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Review

Prospects of Integrated Photovoltaic-Fuel Cell Systems in a Hydrogen Economy: A Comprehensive Review

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Abstract: Integrated photovoltaic-fuel cell (IPVFC) systems, amongst other integrated energy generation methodologies are renewable and clean energy technologies that have received diverse research and development attentions over the last few decades due to their potential applications in a hydrogen economy. This article systematically updates the state-of-the-art of IPVFC systems and provides critical insights into the research and development gaps needed to be filled/addressed to advance these systems towards full commercialization. Design methodologies, renewable energy-based microgrid and off-grid applications, energy management strategies, optimizations and the prospects as self-sustaining power sources were covered. IPVFC systems could play an important role in the upcoming hydrogen economy since they depend on solar hydrogen which has almost zero emissions during operation. Highlighted herein are the advances as well as the technical challenges to be surmounted to realize numerous potential applications of IPVFC systems in unmanned aerial vehicles, hybrid electric vehicles, agricultural applications, telecommunications, desalination, synthesis of ammonia, boats, buildings, and distributed microgrid applications.

Keywords: solar energy; photovoltaic-fuel cell system; integrated energy system; power generation; hydrogen energy; hydrogen economy; zero emissions; photovoltaics; fuel cells

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1. Introduction

Globally, there is an increasing emphasis on the decarbonization of economies and a quicker transition from the use of fossil fuels to renewable energy resources to mitigate the unravelling risks posed by the anthropogenic interferences on the climatic systems from the inception of the first industrial revolution. As the political will to adopt and scale-up clean energy technologies (CETs) increases across the globe, there is an urgent need to facilitate the technological transition by developing novel CETs or optimizing the existing ones. Of all the renewable energy resources available to mankind (including solar, hydro, wind, geothermal, biomass, tidal, etc.), solar energy appears to be the most sustainable because it is inexhaustible, ubiquitous across the globe, and it is not subject to price controls, unlike fossil fuels. Because of this, renewable energy technologies (RETs) that use solar energy as a prime mover will continue to attract research and development attention because they can be deployed across the globe. One of such RETs is integrated photovoltaic-fuel cell (IPVFC) system, which uses photovoltaics and fuel cells to majorly generate power and hydrogen, using solar energy as the prime mover.

In 1988, Rahman and Tam [1] investigated the feasibility of grid-connected and stand-alone applications of IPVFC systems and reported that their prototype, which was tested in the United States and Japan, could create new possibilities of combining photovoltaic (PV) modules and fuel cells (FCs). Over the years, different aspects of IPVFC systems have been studied because of their potential to reduce greenhouse gases (GHGs) from the subsisting fossil fuel-dominated energy infrastructures [2,3]. The use of generating components such as PV modules, FC stacks and wind turbines (WTs) in hybrid/integrated power systems have huge environmental and health benefits because they do not produce GHGs and other emissions [4,5]. However, it has been argued that the life cycle assessment (LCA) of renewable energy systems should be the basis for determining their total greenhouse gases emissions since the manufacturing processes, transportation, decommissioning or end-of-life management may involve emissions [6]. Nonetheless, renewable energy systems are more sustainable because whilst the supply chains of manufacturing both conventional and renewable energy systems may involve the combustion of fossil fuels, renewable energy technologies do not emit significant greenhouse gases during their operation stage.

Primarily, the purpose of the integration is to achieve integrated qualities that the subsystems cannot achieve individually. The objectives of integrated energy systems may include increasing the energy and exergy efficiencies, reducing overall cost, improving the reliability of the system, reducing the overall greenhouse gas emissions, et cetera [7,8]. There are various competing power generation methodologies which have recently appeared in the literature. These include hybrid solid oxide fuel cell–microturbine system [8,9], integrated parabolic dish-Rankine-organic Rankine cycle-fuel cell system [10], integrated PV-Fuel cell-wind turbine system [11,12], hybrid solid oxide fuel cell (SOFC)-thermophotovoltaic system [7], integrated PV-wind turbine-battery-diesel system [13], and PV-fuel cell-diesel system. Later, comparisons among these competing technologies are presented in Section 4.

As the applications of solar hydrogen and fuel cell attracted interests globally in 1990s, particularly for distributed applications, work by Yilanci et al. [14] compiled the attributes of some demonstration plants across the globe up to 2009 based on different system configurations. Then, they computed the maximum energy and exergy efficiencies of an IPVFC system to be 9.7% and 9.3%, respectively. Diverse investigations have been conducted over the years. For instance, recently, Shaygan et al. [15] estimated the exergy efficiency of an IPVFC system to be 21.8%. This finding clearly shows that there is still room for improvement of the thermodynamic efficiencies of IPVFC systems, particularly the exergetic efficiency which estimates the maximum theoretical efficiency limit of the system as it interacts with the environment at ground state [16]. There were also studies that focused on the integration and applications of IPVFC systems [15,17–19]. Curiously, the applications of IPVFC systems are not yet commonplace even with their huge potential grid-connected and stand-alone applications.

Consequently, this study was motivated by the need to evaluate and update the state-of-the-art of IPVFC systems including the design methodologies, optimization strategies, recent advances in materials for the components, energy management system and control strategies, and case studies on the applications of IPVFC systems. Therefore, this paper aims to undertake a comprehensive review of the progress of IPVFC systems since it could be an enabling CET in the upcoming hydrogen economy.

Here, the specific objectives of this study are to:

- Examine the potential applications of IPVFC systems.
- Assess how close IPVFC systems are towards commercialization.
- Evaluate the applicability of IPVFC systems in a hydrogen economy.
- Produce a comprehensive paper that can provide researchers, policymakers, and industrialists a quick overview of the possible integration of photovoltaics and fuel cells for power and hydrogen generation.
- Outline a roadmap for addressing the limitations of IPVFC systems.

1.1. Research Methodology

The methodology for this study can be categorised into five phases. Phase I: Planning. Phase II: Searching, organisation and recording. Phase III: Reviewing and documentation.

Phase IV: Writing and revision. Phase V: Scholarly communication. These phases include the following activities and approaches. (1) Reputable databases where peer-reviewed materials (including articles, reviews, conference papers and books) can be found were used. Databases searched include ScienceDirect (https://www.sciencedirect.com/, Web of Science (https://www.webofscience.com/wos/woscc/basic-search), IEEExplore (https://ieeexplore.ieee.org/document/7973535), Springerlink (https://link.springer.com/), Wiley-online (https://onlinelibrary.wiley.com/), Google Scholar (https://scholar.google.com/), and The University of Manchester online Library gateway (https://www.library.manchester.ac.uk/). (2) The titles "Integrated/hybrid Photovoltaic-Fuel Cell Systems", Integrated/hybrid Photovoltaic-Fuel Cell Systems for power generation" and "Integrated/hybrid Photovoltaic-Fuel Cell Systems for hydrogen generation" were used for the search across the databases. (3) For each database, these titles were used for the search. All the titles of the materials that emerged from the search were visually assessed first. The titles that were apparently out of scope were ignored while the abstracts of possible materials within scope were read. After reading the abstract, materials outside the scope were ignored; while the title, digital object identifier (DOI) and web address of those that fell within scope were copied into a Microsoft word document. (4) The compilations were initially based on themes such as design methodology, optimization, energy management and control, materials, techno-economic study but new themes were created as more materials with new themes emerged. Some studies also covered more than one aspect of the system, but the respective findings were segregated during the review phase. (5) After going through the databases, each of the material was studied in greater detail. The key findings or relevant information from the studies were noted. The references cited in each study were also checked to see if they were relevant for the current study. The title and DOI of relevant materials found in the reference, that had not been listed previously, were included in the Microsoft word document. (6) After studying and critically evaluating the relevant materials available, the themes that finally emerged were used to create the structure of the report. (7) The report went through several internal reviews and updates before a manuscript was produced for publication.

1.2. Research Contributions

The major contribution of this systemic and systematic review of IPVFC systems is that it updates the knowledge of the systems and their applications based on peer-reviewed materials since 1980. There are no existing papers in the current literature that covered the fundamental engineering and development attributes of IPVFC systems comparable to the current study that have emerged after an extensive search of publicly available databases. Therefore, we believe that this paper is timely as it reviewed the state-of-the-art of IPVFC systems and future directions towards their full commercialization within the context of a hydrogen economy. We hope that this paper will guide researchers on pathways to feasible and novel/original engineering contributions so that the application of IPVFC systems in the imminent hydrogen economy can be facilitated. Furthermore, a roadmap for advancing the state-of-the-art of IPVFC systems and recommendations on how to address the current technical issues were presented.

Henceforth, Section 2 will focus on the design methodologies of IPVFC systems. Section 3 presents a critical analysis of the design, research and development studies that have been done over the past four decades. Section 4 focuses on the potential applications of IPVFC systems while Section 5 presents the prospects and challenges associated with IPVFC systems. Eventually, Section 6 summarizes the findings and presents a roadmap for the future to address aspects that would enhance the overall performance of the systems. Section 7 presents the conclusions of the study.

2. Design Methodologies, Composition and Configurations of IPVFC Systems

IPVFC systems have flexible configurations to accommodate different types of components which is an undeniable engineering advantage. The autonomous operation of the system is facilitated by an energy management system, which provides a logical algorithm that controls the flow of energy in the system [20]. The modularity in the design of IPVFC systems implies that they are easily scalable [21]. Thus, the system can be configured to meet users' requirements and satisfy specific use cases. Notwithstanding, to contextualize this study, there are four categories of design methodologies of IPVFC systems, although there could be variations in the composition of a category depending on the use case. The following are brief descriptions of the categories:

- Category 1: PV, fuel cell and batteries can supply power to the load.
- Category 2: PV and fuel cell supplies power to the battery bank/supercapacitor so that it can supply power to the load.
- Category 3: Combined heat and power (CHP) design in which the PV is replaced with photovoltaic-thermal (PV/T) component.
- Category 4: Compact design that replaces proton exchange membrane electrolyser (PEME) and proton exchange membrane fuel cell (PEMFC) components with a unitized regenerative proton exchange membrane fuel cell (URPEMFC) component.

The first category of IPVFC systems is typified by the configuration in Figure 1. This design methodology for power generation is composed of a photovoltaic module, DC/DC converter for the photovoltaic, battery, step-down converter for electrolyser, electrolyser, fuel cell, step-up for the fuel cell, and a DC/AC inverter [20]. In this configuration, a DC/DC converter is used to connect the PV modules, electrolyser, fuel cell and battery to the DC-bus bar. A DC/AC inverter is connected to the DC-bus bar to change the DC to AC for AC loads [22]. Integrating PV modules with batteries and FC stacks makes the integrated system more sustainable because the system can reliably satisfy load requirements, even in the absence of solar radiation [23]. This category may use a proton exchange membrane electrolyser to generate hydrogen and proton exchange membrane fuel cell to convert the stored hydrogen to meet power demanded [24]. PEMFC has a high energy density per unit area, zero greenhouse gas emission, modular design, noiseless operation, limited moving parts and it is not limited by the Carnot efficiency [25,26]. This configuration is suitable for buildings, stationary applications, grid-connected systems, and mobile applications. As a variation of this design, the system can be configured so that batteries can provide the basic power while peaks in demand for power can be met with the fuel cell. This feature is crucial in achieving optimal operational efficiency of renewable energy-based smart grids since the intermittency of solar energy could lead to excess electricity generation or shortage of it.

