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Editorial

Fuel Cell-Based and Hybrid Power Generation Systems Modelling

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The World Economic Forum's Global Risks Report 2022 identifies climate change as a paramount threat to humanity. Global temperatures have risen by a concerning 1.2 °C since pre-industrial times, and this alarming acceleration is projected to continue, with estimates suggesting a further increase of 5 °C by the end of the century. The repercussions of climate change are far-reaching, impacting sectors like agriculture, energy, economics, finance, social dynamics, political landscapes, and public health [1], and achieving sustainable and inclusive development hinges on effectively addressing environmental degradation, necessitating a resolute political commitment from the international community. While this commitment is widely acknowledged as essential, there remains a significant disparity in the level of action taken by individual nations [2]. For 35 years, the scientific community has been acutely aware of the threat posed by global warming, a direct consequence of humanity's escalating anthropogenic carbon dioxide emissions. This period has been marked by sustained international efforts to mitigate this existential challenge. The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 and produced its first science report in 1990. Two years later, the landmark Rio Earth Summit yielded the Rio Declaration and Agenda 21, a comprehensive framework for achieving sustainable development. This pivotal event coincided with the adoption of the "United Nations Framework Convention on Climate Change" (UNFCCC), a critical forum for negotiating global greenhouse gas (GHG) emission limitations. Building upon the UNFCCC, the first international agreement to mandate GHG emission reductions, the Kyoto Protocol, was adopted at COP3 (Conference of the Parties) in 1997. The fight against climate change gained further traction with the birth of the Paris Agreement at COP21 in 2015. This landmark accord garnered commitments from 196 nations to limit global temperature rise to well below 2 °C above pre-industrial levels, with an aspirational goal of 1.5 °C. The most recent COP26, held in Glasgow, witnessed significant development and numerous countries pledging to achieve net-zero emissions. COP27 in Egypt further solidified these commitments while establishing an innovative loss and damage fund to assist developing nations disproportionately impacted by climate change [3]. COP28 in Dubai marked a pivotal shift in climate action. The final agreement enshrined a move away from fossil fuels, potentially representing a turning point. It also significantly bolstered renewables and energy efficiency, with ambitious plans to expand their impact in the rest of this decade. Notably, COP28 finalised the loss and damage fund for developing countries, and fostered a greater sense of inclusivity in the discussion on solutions, including the return of nuclear power to the climate debate [4].

The preceding statements underscore the paramount significance of the battle against global warming in the context of international politics. It is a battle that can only be won through the application of cutting-edge scientific research, towards the development of advanced technologies for non-pollutant GHG-free power generation systems.

Pursuing a successful energy transition demands a multifaceted scientific strategy anchored by two pillars: fundamental research, to elucidate underlying scientific principles, and technological research, to develop practical solutions. The latter focuses on mitigating GHG emissions through two key strategies: (i) the adoption of alternative energy sources

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Citation: Barbera, O. Fuel Cell-Based and Hybrid Power Generation Systems Modelling. *Energies* **2024**, *17*, 3340. https://doi.org/10.3390/en17133340

Received: 8 May 2024
Accepted: 17 June 2024
Published: 8 July 2024

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and (ii) the use of hybrid and fuel cell-based power systems. Hybrid power systems can be defined as energy systems that integrate multiple energy sources, for more efficient, reliable, and cost-effective electricity generation, compared to single-source systems. By capitalising on the complementary nature of various energy sources, hybrid systems offer a sophisticated approach to maximising energy output and enhancing efficiency. This is achieved, through the strategic integration of diverse generation technologies; allowing the system to adapt to fluctuating environmental conditions and optimise energy production based on the most readily available resource. Hybridisation tackles energy demands in remote areas and existing facilities. Additionally, hybrid systems can incorporate energy storage or conventional backup sources, like diesel generators, for further enhanced system reliability. On the other hand, hybrid configuration implies a further system complication due to the request for efficient and smart management of different power sources as a function, in principle, of loads and costs. System sizing and optimisation are, generally, the focus of research in hybrid power sources. Consequently, understanding the functioning of hybrid energy systems is fundamental and studies cannot ignore their numerical modelling, generally based on two main approaches: analytical modelling and simulation. The first technique employs mathematical equations and established scientific principles to represent the behaviour of each component within the system. While well-suited for simpler systems, it can become intricate for larger systems with numerous components, making analysis challenging. The second leverages computer software to create a virtual representation of the system, and to simulate its behaviour. The model is over-time evolving, based on pre-defined rules or relationships between variables. Offering versatility, it applies to simple and complex systems. Popular software tools used for hybrid power system modelling include HOMER (HOMER Energy LLC), MATLAB/Simulink (MathWorks), and PSYCADE (OPAL-RT Technologies). The choice of modelling technique depends on several factors, including the system's complexity, the desired level of accuracy, and the available resources. Numerical modelling including energy and exergy analysis of hybrid power systems is also considered by scholars as well as cost modelling [5,6].

