lifetime and efficiency of the FC as it is operated at a steady operating point. Subsequently, the battery or supercapacitor could be designed based on the remaining required peak power. Suetakanal et al. [30] modified the method proposed by Cai et al. specifically for UAVs in their conceptual design of a blended-wing-body FC-battery UAV to achieve the lightest option for the energy system. They chose a 650 W FC based on the required power for cruising. They simulated a 2-h mission profile and proved that the 100 Wh battery pack stayed within its SoC limits while the FC power remained constant, operating at high efficiency.

Nishizawa et al. [55] not only validated the performance of direct hybrid systems comprising a FC and battery but also provided guidelines for battery sizing. In their approach, the first step is to choose a FC based on the appropriate power, but this is not discussed in detail. The selected FC has a voltage range that forms the basis for the battery open circuit voltage selection. This is preferably as close as possible to the rated FC power corresponding to the lowest FC voltage to ensure it is fully loaded before the battery kicks in. Using this approach fixes the cells in the pack. Multiple battery packs can be connected in parallel if increased capacity is required.

Table 5
Literature overview of various FC hybrid system designs and sizing methodologies for fixed-wing UAVs.

Source	Fuel cell	Hybrid system type	FC sizing method	Other energy systems sizing methods	Considered ambient conditions or degradation
Dudek et al. 2013 [222]	200 W open cathode	Direct FC + bat	Average cruise power	No information	No
Nishizawa et al. 2013 [55]	400 W closed cathode	Direct FC + bat	No information	Voltage matching	No
Lee et al. 2014 [223]	200 W closed cathode	Direct FC + bat + solar	Average cruise power	No information	No
Savvaris et al. 2016 [224]	500 W open cathode	FC + bat	Average cruise power	No information	No
Gong and Verstraete, 2017 [219]	150 W open cathode	Direct FC + bat	No information	No information	No
Lapeña-Rey et al. 2017 [225]	200 W open cathode	FC + bat	Average cruise power	Additional required power	Not in design but showed importance
Gong et al. 2018 [59]	150 W open cathode	Direct FC + bat + supercap	No information	Voltage matching	No
Özbek et al. 2020 [46]	250 W open cathode	FC + bat	UAV designed around FC	No information	No
De Wagter et al. 2021 [226]	800 W open cathode	FC + bat	UAV designed around FC	No information	No
Desantes et al. 2022 [227]	40 kW closed cathode	FC + bat	3 × average cruise power	No information	No
Suewatanakul et al. 2022 [30]	650 W	FC + bat	Average cruise power	Energy required for peaks	No
Zhou et al. 2022 [228]	800 W	FC + bat	Average cruise power	No information	No
Aslam et al. 2023 [229]	1500 W	FC + bat	Average cruise power	Capacity to match total energy	No
Achour et al. 2024 [230]	50 W	FC + bat	Optimisation	Energy required for peaks	No

Fuel cell (FC), battery (bat), solar panels (solar), supercapacitor (supercap).

Lee et al. [223] analysed flight test data of a UAV power system, which was powered by PV cells, a FC and a battery, with the aim of creating a model. During the design of the hybrid system, a 200 W FC was chosen based on the average power requirement. The bus voltage was determined by the battery, which was selected based on the voltage range of the FC. The hybrid system performed well during the demonstration flight. After a 14-h flight, the FC suddenly failed, which was attributed to low power output as suggested by the authors. This issue is briefly discussed in Section 3.5.3 and highlights the need for more attention to be given to the FC in UAV hybrid systems.

Verstraete et al. [218] conducted dynamic tests on an indirect hybrid system with an active 6-cell LiPo battery and a 200 W open cathode PEMFC specifically designed for UAVs. The tests involved multiple power steps ranging from 0–400 W, and their aim was to determine the role of battery characteristics. Although they did not focus on the sizing of the various energy systems present in hybrid systems, their conclusions were significant. They found that battery capacity and C-rate considerably impact the system's dynamic performance and recharging characteristics. Therefore, selecting a battery for hybrid systems requires a trade-off between boost capability, capacity, mass and mission endurance.

Gong et al. [214] analysed the performance of a direct hybrid system comprising a 200 W open cathode PEMFC and a battery. They evaluated the system operation under different flying and climbing speeds representing typical mission states. They concluded that optimising the hybrid system size based on the power profile can enhance fuel consumption and overall performance. In addition, they mentioned the possible impact of ambient conditions on the FC performance, including wind increasing the required power and ambient temperature variations.