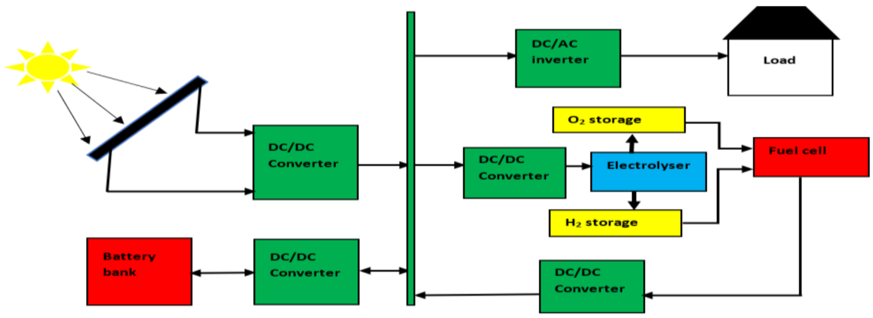

Figure 1. Schematic diagram of an IPVFC system including a PV, battery, electrolyser, and fuel cell.

The second category of IPVFC systems is shown in Figure 2. This is more suitable for automotive and unmanned aerial vehicle (UAV) applications. Integrated fuel cell hybrid electric vehicles and fuel cell electric vehicles are actively being investigated as potential replacements for internal combustion engines in the automotive industry [27,28], and the trend will likely continue onwards because the automotive sector is a major contributor of emissions [29].

In this configuration, a PV module and an FC stack charge the battery bank which provides tractive power to drive the entire system. This configuration provides a more stable power source compared to configurations in which electrical energy is supplied to the load directly from the PV module. For shorter periods, batteries can supply constant direct current if charged, while fuel cells can provide direct current to keep the battery charged for a longer timeframe using hydrogen. In this category, hydrogen may be produced within or outside the system or obtained from hydrogen filling stations to reduce the weight of the electrolyser from the total weight of the system.

Lead acid batteries [24] have achieved technological maturity and most IPVFC systems use it. Nonetheless, Li-ion batteries are uniquely compatible with renewable energy resources [18], and their utilization will continue to increase until a more efficient and safer battery cell is innovated. Supercapacitors (SC) have high-power density, fast dynamics and a relatively longer lifetime compared to batteries, but they discharge fast. Supercapacitors have been used in this configuration to assist stabilize the power supplied by a PV module and a PEMFC stack [30]. Thus, combining batteries and SC have been reported to be beneficial for improving the reliability of the system [31,32]. PV modules and FC stacks are used without batteries/SC to reduce the overall cost of the system when it is not necessary to store electrical energy [33]. Boost converters are used to adapt the low DC from the PV and the FC to a regulated bus bar DC [34]. The boosting and inversion of unregulated low-voltage output from the FC can be efficiently achieved at a low cost and compactness using a boost-inverter with a bidirectional backup battery storage [35]. A bidirectional converter and a boost converter can also be combined to manage the flow of current in IPVFC systems so that the current/voltage output of FC can be regulated by a boost converter, whilst the bidirectional converter regulates the current/voltage from the battery and supercapacitor [32]. Bus bars enable the electrical connection of the components to ensure that the DC sources and the DC supplies are properly integrated to facilitate an effective spatial topology of IPVFC systems.

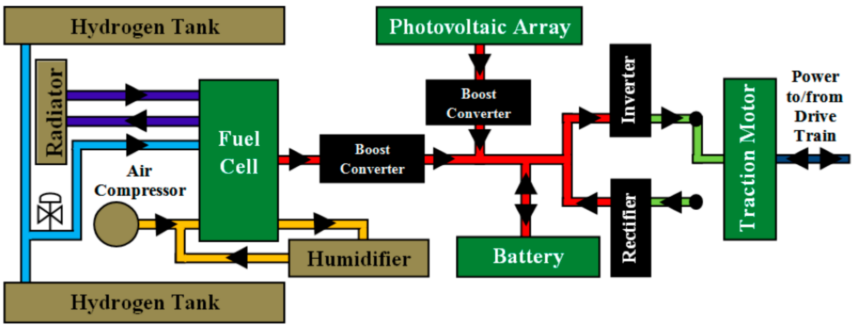

Figure 2. Schematic diagram of IPVFC system as power source for automotive applications [36].

The third category of IPVFC systems uses a photovoltaic-thermal (PV/T) module or solar thermal collectors [37] instead of a PV module to achieve a co-generation system (or combined heat and power (CHP)). Consequently, electricity and hot fluid can be generated as shown in Figure 3. This configuration is predicated on the preconception that harnessing the thermal energy from the PV module could lead to improved energy and exergy efficiency of the first category of IPVFC system. Further design variation of this category involves harnessing the waste heat from the PEME and PEMFC to perform additional thermal work such as heating of air, water, or other fluids since they operate between 70 and 100 °C.

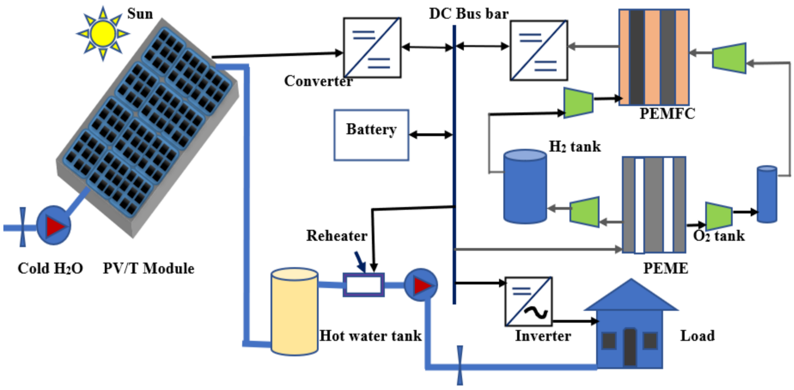

Figure 3. Schematic diagram of an IPVFC system including a PV/T, battery, electrolyser and fuel cell [38].

The fourth category of design methodology of IPVFC systems replaces the electrolyser and fuel cell components with a unitized regenerative fuel cell. The electrolyser and fuel cell exist as separate components in categories 1, 2 and 3. Category four unifies the electrolyser and fuel cell as a URPEMFC system [39], so that it can perform the functions of an electrolyser and a fuel cell [40] as shown in Figure 4. This intimate unification implies lesser cost and complexity compared to discrete reversible proton exchange membrane fuel cell (DRPEMFC) systems in which the components exist separately.

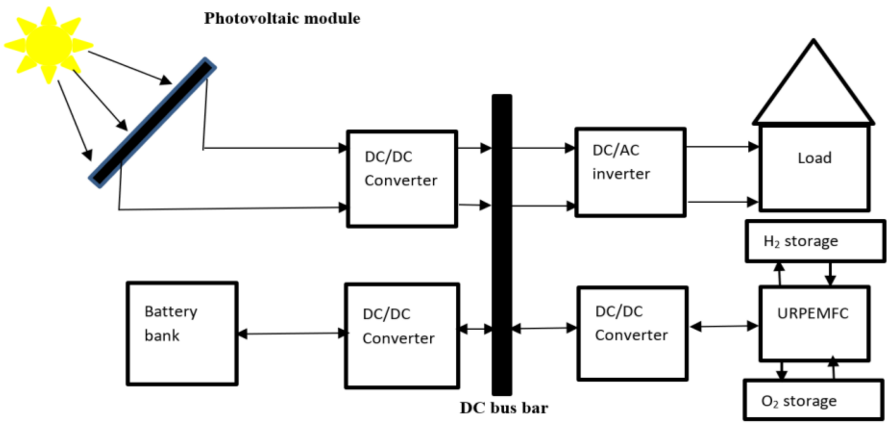

Figure 4. Block diagram of an integrated IPVFC system in which the electrolyser and fuel cell components are replaced with a unitized regenerative fuel cell system [41].

In addition, to using PEMFC, solid oxide fuel cell (SOFC) has been proposed to build IPVFC systems as a potential replacement for diesel generators. This can use a liquid fuel, a solid fuel, or a natural gas reformer to process the fuel [8]. The reformation process may include a water gas shift reaction [42] to produce hydrogen that can be utilized to generate power using PEMFC component. Tejwani and Suthar [43] investigated the use of PV and SOFC components for power generation using P-Q control approach. A 50 kW PV array served as the basic power source while a 30 kW SOFC acted as the backup. SOFC can be integrated with micro-turbine [9,44] and/or thermophotovoltaic (TPV) module [7] for co-generation or multi-generation systems because of the high operating temperature of SOFC. As an example, Arsalis et al. [45] integrated 70 kW PV arrays with 137.5 kW SOFC for CHP application. In addition, a TPV component can be used to recover exhaust heat from high temperature of SOFC (800–1000 °C) for power generation regardless of the weather conditions, unlike solar photovoltaic systems that depend on solar radiation [46]. Systems composed of TPV and SOFC components could evolve considering the renewed interests in TPV applications [47,48]. Figure 5 shows a configuration in which waste heat from the SOFC component can be recovered for power generation using a thermophotovoltaic component. Although the integration of SOFC with PV or TPV could result in a multi-generation system, the steam reform process of solid, liquid, or gaseous fuels produces carbon dioxide unlike the use of PEME in conjunction with PEMFC or URPEMFC which are cleaner alternatives. Direct ammonia fuel cells (AFC) [49] is another type of fuel cell that has been proposed for IPVFC systems, although it has a complex fuel processing characteristics compared to a PEMFC component.

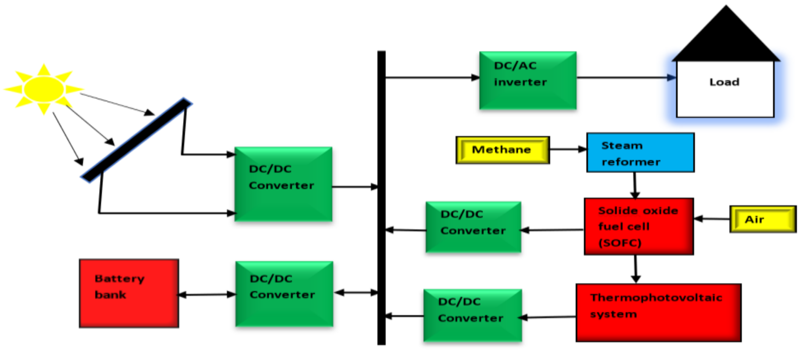

Figure 5. Block diagram of an IPVFC system including SOFC and TPV components.

An essential component which applies to all the categories of IPVFC systems is the maximum power point tracker (MPPT). It ensures that the maximum power is extracted from PV modules based on the available solar radiations, regardless of weather conditions. Examples of MPPT algorithm and implementation methodologies are perturb and observe method, incremental conductance method, short-circuit current method, open circuit voltage method, fuzzy logic controllers, and artificial neural network controllers [50,51]. Karami et al. [52] used MPPT and compensators to extract the maximum power from the PV modules and FCs as the demand for power varied with time. Padmanaban et al. [53] demonstrated how the Jaya-based MPPT method can be used to track the MPP of PV modules for an IPVFC system. Energy management system (EMS) or Power management system (PMS) is also necessary for controlling the energy flow in an integrated IPVFC system. Equally important for optimal operating conditions of IPVFC systems are the ancillaries and health monitoring of components such as compressors, pumps, fan/blowers, charge controller for the batteries, as well as sensors to measure temperature, pressure, mass flow rates, and humidity. The compressors are used to store gases from the PEME in tanks or for feeding the reactant gases into the fuel cell component as illustrated in Figure 3. Pumps are required to feed water into the electrolyser or PV/T components. Fans/blowers are used to cool the temperature of the components such as the batteries, PEME and PEMFC. In the design phase of IPVFC systems, the power consumed by the ancillaries are discounted from the power produced by the system. The deductions are done to ensure that the power consumed by the actual loads and the ancillaries are considered during capacity sizing of an IPVFC system. Touati et al. [54] assumed that 20% of a 12 kW installed capacity is consumed by the ancillaries to cool the PEMFC and pressurize gases. To enhance the reliability of the system, power supply to the ancillaries were configured so that the ancillaries for the PEMFC are not connected to the PV modules since it is subject to intermittency; although the ancillaries of the PEME can be connected to the PV modules since electrolysis can take place during the day.