Feasibility studies for hybrid power systems provide a holistic view, encompassing the electrical system, financials, and site-specific characteristics. They offer a scientific approach to optimising new hybrid power systems, reconfiguring existing ones for efficiency, and identifying new renewable assets. For example, the analysis of scenarios, which involves implementing a hybrid power system composed of photovoltaic, wind, and battery energy storage systems, is fundamental to determining the ideal proportion of energy supply through an analysis of technical, financial, and social aspects [7]. Hybrid systems can integrate heterogeneous technologies, as in [8], where anaerobic digestion, pyrolysis and solar PV were integrated forming a plant which can produce energy and fuels such as green hydrogen, refuse-derived fuels, bio-compressed natural gas and compost. The study compared the financial feasibility of three scenarios—generating electricity and fuels, generating electricity alone and generating fuels alone—by modelling their levels of energy output and financial performance. Hybrid power systems can be conceived without renewable energy sources and studied using energy, exergy, economic, and life cycle environmental analyses. A biogas power generation and hydrogen generation system can be integrated with a solar thermal energy storage unit, a SOFC-Micro Gas Turbine unit, and a waste heat utilisation unit. In this case, higher efficiency could be achieved concerning conventional power systems [9]. Another innovative configuration of a power plant was modelled in [10] where, alkaline fuel cells, which generate a significant amount of waste heat, were coupled with thermogalvanic cells for electric power generation by harvesting the low-grade exhaust heat produced.

Hydrogen and battery technologies, which have a primary role in the energy transition, due to their ability to mitigate the fluctuation in energy production from renewable sources and to be applied to stationary and automotive applications, are developed from electrochemical and engineering points of view. The research activity on active materials is supported by technological research addressing the methodologies for devices (fuel cell stack and battery) and power unit construction. The latter results from assembling the device and ancillaries, for gas and temperature management, current and voltage management, digital control units, and so on. Fuel cell (FC) technology offers a promising path towards a clean and sustainable energy future. However, optimising their design, operation, and integration with other energy sources necessitates robust mathematical modelling techniques. These models act as virtual representations of the complex electrochemical and physical processes occurring within an FC system, enabling researchers and engineers to calculate performance, and models can predict the FC system's electrical output, efficiency, and response to varying operating conditions. This is crucial to design control strategies that maximise efficiency and system stability, optimise the design by simulating different design parameters within the model before building physical prototypes, and reduce development time and cost while achieving desired performance characteristics. Various mathematical modelling approaches are used for FC power systems; each with its strengths and limitations: Empirical Models, which rely on experimental data to establish relationships between input variables (e.g., temperature, pressure, fuel flow) and output variables (e.g., voltage, current). They are simple to implement but may not be accurate under conditions outside the range of the experimental data used for model creation. Semi-empirical models, combining empirical relationships with fundamental physical principles governing the electrochemical processes within the FC. They offer improved accuracy compared to purely empirical models but may still require some experimental data for parameter estimation. Physics-based models, representing the most complex approach, account for the fundamental governing equations that describe mass transport, heat transfer, and electrochemical reactions within the FC. They offer the highest level of accuracy but require a deep understanding of the underlying physical and chemical phenomena and significant computational resources. More detailed information can be found in [11]. In this context, the industry and the scientific community need advanced FC systems models that can replicate real-world operating conditions. In [12], a comprehensive methodology to calibrate and validate multi-physics dynamic FC systems models was developed to accurately describe the behaviour of the FC stack and components of the "balance of plant". The model was calibrated using experimental data from a Toyota Mirai FC electric vehicle's controller area network (CAN) bus system. An FC system for aircraft application was modelled in [13] to evaluate the applicability of this technology to an existing regional aircraft and assess its electrification. Specifically, a general mathematical model was developed, involving multiple scales, ranging from individual cells to aircraft scales. Then, different sizing approaches were used to compute the overall weight of the hydrogen-based propulsion system, to optimise the system and minimise its weight. In [14], a novel combined heat and power system, integrating solid oxide FC and organic Rankine cycle, was studied by mathematical modelling to achieve the efficient and clean utilisation of poultry litter. In [15], a model of a SOFC system with a recycling of the anode off-gas was proposed to improve the system fuel utilisation under a low rate of stack fuel utilisation.