Lapeña-Rey et al. [225] summarised the design, characterisation, and flight tests of a surveillance UAV. The UAV was designed for missions below an altitude of 1000 m. The hybrid system consisted of a 200 W open cathode FC and a LiPo battery with a maximum power of 2200 W and 110 Wh. Although the authors did not consider the effect of ambient conditions on the FC directly, they were the first to calculate the average power used during cruising in the worst atmospheric flying conditions. This value was approximately 155 W, related to the propeller efficiency. They mentioned that the FC power should be well above that value to have some margin related to the power required for FC cooling, depending on the ambient temperature. The batteries provided power during takeoff, climbing, and high-demanding flight phases. Recharging the battery using the FC was also possible. During flight testing, the authors focused on testing the FC stack at the extreme limits of its operating window. They flew the aircraft in Spain, where the maximum ambient temperature was 37 °C and relative humidity was 30%. As expected, the FC underperformed with a power output of less than 180 W due to lower electrochemical reaction kinetics and increased fan power for cooling. In addition, the sodium borohydride storage and hydrogen generator might have also contributed to the lower performance. Fortunately, the power consumption of the UAV was lower than expected due to favourable flying conditions involving thermals. This resulted in the system performing quite well during the first two hours. Afterwards, the thermals became so strong that the UAV suddenly started to ascend. This lowered the required FC power but also resulted in the FC operating temperature declining strongly by the increase in altitude. The low-temperature protection of the FC was activated, causing it to shut down. According to the authors, operating a UAV with FC under different ambient conditions is a significant challenge due to the combined influence of the FC performance and the UAV flying characteristics. This is further complicated by the FC performance under dynamic loads, which are unavoidable in UAVs, and FC durability.

Özbek et al. [46] designed a fixed-wing hybrid FC UAV in an iterative procedure. Instead of starting with the drone, they began with selecting the FC, a 250 W open cathode FC with a LiPo battery for high-demanding flight phases. In the next step, they calculated the design requirements of the UAV to achieve the proposed goals, such as endurance, wing loading value, and maximum takeoff weight (MTOW). The design process involved creating a list of all necessary off-the-shelf components and determining their respective masses. This allowed the researchers to calculate the maximum mass limit for the wing, fuselage, and tail structural components. After several iterations, they built three prototypes. The power consumption during the cruise was approximately 160 W, and they emphasised the importance of considering ambient conditions, such as wind, when evaluating their design methodology. In a later study conducted by Özbek et al. [232], it was found that a 250 W open cathode PEMFC was only able to produce an output of 160–170 W. This was attributed to the lack of FC conditioning and the direct use of ambient air. The authors also suggested that when designing a hybrid system, the different battery characteristics and ambient conditions should be taken into consideration.

De Wagter et al. [226] designed the NederDrone, a fixed-wing hybrid lift hybrid PEMFC UAV that can take off and land vertically by using 12 propellers. They started from an 800 W open cathode PEMFC and hydrogen storage system. Subsequently, they designed the energy system of the UAV and selected batteries to provide the 1400 W of power needed for hovering. Moreover, they added four additional batteries for emergency landing in case the FC fails. They successfully completed a 3-h and 38-min offshore demonstration flight in moderate wind.

In a study by Farajollahi et al. [233], two hybridisation strategies were compared using modelling. One strategy allowed for battery recharging, while the other did not. The study found that the use of a strategy with battery recharging reduced the weight fraction of the propulsion system by almost 8%.

Aslam et al. [229] proposed a design for a hybrid system for a fixed-wing UAV with a MTOW of 21 kg. They suggested that the FC should be designed based on the required cruise power, estimated to be around 820 W. Interestingly, they opted for a FC of 1500 W to accommodate the power consumption of the BoP. This approach raises some questions about the efficiency and necessity of such a large safety margin. Similarly, Desantes et al. [227] employed a comparable methodology in their design of a fixed-wing UAV using a FC and carrying a payload of 75 kg. They selected a closed cathode FC with a power output of 40 kW, notably thrice the minimum required cruise power. This decision, while potentially providing a significant safety buffer, also prompts further inquiry into the reasoning behind such a substantial increase over the minimum power requirement. It would be interesting to explore the implications of these design choices on the overall performance and efficiency of the UAVs.

An advanced methodology for sizing an electric vertical takeoff and landing (eVTOL) UAV powered by a combination of a hydrogen FC and battery was proposed by An et al. [234]. Their study considered open cathode PEMFCs as the primary energy source for the eVTOL steady-level flight, climb phase, and descent since less power is required during these phases. For hovering, vertical takeoff, and transition phases, batteries were primarily relied upon. During the first step of the sizing process, a multi-mode constraints analysis is conducted to identify the design area and initial point based on the design requirements, mission profile, and assumptions. This result is then used in the second step to determine the size of the electric propulsion system, such as the battery and FC, based on regression models. The next step involves analysing the mission to predict the mass of the battery and hydrogen storage system. This data is then combined in the final step, where the MTOW is determined. An optimisation routine is implemented to minimise the MTOW by iteratively stepping through steps two and three. Çınar et al. [235] discussed a similar methodology to size a hybrid system consisting of a FC and battery by minimising power consumption through an optimisation problem.