Sizing of IPVFC systems depends on the load profile of the application [19]. Accurate sizing is a major challenge with IPVFC system deployment due to the intermittency of solar radiation. Different approaches adopted to size and optimize the capacity of IPVFC systems are presented in Section 5.2. The interrelationships between the dynamic load profile, power generation, hydrogen generation and solar radiation availability require reliable control strategies [55]. During operation of an IPVFC system, the amount of hydrogen consumed by an FC stack is proportional to the power drawn from the FC stacks;

while the hydrogen produced from the electrolyser is proportional to the power supplied to the electrolyser [56]. The power available for hydrogen production depends on the solar availability, the power consumed by the loads, the power consumed by the ancillaries, the power used for charging batteries/SC components and the power lost due to conversion losses. Hourly load current can be multiplied by the number of hours of operation of an IPVFC system to get the daily load [55]. This means that the ampere-hour for all the load components/ancillaries can be added to estimate the expected capacity of the system.

Table 1 summarizes some studies to highlight the design intents and compositions of some IPVFC systems.

Table 1. Description of key studies on IPVFC systems.

Year	References	Description of Project/Study	Photovoltaic Array Size	Electrolyser Capacity	Fuel Cell Capacity	Battery Capacity
2020	Lokar and Virtic [18]	IPVFC designed to be self-sufficient and independent of the grid.	24 polycrystalline PV modules (280 W each).	7 kW Alkaline electrolyser, 12.5 V and 400 A. Produces 1.66 m^3 h^{-1}.	70-celled 7 kW PEMFC with power density of 533.3 mW cm^{-2} and current density of 800 A cm^{-2}	6.6 kWh Li-ion battery.
2020	Hassani et al. [57]	Stand-alone IPVFC system with 500 W inverter, 0.02 m^3 and 30 Pa hydrogen tank.	640 Wp, 8 panels, 2 in series and 4 in parallel.	PEME is used as a reverse of PEMFC.	PEMFC with 510 W capacity.	100 Ah, 4 batteries, 2 in series and 2 in parallel.
2019	Shaygan et al. [15]	Energy, exergy, and economic analysis of IPVFC system. Exergy efficiency is 21.8%; cost of electricity is USD 0.127 $(kWh)^{-1}$.	64 PV modules with area of 2.16 m^2 (329 W each).	PEME with daily output of 158 kg	5.5 kW PEMFC.	Not used
2010	Ganguly et al. [33]	IPVFC powers stand-alone 90 m^2 floriculture Greenhouse.	51 PV module, 75 Wp each	3.3 kW PEME	2 PEMFC, 480 W each	Not used
2009	Cetin et al. [17]	Demonstration system at Pamukkale University in Denizli, Turkey	5 kWp PV array.	PEME consumes 6.7 kWh m^{-3} power and produced 0.53 m^3 h^{-1} of hydrogen.	2.4 kWp PEMFC.	12 V; 150 Ah dry cell batteries.
2003	Ghosh et al. [20] and Meurer et al. [24]	PHOEBUS is an IPVFC system demonstration plant connected to 220 V DC-busbar.	Each PV contains 600 cells in series to give 220 V.	21-celled Alkaline (KOH) electrolyser with 26 kW capacity at 35–37 V, 3000 A m^{-2}, 7 bar and 80 °C.	33-celled PEMFC with a capacity of 5.6 kW at 35 V and 200 A, 2–2.3 bar, and 80 °C.	110 Lead acid battery at 138 Ah in series. Capacity is 303 kWh (at 10 A).

Within the categories of IPVFC systems, different types of PV cells, fuel cell and electrolyser can be used. For instance, Lead acid [24], Li-ion [18] batteries and supercapacitors [30] were considered as potential energy storage components for IPVFC systems. Hydrogen can be stored as a compressed gas in tanks [20] or in metal hydride storage [17]. Alkaline electrolyser [18] or PEME [57] can be used as a source of hydrogen. PEME is adapted to compensate for the possible fluctuations of solar energy because of its fast response to current fluctuations. The US Department of Energy found out that a PEME produces hydrogen at 99.99% of purity level for less than USD 10/kg. This high level of purity of hydrogen is suitable for the operation of PEMFC. The current density is 4–5 times that of an alkaline electrolyser and it uses no corrosive electrolyte unlike alkaline electrolyser, although alkaline electrolyser is more matured technologies [58,59]. PEMFC is widely used for IPVFC applications since it uses hydrogen [57] which can be generated from water electrolysis using excess electricity from the PV array. Polycrystalline solar cells [18] have higher conversion efficiency than monocrystalline solar cells but there are interesting advancements in solar cell materials which will be discussed in Section 5.5.

3. Research, Development and Feasibility Studies of IPVFC Systems

Over the last four decades, efforts to design, develop and optimize self-sufficient IPVFC systems have been growing steadily. More so, large-scale IPVFC systems can be designed to include processes or components to achieve an integrated multigeneration system. As an example, an industrial scale IPVFC-based system was installed at a demonstration facility in Neunburge Vorm Wald, Germany to facilitate stationary and mobile power applications and automated liquid hydrogen filling station [60]. A German-Saudi Arabia program investigated the scientific and engineering feasibility of solar hydrogen production and utilization [61]. This project provided valuable information that gave insights into the technical and operational feasibility of solar hydrogen.

Ghosh et al. [20] and Meurer et al. [24] reported an extensive technical feasibility of the design, development and operation of PHOEBUS, which is a self-sufficient IPVFC system installed in the Central Library in Forschungszentrum Julich in Germany. It was reported that the battery bank was able to supply energy to the loads for three days in the absence of solar radiation. The operational experience suggested that a PEMFC is more reliable than an alkaline fuel cell. A hydrogen tank with a volume of 25 m^3 buffer tank operated at 7 bar and a hydrogen tank of 26.8 m^3 was operated at a maximum pressure of 120 bar. The oxygen tank buffer had 5.5 m^3 capacity at the pressure of 7 bar, while the high-pressure of 70 bar was applied to store oxygen in a tank of 20 m^3. The DC/AC inverter had a capacity of 15 kVA and an output of 230 V AC. It was reported that the PV modules inclined at 40° performed better than those inclined at 90°.

Lokar and Virtic [18] considered an independent operation of an IPVFC system on the grid using 24 polycrystalline PV modules, a 6.6 kWh Li-ion battery, a 7 kW electrolyser, a 7 kW PEMFC with a power density of 533.3 mW cm^{-2} and a current density of 800 A cm^{-2}. They concluded that the system was self-sufficient, which makes it suitable for remote applications where continuous power supply is required. Hassani et al. [57] investigated a stand-alone IPVFC system using 8 PV modules, 100 Ah batteries, a PEME and a PEMFC with 510 W capacity. Table 2 shows the timelines of the development of IPVFC systems and the research themes that dominated the decades from 1980 to date. The body of evidence from modelling studies, experimental investigations, feasibility studies and demonstrations indicate that IPVFC systems are suitable for stand-alone and grid-connected applications. In the following sections, specific investigations on energy management systems, modelling and simulations, economic analysis, and optimization studies will be highlighted.

Table 2. Timelines and themes that dominated the development of IPVFC systems.

Decades	1980–1989	1990–1999	2000–2009	2010–2019	2020–2030
Research themes	Initial feasibility studies of solar hydrogen generation.	Demonstration plants for potential industrial scale and commercial applications.	Energy and exergy analysis; Dynamic modelling and simulation; Potential integration with other RETs.	EMS and Controller developments; Size and cost optimisation; Integration with other RETs; Case studies.	Case studies; Implementation for stand-alone and microgrid applications.
References	Rahman and Tam [1]; Kauranen et al. [62]; Grasse et al. [61].	Meurer et al. [24]; Ulleberg [63]; Kauranen et al. [62]; Friberg [64]; Goetzberger et al. [65].	Yilanci et al. [14]; Hwang et al. [55]; El-Shatter et al. [66]; Choi et al. [67]; El-Maaty et al. [68]; Zervas et al. [69].	Thounthong et al. [70]; Silva et al. [71]; Hassani et al. [19]; Chávez-Ramírez [72]; Ganguly et al. [33]; Bambang et al. [32]; Karami et al. [52]; Padmanaban et al. [53]; Touati et al. [54]; Lajnef et al. [56]; Hajizadeh et al. [73]; Dash et al. [74]. Majidi et al. [75]; Zhang et al. [76]; Ghenai et al. [77]; Sharma et al. [78]; Lee et al. [79]; Srisiriwat et al. [80]; Castañeda et al. [81]	Lokar et al. [18]; Hassani et al. [57]; Temiz et al. [82]; Kafetzis et al. [83]; Elmouatamid et al. [84]; Gonzalez et al. [85].

Given the resurgent research efforts between 2010–2019, it is most likely that implementations of the systems as a power and hydrogen source in the next decade (2020 to 2030) might increase significantly considering that there are recent improvements in the components of the system. In addition, the disruptions in the energy supply chain during the COVID-19 pandemic revealed that countries will favor localized sustainable energy to reduce the emission of greenhouse gases, as well as achieve energy security. In addition, the SDG framework relies on clean energy production and usage. Systems such as IPVFC systems can be upscaled urgently as part of CETs to meet the growing demand for energy since there are only 10 years left until the set 2030 deadline for achieving the SDGs.

3.1. IPVFC Systems in the Context of a Hydrogen Economy

The use of fossil fuels as energy sources generates enormous amount of environmental burden starting from exploration, production to usage [86].

In a hydrogen economy, hydrogen plays a significant role to provide heat, electricity, energy storage, as well as act as input material for synthesis of industrial chemicals [87]. From Figure 6, renewable and non-renewable energy sources can be used as energy inputs to produce hydrogen from water, biomass, or fossil fuels. However, in a hydrogen economy, hydrogen produced from non-fossil-fuel-based feedstocks and renewable energy sources would be preferred. IPVFC systems are well positioned in a hydrogen economy as they can provide hydrogen through water electrolysis or utilize hydrogen from other sources to generate electricity using a FC component. The technological sustainability of IPVFC systems can be enhanced by integrating them into hydrogen gas grid that depends on renewable energy sources such as solar, hydropower, wind, geothermal, tidal, and biomass. Hydrogen production from gasification of coal, oil, biomass, or reformation of natural gases can be integrated with carbon capture technologies or carbon dioxide sequestration process to reduce the net contribution to global warming and climate change. The use of PV modules to produce hydrogen from water electrolysis is versatile because the process is simple and has no significant environmental burden. Yilanci et al. [14] described different methods of generating solar hydrogen including photoelectrolysis, water electrolysis, water thermolysis, and photobiological approaches. Siddiqui and Dincer [49] showed that an IPVFC system can support ammonia production by using water electrolysis to generate hydrogen and pressure swing adsorption (PSA) to generate nitrogen so that ammonia can be produced using an ammonia synthesis reactor (ASR). The ammonia produced is stored for power generation using a direct ammonia fuel cell (AFC). This configuration has energy and exergy efficiencies of 15.72% and 16.55%, respectively. Because of this, IPVFC systems could also be a sustainable source of hydrogen for chemical industry processes.