These systems/power units are often integrated into hybrid power systems formed by heterogeneous power sources such as photovoltaic, wind, internal combustion engines, batteries, turbines and others. In the following paragraphs, there will be illustrated some examples from the scientific literature; focusing on hybrid power systems using fuel cells and batteries.

In [16], fuel cells are combined with an internal combustion engine, utilising ammonia decomposition as the primary fuel source. The system comprises an ammonia decomposition subsystem, a fuel cell, an internal combustion engine, a heat exchanger, and a power electronic converter. A hybrid system combining solar-assisted reforming of methanol and FC power generation was modelled in [17], where methanol is used as a coolant for the FC subsystem to take away the waste heat, and reformed for hydrogen production with the assistance of the solar energy subsystem. An artificial intelligence-based methodology was employed for analysing and optimising a grid-tied solar photovoltaic-FC hybrid power system. Demonstrating how AI techniques can assist in decision-making, improving system performance, achieving higher energy efficiency levels, and financial viability [18]. A biomass-based power generation system which includes a system to produce syngas, a fuel cell, a gas turbine, and an organic Rankine cycle was modelled in [19]. An optimisation of a multisource hybrid photovoltaic/wind/diesel/FC system was performed in [20]. The study also examines, and compares, the techno-economic viability of an off-grid hybrid photovoltaic/wind/diesel/FC, photovoltaic/diesel/FC, and wind/diesel/FC systems. Finally, in transportation applications, the optimal design of a renewable energy hybrid power system (photovoltaic, FC, and battery) for a tugboat was presented in [21].

This Special Issue aims to illustrate the most research advances in modelling fuel cell-based and hybrid power systems. It focuses on the mathematical modelling of FC and hybrid systems, and shows different approaches, considering FC technology (PEFC, SOFC, DMFC), system architecture, hybridisation level, application, and power management. It consists of ten contributions spanning from modelling high- and low-temperature fuel cell-based and hybrid power systems for stationary and automotive applications, to hydrogen production modelling from reforming and photoelectrolysis. It furnishes a comprehensive overview of the applicability of modelling techniques across diverse domains relevant to low-GHG or GHG-free power systems (see list of contributions).

Hydrogen production from reforming and photoelectrochemical devices was the focus of Contribution 1, which describes a design-for-optimization study, aimed at unifying temperature distribution by novel arrangements of catalyst segments in the model of a biogas reforming reactor, and Contribution 10, proposing a multi-physics-based numerical model of a tandem photoelectrochemical cell, an innovative concept for solar-to-hydrogen water conversion. A fuel cell/battery hybrid power system for a UAV was modelled in Contribution 2, and SOFC systems were modelled in Contribution 3 and Contribution 4; in particular, the first considered an anode-off recirculation subsystem, the second the presence of an additively manufactured, high-temperature, heat exchanger in an LNG-fuelled SOFC system. Micro-combined heat and power cogeneration for residential applications was the object of Contribution 5, wherein a hybrid PV/SOFC power system was modelled. A numerical, dynamic model of a low-temperature FC stationary power system, for supporting and adding flexibility to a renewable energy-sourced grid, was proposed in Contribution 6. Low-temperature FC power systems of commercial hydrogen-fed vehicles (Toyota Mirai I and II) were modelled and analysed in Contribution 7; the models' validation was carried out using experimental data, acquired during use under road driving conditions. Contribution 8 presented a three-dimensional, steady-state, two-phase, multi-component and non-isothermal DMFC model. The DMFC model was validated against experimental measurements. Finally, a hybrid power system power train for application in an autonomous marine vehicle (low-temperature FC/battery) was modelled and investigated in Contribution 9.

Mathematical modelling plays a critical role in unlocking the full potential of new power generation technologies. By continually refining and advancing these models, researchers and engineers can design, optimise, and integrate FC-based and hybrid power systems for a cleaner and more sustainable energy future, paving the way for wider adoption of this promising technology.

Conflicts of Interest: The author declares no conflicts of interest.

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