Achour et al. [230] proposed a methodology that utilises particle swarm optimisation to design a fully active hybrid system design combined with energy management. The authors concluded that the best sizing method for a FC is to match the power of the longest-duration mission segment, which is generally cruise, and this was evaluated across two different power profiles. During high-demanding flight phases, the battery is necessary to provide power and avoid unsteady power profiles for the FC. The authors also mention that the battery capacity should not fall below 20% at the end of the mission to prevent deep discharges.

To conclude, the current research lacks guidelines for designing PEMFC hybrid systems for UAVs regarding FC sizing and BoP configuration combined with selecting other energy systems, dependant on the UAV application. In addition, although various works suggested its importance [20,22,155,236,237], ambient conditions and degradation are not considered, representing a significant knowledge gap.

5. Conclusion & Future perspectives

PEMFCs are expected to improve the endurance and payload of electric UAVs, potentially leading to new applications. Currently, PEMFC UAVs are in the demonstrator phase, and some manufacturers offer FC systems suitable for UAV implementation. However, due to mass considerations, the management of the operating conditions is performed by simplified management systems compared to other PEMFC applications. Additionally, due to the limited power density and slow dynamic performance of PEMFCs, they are generally combined with other energy systems to form hybrid systems. However, there is a need for better guidelines on hybridisation linked to the UAV application, as the current literature lacks this information.

Designing a suitable hybrid system by combining different systems can be challenging as it requires balancing cost, mass, endurance, payload, and flying behaviour. This review highlights that when designing hybrid systems for UAVs, it could be important to consider ambient conditions and degradation as they have a high impact on the performance of PEMFC systems. However, most works discussing UAV hybrid system design only consider the FC performance at standard ambient conditions and do not include degradation or durability.

The current research trend in this field is to optimise and compare various energy management strategies in terms of fuel consumption by using simplified models for the different energy systems present in the hybrid system. It is anticipated that the FC will be the most expensive yet crucial element in extending the endurance of UAVs, but also the component most sensitive to ambient conditions, potentially affecting applicability. Additionally, understanding the degradation of FCs employed with simplified operating conditions management systems is essential to estimate the lifespan of PEMFC UAVs.

We conclude that ambient conditions and degradation are crucial to assess the feasibility of PEMFC UAVs for commercial applications. This assessment should be linked to the UAV application for hybrid system design and optimisation. Additionally, it is important to evaluate whether a hybrid system is necessary for the specific UAV application. Investors generally want to assess the applicability, operating region, performance and lifetime before making significant investments. Therefore, this review suggests the following main areas for future work in order of priority:

1. It is recommended to focus more on the PEMFC performance of systems specifically designed for UAVs. Limited literature is available for PEMFCs with simplified operating condition management systems, as this is linked to mass considerations and

is specific to UAV applications. Therefore, experiments should be performed to assess the impact of ambient conditions and degradation to evaluate the typically employed operating conditions management strategies in FCs for UAVs. However, these experiments are expensive due to the required testbenches and FC systems. Therefore, a hybrid approach combining data-driven and physics-based modelling is advised. Possible limits regarding operation regions, applicability and short lifetimes may make the current PEMFC technology for UAVs unfeasible for commercial applications. One interesting idea is to use these models to research the benefits of optimal control of the BoP systems to improve PEMFC performance by lowering sensitivity to ambient conditions and increasing durability.

2. Guidelines for designing hybrid systems, including the selection of layouts, sizing of energy systems, and their characteristics, are necessary to meet UAV application requirements. Therefore, creating models of hybrid systems that align with realistic UAV applications is recommended. Ideally, the impact of ambient conditions and degradation can be considered to potentially improve the design using this information. The main goal could be assessing the feasibility of a PEMFC UAV for a certain application considering the payload, mission profile, ambient conditions and degradation linked to the location by proposing various optimised hybrid system layouts. In addition, these models can help assess the potential role of other energy systems, such as solar panels, supercapacitors and new battery types.
3. The energy management strategy can be improved by optimising PEMFC performance linked to ambient conditions and degradation, resulting in health-aware energy management strategies that can enhance performance and durability.

CRediT authorship contribution statement

Jorben Mus: Writing – original draft, Visualization, Project administration, Investigation, Conceptualization. **Dharmjeet Madhav:** Writing – review & editing, Conceptualization. **Maarten Vanierschot:** Writing – review & editing, Supervision. **Veerle Vandeginste:** Writing – review & editing, Supervision. **Frank Buysschaert:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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