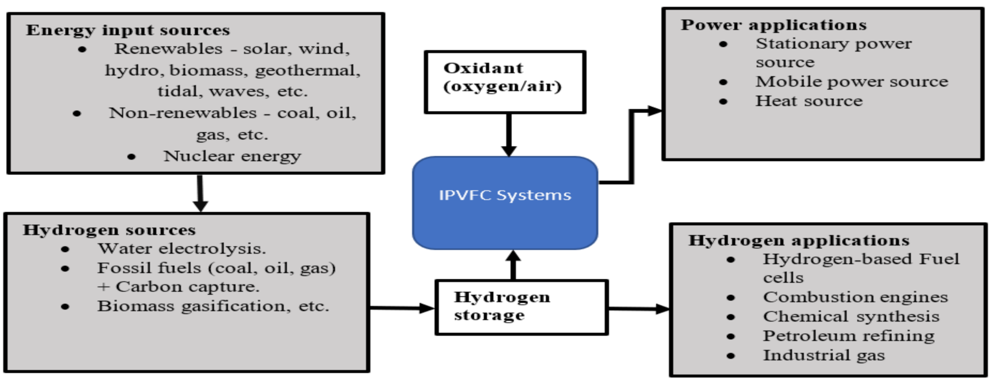

Figure 6. Energy inputs, materials, and applications of IPVFC systems in a hydrogen economy.

3.2. Progress in Energy Management System and Controllers for IPVFC Systems

The major operational challenge inherent in IPVFC systems is the variability of the solar radiation [34]. This makes energy management system a key requirement for IPVFC systems to be used as an autonomous and self-sufficient energy system. Studies have shown that EMS and controllers improve the operational efficiency of IPVFC systems. Hajizadeh et al. [73] proposed dynamic models of PEMFC, PV module and battery bank and a control strategy for managing the DC and AC sides of a grid-connected IPVFC system. Dai and Bajpai [74] proposed a power management control strategy (PMCS) that suppresses the fluctuations in the outputs of a PV module and an FC stack as they supply power to the load. The approach modelled the controller of each of the components separately. A

PMCS is also a key safety factor because it ensures that the charging and discharging of the batteries are done within safety limits. Controllers for electrolyser component ensure that excess hydrogen gas is not generated beyond the capacity of the tank.

A typical control algorithm [74] for an IPVFC system compares the maximum power output from PV modules and the load; and uses the excess power to charge the battery at a constant current or a constant voltage depending on the state of the charge (SOC) of the batteries. If the SOC is equal to or greater than 99.5%, the excess power from the PV modules is used by the electrolyser for generating hydrogen. The algorithm turns OFF the electrolyser if there is no excess power from PV modules or when the pressure of the hydrogen tank reaches a pre-set value. The FC is turned ON when the batteries cannot meet the load demanded.

Kong et al. [88] showed that PMCS reduces the impacts of the intermittency of solar radiation and power curtailment of an IPVFC system designed for grid applications. A non-linear control strategy proposed by Fadil et al. [89] managed the stability of energy flow in an IPVFC system under distributed generation. An IPVFC system suppressed the ramping up and down of the system during intermittent energy production caused by unsteady solar radiation [90]. El-Shatter [66] used a Fuzzy regression model and a controller to maximize the power generated from an IPVFC system under variable insolation since more power is generated in summer than in winter. Majidi et al. [75] investigated how an optimal operation of IPVFC system can be achieved by an PMCS to minimize the system cost, and achieve high efficiency and reliability. Based on a demand response program, deterministic and stochastic programming, transferring electrical and thermal loads from expensive peak periods to cheaper off-peak periods will reduce the overall cost of operation. Kafetzis et al. [83] proposed a supervisory control framework based on a hybrid automata algorithm combined with propositional-based logic which can be used for energy management and control of renewable energy-based microgrids.

3.3. Software for Design, Modelling, and Simulation of IPVFC Systems

The use of software for model-based system engineering, numerical modelling and simulation have helped to investigate different aspects of IPVFC systems [50,91,92]. Gonzalez et al. [85] outlined useful open-source software that can aid modelling and experimental investigations of IPVFC systems. Choi et al. [67] modelled and simulated 500 W IPVFC system using a fuzzy regression with the aid of LabVIEW software. LabVIEW enabled an integration of data acquisition and monitoring of power generation from an IPVFC system. Essentially, IPVFC systems need to effectively self-monitor, self-diagnose and self-repair with minimal human intervention if it must be deployed at remote locations as autonomous power sources [21]. At the center of effective self-monitoring, self-supervision and autonomous operation may well be the development of artificial intelligence-based energy control system which will intelligently decide how to meet demands based on the prevailing meteorological data, operating status of the system, supply capacity and efficiencies of the components [41,84]. This aspect of the system requires more research. Natarajan et al. [93] modelled and simulated the coupling of PV modules and a PEMFC for power generation using MATLAB/Simulink. El-Aal [68] studied different topologies of IPVFC systems for power generation and recommended that detailed studies of the components were necessary. From an operations perspective, Adi and Chang [94] applied temporal flexibility analysis to quantitatively evaluate an IPVFC system's operability based on the dynamics of energy demand and supply.

Ahmadi et al. [95] studied the transient behavior and the thermodynamics of an IPVFC system for heating, cooling and power generation using TRNSYS and MATLAB software. They achieved energy and exergy efficiencies of 29% and 36%, respectively. Similarly, Shaygan et al. [15] used MATLAB to perform energy and exergy analysis of the components of an IPVFC system and concluded that the annual exergy efficiency of the compressor, electrolyser, fuel cell, and PV modulus were 75.9%, 11.2%, 32.8% and 10.8%, respectively, based on the solar radiation and ambient temperature in Tehran, Iran.

The annual average exergy efficiency of the system was 21.8% while the cost of electricity produced by the system was USD 0.127 $(kWh)^{-1}$. Lajnef et al. [56] used SimPowerSystems in MATLAB to model and integrate the components of an IPVFC system for dynamic simulations. They found out that the hydrogen produced by the electrolyser caused the pressure of the storage tank to vary based on the power supplied from the PV modules at 1000 and 800 W m^{-2}. To implement and test a controller of a laboratory-scale IPVFC system, Amin et al. [32] plugged dSPACE DS1104 board into a PC mainboard. They observed that the DC bus voltage was well regulated with an overshoot of about 6.23% and voltage ripple of 4.25% for different load changes.

The integrated energy model of an IPVFC system is a complex integration of the mathematical models related to each of the components of the system. Modelling of IPVFC systems is enhanced by limiting the scope of the modelling to the specific components included in an IPVFC system. Thus, the fundamental equations listed can be modified to satisfy different categories of IPVFC systems and their use cases. The key mathematical equations and physical models for the components of an IPVFC system are presented as follows.

Numerical model of a PV module involves a system of transcendental equation [92]. Equations (1)–(5) is a system of transcendental equations that models the power output from the PV component which can be modelled and simulated using block-based or code-based modelling approaches (Ogbonnaya et al. [96]; Unlu [97]; Bellia et al. [98]; Muhammad et al. [99]; Zeitouny et al. [100]).

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \tag{1}$$

$$I_{ph} = (I_{sc} + K_i\, (T_{cell} - T_{ref}) \times \frac{G}{G_{ref}} \tag{2}$$

$$I_s = I_{s,ref}\left[\frac{T_{cell}}{T_{ref}}\right]^3 \exp\left[\frac{1}{k}\left(\frac{E_g}{T_{ref}} - \frac{E_g}{T_{cell}}\right)\right] \tag{3}$$

$$I_{pv} = I_{ph}N_p - I_sN_p\left[\exp\left(\frac{qV_{pv}}{AN_skT}\right) - 1\right] \tag{4}$$

$$P_{pv} = I_{pv} \times V_{pv} \tag{5}$$

The PEMFC combines hydrogen and oxygen based on Equation (6). Due to the electrochemical and thermodynamic attributes of PEM technologies, the PEMFC has a negative Gibbs free energy because energy is released from the system (see Equations (7) and (8)). The efficiency of the PEMFC can be calculated with Equation (9), while the rate at which hydrogen is consumed by the PEMFC component is expressed in Equation (10). Net voltage (Equation 11) and Nernst potential (Equation (12)) can be substituted into Equation (13) to calculate the power output (Equation (13). Overpotentials due to reactions, material resistance and transport gradient are classified into activation, Ohmic and concentration (or transport) overpotentials (Equations (14)–(18)) and they are usually substituted into Equation (11). The regions of activation, Ohmic and concentration overpotentials can be visualized by a polarization curve (Shaygan et al., Ganguly et al., Spiegel) [15,33,101,102].

$$2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(l)} + \text{electricity} + \text{heat} \tag{6}$$

$$\Delta\overline{g_{f,FC}} = (\overline{g_f})_{H_2} + \frac{1}{2}(\overline{g_f})_{O_2} - (\overline{g_f})_{H_2O} \tag{7}$$

$$\Delta G^o{}_{FC} = -nFE^o \tag{8}$$

$$\text{Electrical efficiency}: \eta_{FC} = \frac{P_{FC}}{\dot{m}_{H_2}HHV_{H_2}} \tag{9}$$

$$\text{Rate of consumption of hydrogen } \left(\dot{m}_{H_2}\right) = \frac{P_{FC}}{2 \times V_{FC} \times \eta_{FC} \times F} \tag{10}$$

$$\text{Net Voltage}: V_{FC} = E_{Nersnt,FC} - V_{act} - V_{Ohm} - V_{Conc.} \tag{11}$$

$$E_{Nersnt,FC} = E_{rev} + \frac{RT}{nF} \log\left(\frac{P_{H_2} \times P_{O_2}{}^{0.5}}{P_{H_2O}}\right) \tag{12}$$

$$\text{Power output}: P_{FC} = I_{FC} \cdot V_{FC} \cdot N_{FC} \tag{13}$$

$$\eta_{act_{anode}} = \frac{RT}{n\alpha F} \log\left(\left(i_{loss} + i\right)/i_{o_{anode}}\right) \tag{14}$$

$$\eta_{act_{cathode}} = \frac{RT}{n\alpha F} \log\left(\left(i_{loss} + i\right)/i_{o_{cathode}}\right) \tag{15}$$

$$\eta_{Ohm_{total}} = i\left(R_{elect} + R_{ion} + R_{CR}\right) \tag{16}$$

$$\eta_{Conc_{anode}} = \frac{RT}{nF} \log\left(1 - \left(i/i_{l_{anode}}\right)\right) \tag{17}$$

$$\eta_{Conc_{cathode}} = \frac{RT}{nF} \log\left(1 - \left(i/i_{l_{cathode}}\right)\right) \tag{18}$$

Equation (19) represents the electrolytic process of splitting water using electricity in the PEME [101]. Contrary to PEMFC, from Equations (20) and (21), a PEME has a positive Gibbs free energy because energy is inputted into the system to generate hydrogen and oxygen gases. Efficiency of a PEME is the ratio of the quantity of hydrogen produced to power supplied, based on higher heating value (HHV) (Equation (22)). Similar to PEMFC, overpotentials in PEME are classified into activation, Ohmic and concentration (or transport) overpotentials as in Equation (23), while the Nernst potential and power input can be calculated with Equations (24) and (25), respectively (Shaygan et al. [15]; Ganguly et al. [33]; Ogbonnaya et al. [26]).

$$2H_2O_{(l)} + \text{electricity} + \text{heat} \rightarrow 2H_{2(g)} + O_{2(g)} \tag{19}$$

$$\Delta\overline{g_{f,EL}} = \left(\overline{g_f}\right)_{H_2O} - \left(\overline{g_f}\right)_{H_2} - \frac{1}{2}\left(\overline{g_f}\right)_{O_2} \tag{20}$$

$$\Delta G^o{}_{EL} = +nFE^o \tag{21}$$

$$\text{Electrical efficiency}: \eta_{EL} = \frac{\dot{m}_{H_2} HHV_{H_2}}{P_{EL}} \tag{22}$$

$$\text{Net Voltage}: V_{EL} = E_{Nersnt,EL} + V_{act} + V_{Ohm} + V_{Conc.} \tag{23}$$

$$E_{Nersnt,EL} = E_{rev} + \frac{RT}{nF} \log\left(\frac{P_{H_2O}}{P_{H_2} \times P_{O_2}{}^{0.5}}\right) \tag{24}$$

$$\text{Power input}: P_{EL} = I_{EL} \times V_{EL} \times N_{EL} \tag{25}$$

The SOC for the battery and its capacity are presented by Equations (26) and (27), respectively (Adi and Chang [94]).

$$\text{State of charge (SOC)}: 100\left(1 - \frac{it}{Q}\right) \tag{26}$$

$$\text{Capacity of battery}: C_{batt}(A.h) = \frac{D_{energy} N_{aut}}{V_{batt} \eta_{batt} DOD} \tag{27}$$

The pressure in the hydrogen tank can be calculated using Equation (28) (Hassani et al. [57]), while the power consumed to compress the gases by the compressor is given by Equation (29) (Shaygan et al. [15]).

$$\text{Pressure in the tank}: P_{H_2} - P_{H_{2\_init}} \left(\frac{N_{H_2} \times R \times T_{H_2}}{M_{H_2} \times V_{H_2}} \right) \quad (28)$$

where $z = \frac{P \times V_m}{T \times R}$.

$$\text{Power consumed} \left(\dot{W}_c \right) = \dot{m}_c \times C_p \times \frac{T_1}{\eta_c} \times \left(\left(\frac{P_{out}}{P_{in}} \right)^{\frac{k-1}{k}} \right) \quad (29)$$

Equation (30) can be used to calculate the power for circulating water to the electrolyser using a pump (Shaygan et al. [15]).

$$\text{Power for circulating water} \left(P_{pump} \right) = \frac{\rho \times g \times Q_w \times H}{\eta_{pump}} \quad (30)$$

Lastly, the load to be serviced by the integrated system is calculated as the sum of the power rating of each load multiplied by the duration of the use of the load as expressed in Equation (31) (Hassani et al. [19]).

$$\text{Energy used per day} \left(E_{load} \right) = \sum P_{load} \times t_{load} \quad (31)$$

3.4. Design Optimization and Techno-Economic Assessment of IPVFC Systems

Optimization of IPVFC systems can improve the overall efficiency, reduce the initial capital outlay and replacement costs [26]. Khemariya et al. [103] investigated the optimal design of an IPVFC system using a hybrid optimization model for electrical renewable (HOMER) software. The findings showed that the total net cost over a 20-year period was USD 56969.99 while the cost of energy was estimated at USD 0.1959 per kWh. Temiz and Javani [82] concluded that an IPVFC system produced about 99.43% of the electricity demand at a levelized cost of electricity of USD 0.6124/kWh [82]. Choe et al. [104] established that using 2 converters and 2 inverters or 2 converters and 1 inverter enhanced the scalability of the system although 1 converter and 1 inverter was cheaper, more efficient, and easier to implement and synchronize with the AC output. IPVFC systems need to balance the energy flow between the PV modules, FC stacks, batteries, and the electrolyser to achieve a reliable operation. Developing an optimization algorithm that can converge fast and achieve accurate results is crucial for mass customization of IPVFC systems because meteorological conditions vary across the globe and the design configuration needs to match users' requirements with diverse use cases. The objective functions of optimization of an integrated energy system may include minimizing cost (e.g., investment, replacement, operation, and maintenance) [105], minimize greenhouse gas emissions, maximize power output, maximize reliability, and to maximize integrated efficiency of the system. Contextually, these objective functions are constrained by meteorological conditions, duration of operation, size of the load, capacity of the system, cost of the components, efficiency of the components and electrical compatibility among the components. The optimization of an IPVFC system can be approached from optimization-based strategies (i.e., genetic algorithm, dynamic programming, particle swarm optimization, differential evolution or rule-based optimization strategies (i.e., fuzzy logical control, state machine) [50,106].

Zhang et al. [76] used a Fuzzy State Machine to propose an optimal energy management of a UAV. Receding horizon optimization has been used to predict future generation from renewable sources, the future load and state of the charge of the battery bank in order to reduce the loss of power supply probability [107]. Zervas et al. [69] proposed a real-time operation optimization for an IPVFC system using a radial basis function and a neural network model to predict the global solar irradiation distribution on a horizontal surface. Majid et al. [108] showed that a multi-objective optimization model can be used to minimize the cost of the system and CO_2 emissions for a grid-connected IPVFC system. They inferred that the cost of the base system can be reduced by USD 544 by implementing a demand response program while the total CO_2 emission can also be reduced by 156 kg per annum. Kannayeram et al. [109] demonstrated that an IPVFC system composed of a PV-battery-SC-fuel cell can be optimized for integration with a smart grid. The study combined a Levy Whale Optimization Algorithm and a Modified Crow Search Optimizer to optimize the parameters of the demand and supply sides of the integrated system. The application of IPVFC systems for Direct Current Microgrids will likely increase in the coming decades because of the need for data centers, communication systems, building electric systems, and plug-in hybrid electric vehicles [109]. Elgammal and Sharaf [110] demonstrated that an IPVFC system can be used for vehicle-to-grid battery charging stations based on a multi-objective particle swarm optimization approach. The optimized system can facilitate an efficient and fast charging since it allows hybrid charging with voltage, current and power.

Meta-heuristic algorithms such as hybrid artificial bee colony-particle swarm optimization (ABC-PSO) performed better than individual ABC or PSO for an optimal sizing of an IPVFC systems for grid integration [111]. The system was designed to meet a total electricity demand of 35 MWh yr^{-1} with a 106 kW PV array, an 8 kW PEMFC stack, a 45-kW electrolyser stack and a 150 kg hydrogen tank. Findings showed that the grid-tied system has 30 kW grid purchase and 25 kW grid sale capacities. Loss of power supply probability and the levelized cost of electricity of USD 0.104 $(kWh)^{-1}$ were minimized using an exterior penalty method. Using a small islet of houses and a water desalination unit as loads, Hatti et al. [112] applied an artificial neural network to track the MPP of PV modules to extract maximum power from the system. The system produced 20 cm^3 of pure water per day but consumed 12,730 kWh per annum. Cetin et al. [17] performed an electrical energy analysis of an IPVFC system with focus on the efficiency, harmonics, voltage and current sags and swells, changes in the voltage and frequency, power outage and transients, impedance, and grounding resistance. In their study, the PV is connected to an inverter to meet the needs of loads with the following ratings: a motor (0.37 kW, 2.5 A; 2 fans (1 kW, 0.35 A); halogen bulbs (250 W); an air-conditioner (0.77 kW, 3.4 A), and a fridge (180 W, 0.9 A). Ultimately, the loads serviced by an IPVFC system depend on the use case, time of the day, weather, and the capacity of the system.

4. Current and Emerging Applications of IPVFC Systems

The resurgence in the research and development of IPVFC systems is not unconnected with the intensified efforts to decarbonize all sectors of the economy including the power generation and the transport sectors that contribute a significant portion of GHGs emissions [113]. In the coming decades, IPVFC systems will be applied as power and hydrogen sources since they are suitable as ideal future energy systems that should meet health, environmental, and techno-economic feasibility. Futuristically, IPVFC systems can be used:

- As a residential power source in remote locations where there is no grid since it can be self-sufficient;
- As a residential power source in urban areas to manage the cost of energy from the grid;
- As commercial power sources in sectors such as agriculture, IT, research, mining, tourism and so forth;
- As power sources for public infrastructure and service points;
- In transportation sector to power vehicles, boats, UAVs, etc.;
- As an onsite oxygen source for medical applications;
- As a source of hydrogen for chemical synthesis and industrial gas.

IPVFC systems are emerging integrated energy systems that could be useful for distributed renewable energy generation and smart grids applications. Of course, there are other competing energy systems but the attributes of IPVFC systems appear to position them for a variety of applications. Table 3 compared different competing technologies and methodologies for power generation.

Table 3. Comparison between IPVFC systems with emerging competing technologies.

Competing Methodologies/Technologies	Description of Attributes	References
PV-battery/supercapacitors system.	Simple and commonly available solar-based system; low temperature system (<100 °C); suitable for mobile and stationary applications; has zero emission during operation.	Glavin et al. [114]
PV-battery/supercapacitors-electrolyser-fuel cell system.	Low temperature system (<100 °C); suitable for mobile and stationary applications, has zero emission during operation; uses hydrogen as energy carrier to increase system reliability.	Meurer et al. [24]; Ogbonnaya et al. [26]; Hassani et al. [57].
Photovoltaic/thermal-battery/supercapacitors-fuel cell system.	Harnesses power and low-grade heat (<100 °C) from the PV; suitable for stationary cogeneration applications; has zero emission; converts excess electricity to hydrogen using electrolyser and generates power using FC.	Goetzberger et al. [65]; Ogbonnaya et al. [26]
PV-wind-battery/supercapacitors system.	Suitable for distributed generation in a location where wind is available; low temperature system (<100 °C) with zero emission during operation; suitable for stationary applications.	Moghaddam et al. [105]
PV-wind-battery/supercapacitors-fuel cell system.	Uses wind and solar energies to generate power and store excess power generated in form of hydrogen. Operates at low temperature (<100 °C) and has zero emission during operation; suitable for stationary applications.	Bukar et al. [12]; Cano et al. [11]; Moghaddam [115]
PV-wind-battery/supercapacitors-diesel system.	Operates at a low temperature (<100 °C); increases the reliability of wind and solar energy with diesel engine. It uses fossil fuel which generates emissions during operation; it is suitable for stationary applications.	Bukar et al. [13] Dufo-Lopez et al. [116]
Parabolic dish-Rankine cycle-organic Rankine cycle-fuel cell multigeneration system.	Solar-based large-scale multi-generation operates at a receiver temperature of 1000 °C; has zero emission during operation; costliest among the systems but suitable for large-scale stationary applications. Energy and exergy efficiencies as 52.82 and 57.39%, respectively	Ozturk et al. [10]
SOFC-Microturbine system.	High temperature system (up to 1000 °C); recovers waste heat from SOFC for power generation; suitable for large-scale stationary applications but generates greenhouse gas emissions.	Ferrari et al. [8]
SOFC-thermophotovoltaic system.	Waste heat from SOFC can be harnessed for TPV power generation at less than 1000 °C using InAs; generates emissions; it can be used for mobile and stationery applications.	Rajashekara [7]; Lu et al. [117]

Comparative analyses of the attributes of the systems show that IPVFC systems will be competitive among these alternative technologies because it is suitable for long-term energy storage; depends on solar energy which is ubiquitous; can be applied for both mobile and stationary applications. It also has zero emissions during operation as the combustion of hydrogen in the fuel cell produces water and heat as by-products. Recently, there was a failure in the supply chain of oxygen for treating patients with coronavirus (COVID-19) [118]. This resulted in many people dying due to lack of oxygen. A design configuration of an IPVFC system could produce onsite oxygen for treating medical conditions that require oxygen since oxygen from PEME is without carbon monoxides or carbon dioxides. We imagine that integrating the IPVFC system with a gas purification system can allow a distributed production of oxygen for hospital use. This means that oxygen can be produced where it is needed whilst shrinking the lead time by eliminating activities such storage and transportation after production in an industrial facility. Interestingly, reliable supply of oxygen is enhanced because the energy required for electrolysis at night when there is no solar radiation can be provided by the battery/SC or the fuel cell components.

4.1. Application of IPVFC Systems in Microgrids

Microgrids are important in the utilization of renewable energy resources because they can facilitate distributed energy infrastructures in which energy can be generated close to the end-users. Ghenai and Bettayeb [77] studied the integration of a 500 kW PV array and a 100 kW PEMFC with the grid to supply power to a University building in Sharjah, United Arab Emirate. The demand was met although 26% of the power consumed was purchased from the grid. The supply mix includes 42% of the power from the PV array and 32% from the PEMFC stack while 5% of the annual output was sold to the grid. Sharma and Mishra [78] proposed a dynamic power management scheme for stand-alone micro-grid in which all the sources, energy storage and loads were connected to a DC link. Hidaka and Kawahara [119] asserted that efficient application of the grid-connected PV arrays for domestic applications requires energy storage which can be facilitated by using solar hydrogen as energy vector to compensate for the fluctuations in power generation due to the intermittency of solar radiation and ambient temperature.

Overall, the modularity of IPVFC systems gives them a huge advantage of scalability from a small-scale residential and commercial applications to large-scale utility applications. Patterson et al. [120] argued that a relatively smaller scale microgrid mitigates transmission loss, and improves control, security, reliability and design flexibility. From a whole-energy system perspective [3,121], building small-scale microgrids supports the proposition for a decentralized-to-centralized strategy for developing countries. Establishment of distributed microgrids can attract public-private partnerships since the power generated will be consumed and managed in the immediate environment whilst excess power can be sold to the national grid. This will immediately improve quality of life and productivity over the period of developing the long-term and long-distance transmission and distribution energy infrastructures. A recent study of renewable energy ecosystem in Nigeria indicates that the deployment of RETs such as IPVFC systems is critical in the utilization of renewable energy resources in Nigeria [2]. This may likely apply to other low-income and developing countries (LIDCs) in Africa, Asia, and the Middle East.

4.2. Off-Grid/Stand-Alone Applications of IPVFC Systems

The dependence of IPVFC systems on solar radiation makes them suitable for remote power sources for autonomous residential applications, telecommunication infrastructure, agro-processing, research activities, sporting facilities and leisure in remote locations. Ulleberg [63] posited that PV arrays, fuel cell and water electrolysis could play a major role in the future stand-alone power systems. Silva et al. [122] conducted a pilot study on the use of an IPVFC system in the National Park of Araguaia, Tocantins-Brazil. Based on their findings, the noiseless and clean attributes make it suitable for distributed generation applications in public spaces such as train stations, zoos, museums, libraries, motor parks/bus stations, markets, etc. This is particularly useful in many underdeveloped countries where public utilities operate without electricity, water, refrigeration of food and drinks, air-conditioning of spaces, lighting, and entertainment. Cordiner et al. [123] analyzed a full year of data collected from six remote off-grid Radio Based Stations (RBS) and found that an IPVFC system can meet 24 h/7 day high quality, autonomous and continuous power supply required by an off-grid RBS, particularly in developing countries where power grids are grossly underdeveloped. Another study by Silva et al. [71] showed that it was feasible to use an IPVFC system for power generation in an isolated community in the Amazon region of Brazil. The system was composed of a PV array of 124 W with 30.1 V, a PEMFC at 5 kW at 48 V; a PEME at 6 kW per $Nm^3\ h^{-1}$ of hydrogen produced; and a lead acid battery (220 Ah at 12 V). The study implied that the costs of the components are still high but using a battery for energy storage appeared to be favored since the cost of adding an electrolyser and a fuel cell will increase the cost of the system. Based on economic analysis, a PV-battery system is cheaper than an IPVFC system of similar capacity, but the inclusion of a fuel cell can protect the battery from stresses associated with the depth of discharge, thereby elongating the life of the battery, and reducing the overall replacement costs of the battery.

Ghenai et al. [124] showed that the integration of an IPVFC system with a diesel generator contributed 13.83% (i.e., 9.44% from PVs and 4.39% from a PEMFC) to the power system of a cruise ship, thereby reducing the greenhouse gas and particulate emissions by 9.84% compared to the diesel generator as the baseline. The use of an IPVFC system as a power source in the transportation sector will reduce the overall emissions since it depends on solar energy, which is a sustainable clean source of energy [113]. An IPVFC system can be a good source of power for mountainous, island and coastal off-grid cities because of the difficulty of connecting such locations with power grids. As an example, Hassani et al. [19] proposed the use of IPVFC systems as power sources in green cities based on the study of a coastal region of Bejaia in the east of Algeria. Lee et al. [79] performed an experimental and model-based study on the use of an IPVFC system as the power source (150–400 W) in a UAV at Goheung Aerospace Centre, Korea. The test flight of the UAV lasted for 3.8 h using an active PMCS that determined the power output from each source. A PMCS was critical in the reliability of the IPVFC system and the overall safety of the UAV because any failure in the power supply could have led to the loss of critical equipment required for the flight or the loss of the entire vehicle. Lokar and Virtic [18] investigated the self-sufficiency of an IPVFC system including a Li-ion battery and found out that the self-sufficiency of the pilot project was 62.13%. However, they recommended that a further 144.2 kg annual shortage of hydrogen can be met by increasing the capacity of the 6.72 kWp PV arrays.

An IPVFC system can be used in the agricultural sector for all-year-round crop and animal production and agro-processing given that it can be operated under distributed and off-grid modes. This allows farmers to meet short-term needs using PV arrays, batteries/supercapacitors, and long-term needs with an electrolyser and fuel cell stacks. Since solar radiation is abundant during summer, excess electricity can be stored as hydrogen so that power can be supplied during winter when solar intensity usually dwindles. Ganguly et al. [33] studied how an IPVFC system can be used to power a greenhouse in a sustainable manner based on the climatic conditions of Kolkata, India. They used 51 solar PV modules to generate hydrogen with an electrolyser (3.3 kW) and charge a battery bank such that the battery bank and two PEM fuel cell stacks (480 W each) can meet the energy demand. IPVFC systems can be used for desalination to convert seawater, brackish water, or fresh water of unknown quality to potable water as well as generate electricity and hydrogen. A feasibility study of seawater electrolysis using an IPVFC system has been conducted to generate hydrogen and oxygen from salty water instead of using fresh water which is better used for domestic, agricultural, and industrial purposes [80]. The presence of NaCl was reported to enhance hydrogen production and the system also produced fresh water as a by-product. Touati et al. [54] studied the potential application of an IPVFC system to provide a stand-alone power source for a desalination plant.

5. Prospects and Limitations of IPVFC Systems

Undoubtedly, IPVFC systems have huge potential applications but there are some current technical challenges that have constrained its commercialization. Some of the key prospects as well as technical challenges are highlighted in this section.

5.1. IPVFC Systems as Sustainable Energy Systems

The cost of building power generation, transmission, and distribution infrastructures creates a huge barrier to energy access in low income and developing countries (LIDCs). Meanwhile, with distributed microgrids, such countries can adopt a decentralized-to-centralized strategy in which RETs such as IPVFC systems and other CETs can be integrated into distributed microgrids. Notably, the addition of an IPVFC system to a distributed microgrid or national grid will not increase national GHGs and particulate emissions. IPVFC systems are useful enabling technology for renewable power-to-gas infrastructures [125]. With a decentralized-to-centralized strategy, distributed microgrids can supply desperately needed energy immediately they are established whilst nearby microgrids can be connected first till they are all connected to the national grid, eventually. The challenge with the prevalent centralized-to-decentralized strategy is that LIDCs may not have the resources to develop the national grid first before developing microgrids or to invest in the two approaches simultaneously. The cost of a national energy infrastructure is capital intensive and could be overwhelming for LIDCs considering that they need to simultaneously invest in other sectors of the economy such as health, education, transportation, water, social services, etc. Consequently, the use of decentralized-to-centralized strategy and enabling RETs and CETs can facilitate energy access for all as stipulated by the SDG 7 if integration of enabling technologies such as IPVFC systems are intensified in the next decade. Further postponement of the use of CETs could create a setback in the achievement of the emission targets in the SDG 13 by 2030 as well as The Paris Agreement [126].

A major limitation to the application of IPVFC systems is that the PV component is costly. Nonetheless, PV modules are used in different technologies for electrical, thermal and mechanical storage applications [127]. Examples of such energy storage hybrid systems include PV-pumped hydro, PV-flywheel, PV-battery, PV-compressed air, and PV-fuel cell (Lui et al. [128]). It appears justifiable that increasing demand for PV-based technologies may drive the cost PV modules further down based on the economy of scale. This could make IPVFC systems more affordable, particularly in LIDCs. Meanwhile, continuous innovation of solar cell types may improve its conversion efficiency [129]. Without overemphasizing the prospects of IPVFC system which have been implied in the previous sections, the remaining part of this section is dedicated to discussing the challenges and limitations of IPVFC systems. Efforts by researchers to solve the challenges are also highlighted.

5.2. Sizing and Cost Optimization of IPVFC Systems

Sizing of solar-based technologies are often challenged by the intermittency of meteorological variables [130,131]. Yet, there is a correlation between the size of an IPVFC system and its cost. The capital cost of most renewable energy technologies is currently higher than diesel or gasoline generators [103,116]. For instance, the use of platinum in PEM technologies makes PEME and PEMFC very costly [7]. Although the cost of PV has fallen over the last two decades due to mass production and wider applications, it is still costly for poorer countries. The high cost of the components of IPVFC systems implies that more efforts are required to improve the economic sustainability since the system ranks high in terms of environmental and social sustainability. If the overall cost of the systems is reduced, end-users may adopt them due to their sustainable features. Thus, cost and size optimizations are essential to reduce the costs associated with over-sizing and under-sizing of IPVFC systems.

Oversizing could lead to high cost of the system and waste of energy while undersizing could lead to system failures, low reliability, poor power quality and unacceptable performance. Where an IPVFC system is used to replace an existing energy supply, historical hourly energy consumption data, meteorological data, cost of the components and the efficiencies of the components may be considered in the optimization scheme. Some researchers have attempted to achieve optimal design configuration for IPVFC systems. Hassani et al. [57] studied optimal sizing and technoeconomic feasibility of an IPVFC system using MATLAB/Simulink and HOMER. Their analysis of the stand-alone IPVFC system appeared to be economically and environmentally viable. Castaneda et al. [81] proposed an optimal sizing of an IPVFC system using Simulink Design Optimisation in MATLAB/Simulink and also studied three control strategies to manage energy flow in the system. It was observed that optimal sizing and effective control were required to ensure that the loads were satisfied; that hydrogen was available to meet off-peak loads; and that the battery's lifespan was better preserved through controlled charging and discharging.

Furthermore, aspects such as government subsidies, grants, and opportunities to sell back excess energy to the grid, that may not be linked to the technical design of the system can be included during economic feasibility studies because they could change the cost structure of different categories of IPVFC systems.

5.3. Risk and Reliability of IPVFC Systems

Based on a study using failure modes, effects and criticality analysis to generate the risk priority numbers and criticality values of the risk items of an IPVFC system, most of the operational risks associated with the system are caused by the variability of the solar radiation [38]. A study of a micro-cogeneration IPVFC system for household applications to supply hot water and electricity by Ozgirgin et al. [132] showed that the power demanded from the grid increased due to a decrease in solar radiation during winter (October to March); but the system was self-sufficient between March and October (summer months). They proposed the use of hydrogen and oxygen produced from the PEME to meet peak demands. The risk of fluctuations in power output can be mitigated by using MPPT algorithm to track the MPP of PV modules and FCs to maintain optimal power outputs. There is a risk associated with sizing because solar radiation fluctuates, and this ultimately influences the amount of energy available to charge the battery and produce hydrogen.

Operationally, the use of fuel cells (which usually have a slow response time) could be a source of risk for applications that require quick dispatch of energy. To reduce the effect of repetitive stepped loads on the system, a FC can be operated at a quasi-steady state while the batteries/SCs with better response time can supply power to the transient and off-peak loads. Nojavan et al. [133] studied how a grid-connected IPVFC system can be used to satisfy uncertain electrical and thermal loads using an information gap decision theory approach. The operator can take the risk to pay less to purchase electricity from the grid but run the risk of not satisfying the load or become risk-averse and purchase excess energy at a higher cost but be certain that the loads will be satisfied.

5.4. Rapid Prototyping and Manufacturing Processes

IPVFC systems are multi-component systems with a wide spectrum of manufacturing processes and technologies. Although, diverse applications of IPVFC systems in the coming decades will benefit from the falling price of PV modules, and advanced manufacturing processes for the components [134], the system is currently limited by its manufacturability. Ogbonnaya et al. [21] proposed that the manufacturing process of an IPVFC system needs to integrate the voice of the customers to capture requirements based on the application context; whilst adapting the supply chain management to a just-in-time system to reduce inventory cost and lead time since most of the components are costly. Adapting manufacturing process technologies to produce PEME and PEMFC components might reduce tooling cost since both components share similar manufacturing processes. High speed 3D printing technology can facilitate a low-cost manufacturing of the parts of the PEMFC and electrolyser [135]. There is also a need for advanced manufacturing techniques to cater for the use of IPVFC systems in microelectronics.

5.5. Advances in the Materials for IPVFC Systems

Currently, there is a need to improve the functional materials for PV modules, batteries, PEME, PEMFC or URPEMFC components. Interestingly, there are recent advancements in the materials for these components which can enhance the future competitiveness of IPVFC systems. Firstly, the emerging solar cells appear to be approaching the 33% efficiency limit of single junction silicon solar cell predicted by Shockley [136]. Yet, upscaling photovoltaic-based power generation depends on the development of photovoltaics that exceed the current efficiency limits of solar cells. Globally, there is a growing utilization of PV modules for electricity generation compared to other renewable energy technologies [137]. The design and material parameters of a PV module influence the power characteristics of the array [138]. Although both mono-crystalline and polycrystalline PV modules [18] are currently in use, the prospects of perovskite solar cells appear to be changing the landscape of PV power generation [139,140]. Recently, hybrid organic-inorganic metal halide perovskites have shown a huge prospects as a future solar cells because of their high efficiency (which is up to 25%), easy processing (using solution-based methods) and their potential for optoelectronic applications [139].

Current commercial batteries such as nickel-metal hydride, lead-acid, lithium-ion and flow batteries have experienced increase in demands for applications in electronic devices, distributed energy systems, grid-connected energy storage system and electric vehicles [141]. However, not all batteries are suitable for storing renewable energy due to the intermittent nature of renewable energy resources. There are research efforts to produce materials that would enhance the efficiency and duration of batteries for storing renewable energy in both small and large scales. Li-ion is suitable for storing renewable energy and it is applicable in mobile devices, distributed generations, mini-grids and in large-scale utilities. It was recently discovered that $LiTi_2(PS_4)_3$ has a better diffusion coefficient, lower energy barrier, longer jump distance and higher entropy for the transition state compared to $Li_{10}GeP_2S_{12}$ [142]. The significance of this result is that the performance and safety of solid-state superionic conductors in Li-ion batteries can be advanced with the novel material. Solid-state electrolyte Li batteries are less flammable, cheaper, has higher energy density, and more stable than the organic liquid electrolytes; and these qualities have motivated their recent developments for electrochemical storage [141]. For thermal management of some of the components prone to thermal stress, phase change materials (PCM) (which change from solid to liquid and vice versa as they absorb and release sensible and latent heat) have also shown the capacity to manage the heat generated in Li-ion batteries (and also PV modules) to increase the efficiency and safety of the components [143]. Examples of PCM for thermal management include paraffin, hexadecane, stearic acid, N-octadecane, N-docosane, Eicosane, polyethylene glycol, 1-Tetradecanol, etc. [143].

Materials for hydrogen storage in IPVFC systems is another aspect that requires further improvements. Efficient storage of solar hydrogen [144] from water electrolysis portends a positive outlook for IPVFC systems. Hydrogen is conventionally stored as compressed gas or liquid hydrogen. While storing hydrogen as a compressed gas increases the weight of the system and requires high pressure (up to 700 bar), cryogenic storage of hydrogen requires low temperature (less than 20 K) to liquify and store hydrogen [145]. Solid metal hydrides offer high volume efficiency, ease of recovery, high safety, and lower loss; thus, their prospects for materials for hydrogen storage can be enhanced by using metal alloys and complex metal hydrides (e.g., $NaAlH_4$ and Na_3AlH_6) [146]. The potential integration of solid-state hydrogen storage with fuel cell-powered portable and mobile electronics may significantly advance the applicability of IPVFC systems. To facilitate such applications, novel forms of hydrogen storages are required. Hydrogen storage is categorised into physically bound hydrogen, chemically bound hydrogen (e.g., metal hydrides and complex hydrides), and hydrolytic evolution of hydrogen (e.g., hydrolysis of metal powders and hydrides) [145]. Although it is still a controversial subject as to how effective porous materials (e.g., zeolites, porous carbon, carbon nanotubes, metal-organic frameworks) can be used to store hydrogen for fuel cell applications, preliminary results indicated that nanotubes can be used to store hydrogen [145,147,148].

Water electrolysis produces clean hydrogen and could play a role in a hydrogen economy [149,150]. However, the electrocatalysts for PEM water electrolysis depend on costly noble elements such as platinum, rhodium, ruthenium and iridium; but alternative electrocatalysts for oxygen evolution reaction (Ta_2O_5, Nb_2O_5, Sb_2O_5 and their mixtures (SnO_2-IrO_2-Ta_2O_5) and hydrogen evolution reaction (MoS_2, Pd/CNTs) are under investigation [59,151]. These include nanostructured thin films and bulk metallic glasses. Aside from catalysts, there are efforts to reduce the costs whilst improving the performance of the membranes, current collectors, and separator plates. Although the alkaline electrolyser is an established technology for water electrolysis, it uses corrosive alkali. Recently, anion exchange membrane was considered for water electrolysis [152]. There is still a need to find membranes better than Nafion due to its chemical and mechanical instability at elevated temperatures. Such potential alternatives include sulfonated polyimide-based, polyphosphazene-based, and polybenzimidazole-based membranes [153]. Generally, material improvements in PEM technology will benefit PEMFC and PEME components as well.

URPEMFC subsystem has potential advantages over DRPEMFC systems because of its better efficiency-cost-complexity interrelationships. Zhigang et al. [154] demonstrated that 50 wt% Pt + 50 wt% IrO_2, and a catalyst loading of 0.4 mg cm^{-2} improved the performance of a URPEMFC system in both electrolyser and fuel cell modes. There are emerging electrocatalysts based on platinum, rhodium, ruthenium and iridium oxides with increasing application in URPEMFC systems [154,155]. Wang et al. [156] reported that a ratio of 5–7 wt% PTFE and 7–9 wt% Nafion improved water management in URPEMFC system. This is due to the combination of the properties of the hydrophobic PTFE and the hydrophilic Nafion that sustained adequate water content in the system as the system switches from electrolyser mode to fuel cell mode and vice versa.

5.6. Efficiency Improvement of IPVFC Systems

Integrating PV modules with a PEMFC improves the sustainability index of IPVFC systems as a portable devices power source, distributed power generators, backup power sources, and automotive power sources [157,158]. The location of the installation of PV modules affects the efficiency of power generation [6]. Thus, thermodynamic losses in IPVFC systems still limit the overall operational efficiency of the system. For instance, whereas the operational efficiency of an IPVFC system is 35.5%, factoring in the energy losses over a year reduces the overall operational efficiency to 3.8% as presented in Table 4 [62].

Table 4. Efficiencies of the IPVFC system for one year [62].

Components	Energy Output (kWh)	Electrical (%)	Operational (%)
PV array	1244	10.8	-
Battery	727	91.1	-
Electrolyser	551	74.7	65.8
Fuel cell	191	47.2	38.6
Gas storage	-	-	98.3
System	-	-	35.2
Overall	-	-	3.8

Energy and exergy efficiency enhancement analysis [26] indicates that the efficiency of the components of photovoltaic-based energy systems and energy recovery processes influence their integrated efficiency. This implies that the integrated efficiency of IPVFC systems will continue to improve as the components are advanced. Ezzat and Dincer [159] showed that the energy and exergy efficiencies of an IPVFC system as a power source for a vehicle was 39.86% and 56.63%. To be attractive as enabling technologies in the upcoming hydrogen economy, research and development efforts should address the unanswered questions concerning IPVFC systems. Table 5 summarizes the status of thematic questions that have dominated investigations of IPVFC systems as a CET for diverse applications.

Table 5. Assessment of critical aspects towards the full commercialisation of IPVFC systems.

Pathway Questions	Status	References
Is the IPVFC system compliant with sustainable development goals?	The system requires additional cost reduction to be appropriate for meeting SDG 7–Affordable and clean energy. It complies with SDG 13–Climate action.	SDG report 2019 [160].
Can it be applied for grid-connected and microgrid applications?	IPVFC system can be applied as grid-connected and microgrid systems.	Padmanaban et al. [53]; Kannayeram et al. [109].
Can it be applied for stand-alone applications?	IPVFC system can be applied as a self-sufficient stand-alone generation system.	Hassani et al. [57].
Has robust design studies been conducted?	HYSOLAR and PHOEBUS are good examples of long-term studies on the design and performance of IPVFC systems.	Ghosh et al. [20]; Meurer et al. [24]; Grasse et al. [61].
Has the system control and power management system been considered?	Evidence of controllability and possible designs for PMCS are available.	Kong et al. [88]; Sumathi et al. [50]; Thounthong et al. [70].
What are the specific application areas?	Agriculture, Hybrid Electric Vehicle, seawater electrolysis, buildings, cruise ships, unmanned aerial vehicles, telecommunication, desalination, ammonia synthesis.	Ganguly et al. [33]; Zhang et al. [76]; Ghenai and Bettayeb [77]; Ghenai et al. [124]; Cordiner et al. [123]; Touati et al. [54].
Are there actual demonstration studies?	Green cities, National parks, University buildings and residential buildings.	Ghosh et al. [20]; Cetin et al. [17]; Silva et al. [122]; Grasse et al. [61].
Is the system currently affordable and competitive compared to competing technologies?	The system is still costly because of the cost of PV, PEME and PEMFC components. However, competing technologies are also costly. Cost will reduce with mass applications and improvement in the conversion efficiencies.	REN21 [137]; Spiegel [161].
Are there software tools for the design, control design, feasibility studies, and dynamic modelling studies	MATLAB/Simulink (modelling and simulation, control design), HOMER Pro (feasibility studies), PvSys (for technical analysis), Aspen plus, TRNSYS, LabVIEW, Simplorer software.	Khemariya et al. [103]; Hatti et al. [112]; Temiz and Javani [82]; Wu et al. [162]; Choi et al. [67]; Hwang et al. [55];
Has the manufacturability been considered?	More investigations are needed on mass commercialization, smart manufacturing, and integration into a lean supply chain.	Ogbonnaya et al. [21].
Has circular economic feasibility been considered?	No study was found on how the end-of-life management of the system can be managed based on circular economic models.	Not applicable

6. Summary and Roadmap for the Future

Overall, the IPVFC systems appear environmentally sustainable, and can be used for grid-connected and off-grid applications. Already, significant experimental, model-based, feasibility and demonstration studies have been conducted. There are available pieces of software to facilitate the design of the components and facilitate their integration. Nevertheless, the manufacturability and circular economic management of IPVFC systems require further investigation. Components such as the PV modules, FC stacks, electrolyser, and batteries/supercapacitors will continue to receive research attention to improve their materials, design, and conversion efficiencies. Nonetheless, governments may need to subsidize these IPVFC systems to make them affordable for poor citizens given that the system can contribute towards a reduction in GHGs and particulate emissions in Nationally Determined Contributions (NDC). Specifically, the key features of IPVFC systems that make them suitable for a wide range of applications are:

- There is no imposition of adverse effects on the environment since they emit no GHGs during operation. The combustion of hydrogen in fuel cells yields water and heat.
- Solar energy, which is the prime mover, is ubiquitous across the globe. The system can be used anywhere across the globe and solar resources are not subject to energy politics and price controls associated with fossil fuels.
- IPVFC systems can provide power in off-grid rural or island communities where grid cannot reach due to landscapes or water bodies.
- There is a potential integration of the systems with smart grids to generate hydrogen with excess electricity.
- Conversion efficiency of IPVFC systems does not depend on the size of the system.
- There are no moving parts and noise. Therefore, energy loss and tear/wear of parts due to friction of moving parts as in mechanical systems are significantly reduced.
- IPVFC systems are scalable because of the modular nature of the components.
- They are suitable for low temperature applications below 100 °C.
- They can function as cogeneration systems if the heat from the PV module, FC and electrolyser are harnessed.
- Generation of hydrogen with excess electricity provides a long-term strategy for energy storage, which can also be applied in industrial processes and chemical synthesis, in addition to its application for power generation.

On the other hand, the weaknesses/challenges associated with IPVFC systems include:

- The consumption of electricity which has high exergy for electrolysis so that it can be recovered using fuel cell results in exergy destruction and a possible reduction of the overall energy and exergy efficiency [26].
- Inadequate sizing could lead to a power failure since solar energy fluctuates throughout the year [103].
- IPVFC systems should still be costly because of the cost of the key components (i.e., PV module, FC, and electrolyser).
- The efficiencies of some of the components such as the PV module, FC and electrolyser need to be improved.
- Fuel cell has slow dynamics, which results in a slow start-up time and the need for substantial time to adjust to dynamic loads [30].
- There is a performance degradation with time, mainly for the battery, FC and electrolyser components [27].

The specific roadmap that may dominate the research and development of IPVFC systems in the coming decades should include:

- Efficiency improvement to enhance competitiveness: Energy and exergy efficiencies of the components need to be continuously improved. There is also the need to innovate functional materials such as phase change materials for thermal energy management, and perovskite solar cells to achieve higher conversion efficiency at a lower cost. In addition, using an integrated converter-inverter unit, URPEMFC, lean system design and cost-effective manufacturing processes can improve the efficiency-cost-complexity interrelationships of IPVFC systems.
- Optimal capacity sizing to reduce system cost: There is still a need to develop multi-objective optimisation algorithms that can predict the size of the components that will reliably meet the load requirements grounded on actual meteorological data of the installation site. This is applicable for all scales of IPVFC system since cost of the system and levelized cost of energy are key decision-making criteria for individuals and organizations that would use IPVFC systems.

- Robust EMS and controllers to enhance system autonomy: One of the advantages of the IPVFC system is that it can operate autonomously over a long period without human intervention. There is a need to develop controllers and energy management systems based on artificial intelligence to enable the system to autonomously predict meteorological data and estimate the quantity of energy that can be generated. This will enable small-scale users to prioritize loads and estimate the cost of energy to be purchased from the grid. It will also improve the operational efficiency of utility grids as the predicted power generation can be used to estimate the power needed from other renewable and conventional generating systems.
- Efficient low-cost storage of hydrogen: There are still research gaps in developing solid-state hydrogen storage approaches that are compatible with fuel cells. Broadly, advancements in hydrogen storage technologies will result in a more compact and efficient renewable hydrogen generation methodologies. An efficient hydrogen storage will also expand the application of IPVFC systems for mobile and portable devices in a hydrogen economy.
- Data-driven reliability studies: Data-driven failure modes, effects and criticality analysis can be performed to investigate the safety and reliability of different design topologies. The risk priority numbers will also enhance the maintainability of the system.

7. Conclusions

This study presents a comprehensive review of the state-of-the-art of IPVFC systems including different categories of generation methodologies, design configurations, feasibility and demonstration studies, optimisation, energy management strategies, et cetera. Based on the systematic review of the publicly available literature from 1980 to date, there is a growing positive outlook for IPVFC systems as emerging clean energy technologies. IPVFC systems can be used as a power source for telecommunication stations, desalination plants, residential/commercial buildings, boats and ships, and generic distributed applications. IPVFC systems are suitable for developing DC microgrids which is attracting much research and development efforts. IPVFC systems are suitable for stand-alone and grid-connected applications. Nonetheless, the manufacturing and supply chain strategies to deliver different scales of the system for different applications to the customers are yet to be studied; and should indeed be prioritized given that reduced cost of production could reduce the overall cost of the system. Overall, this paper provides a systemic overview and current themes which can be useful to research and development efforts to advance different categories of IPVFC systems towards full commercialisation.

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Nomenclature and Abbreviations

Abbreviations	
A	ideality factor
A_{anode}	activation constant at the anode
$A_{cathode}$	activation constant at the cathode
A_{cell}	active area of the solar cells
B_{anode}	anode empirical constant
$B_{cathode}$	cathode empirical constant
C_{batt}(A.h)	capacity sizing of the battery
C_p	specific heat capacity of hydrogen (14,320 J $kg^{-1}\cdot K^{-1}$)
CET	clean energy technology
D_{energy}	total energy required
DOD	depth of discharge
E^o	standard potential at equilibrium.
E_{rev}	standard potential of the reaction
F	Faraday constant
FC	fuel cell
g	gravitational constant (m s^{-2})
$(\overline{g_f})_{H_2}$	specific Gibbs free energy of hydrogen
$(\overline{g_f})_{H_2O}$	specific Gibbs free energy of water
$(\overline{g_f})_{O_2}$	specific Gibbs free energy of oxygen
G	solar radiation (Wm^{-2})
GHG	greenhouse gases
H	pump head
HHV_{H_2}	higher heating value of hydrogen
i	current density (A m^{-2})
I_{EL}	current density of the electrolyser (A m^{-2})
I_{FC}	current density of the fuel cell (A m^{-2})
$i_{l_{anode}}$	anodic electrode limiting current density (A m^{-2})
$i_{l_{cathode}}$	cathodic electrode limiting current density (A m^{-2})
i_{loss}	lost internal current density (A m^{-2})
I_{pv}	output current from the PV (A)
$i_{o_{anode}}$	anode exchange current density (A m^{-2})
$i_{o_{cathode}}$	cathode exchange current density (A m^{-2})
I_{ph}	photocurrent (A)
I_s	saturation current
IPVFC	integrated photovoltaic-fuel cell system
k	Boltzmann constant
$\dot{m}_{H_2}$	mass flow rate of hydrogen (kg s^{-1})
$\dot{m}_c$	mass flow rate in the compressor (kg s^{-1})
n	number of electrons
N_{aut}	days of autonomy
N_p	number of modules in parallel
N_s	number of solar cells in series
PEME	proton exchange membrane electrolyser
PEMFC	proton exchange membrane fuel cell
P_{EL}	power input into the electrolyser (W)
P_{FC}	power output from the fuel cell (W)
P_{H_2}	partial pressure of hydrogen (atm)
P_{pv}	output power from the PV (W)
P_{O_2}	partial pressure of oxygen (atm)
P_{H_2O}	partial pressure of water (atm)
P_{in}	inlet pressure of hydrogen from compressor (atm)

P_{load}	load power (kWh)
PMS	power management system
P_{out}	outlet pressure of hydrogen from compressor (atm)
PV	photovoltaic
R	gas constant (J k^{-1}. mole $^{-1}$. K^{-1})
R_{CR}	specific constant resistant (Ohm m^{-2})
R_{elect}	electrical resistance (Ohm)
R_{ion}	resistance to ions in PEM (Ohm)
RETs	renewable energy technologies
Q_w	volumetric flow rate of water (m^3 s^{-1})
V_{pv}	oltage of the PV module (V)
t_{load}	duration of the load power (h)
T_1	inlet temperature of hydrogen into the compressor (K)
T	temperature (K)
T_{cell}	temperature of the PV cells (K)
TPV	thermophotovoltaic
T_{sun}	temperature of the sun (K)
UAV	unmanned aerial vehicle
V_{act}	activation overpotential (V)
V_{batt}	battery voltage (V)
V_{conc}	concentration overpotential (V)
V_{EL}	net voltage of the electrolyser (V)
V_{FC}	net voltage of the fuel cell (V)
V_{H_2}	volume of hydrogen in the tank (m^3)
V_{pv}	output voltage from the PV (V)
V_{Ohm}	Ohm overpotential (V)
V_m	molar volume of hydrogen (m^3)
q	charge
Q	maximum capacity of the battery
$\dot{W}_c$	power consumed by the compressor
WT	wind turbine
z	compressibility factor
Greek Letters	
α	charge transfer coefficient assumed to be 0.5
$\Delta\overline{g_{f,EL}}$	average change in specific Gibbs free energy in electrolyser.
$\Delta\overline{g_{f,FC}}$	average change in specific Gibbs free energy in FC
η_{batt}	battery efficiency
η_c	mechanical efficiency of the compressor
η_{EL}	electrical efficiency of electrolyser
η_{FC}	electrical efficiency of fuel cell
η_{pump}	efficiency of the pump.
τ_{glass}	transmissivity of the glass top of the PV
ρ	density of water (kg m^{-3})
Subscripts and Superscripts	
EL	electrolyser
FC	fuel cell
k	ratio of specific heat
pv	photovoltaic

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