Advancements in Green Hydrogen Production: A Comprehensive Review of System Integration, Power Grid Applications, and Cost Optimization

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Abstract- Hydrogen is acquiring a promising recognition as a new trend in energy storage technologies due to its advantageous features including fast response, high energy density, and unconstrained storage capacity. Thus, it offers an effective solution for addressing the stability challenges posed by the large-scale integration of renewable energy sources (RESs) into power systems. Accordingly, this paper presents a comprehensive review of advancements in green hydrogen production (GHP), with a focus on water electrolyzers (WELs) and their integration into power systems. Specifically, it examines WEL types, operational characteristics, and the role of DC converters in system connectivity and efficient power flow. Furthermore, various control strategies to optimize converter performance are thoroughly analysed, along with WEL applications in frequency and voltage regulation, congestion management, and black start operations. Moreover, recent efforts to minimize hydrogen production costs through optimal system configurations and resource management are reviewed. It's worth indicating that alkaline WELs have the lowest capital cost, qualifying them as a cost-effective option for large-scale hydrogen production. Therefore, this article seeks to aid researchers and stakeholders by providing an insightful overview of the present status of WEL emergence in modern energy systems, highlighting key technological advancements, challenges, and prospects.

Keywords: Renewable energy sources; Green hydrogen production; Water electrolyzer; DC converters; Power system stability.

List of Abbreviations

AEM	:	Anion exchange membrane	LCOH	:	Levelized cost of hydrogen
AL	:	Alkaline	Li-ion	:	Lithium ion
ANFIS	:	Adaptive neuro-fuzzy inference system	LTTS	:	Low temperature thermal storage
BBC	:	Buck-boost converter	MPC	:	Model predictive control
CAES	:	Compressed air energy storage	Na-s	:	Sodium-sulfur
CES	:	Cryogenic energy storage	Ni-cd	:	Nickel-cadmium
DC converter	:	DC-to-DC converter	NPV	:	Net present value
DER	:	Distributed energy generator	PEM	:	Proton exchange membrane
DL	:	Deep learning	PHSS	:	Pumped hydro storage system
DTR	:	Dynamic thermal rating	PID	:	Proportional integral derivative
EST	:	Energy storage technology	PV	:	Photovoltaic

EV	:	Electric vehicle	RES	:	Renewable energy system
FC	:	Fuel cell	RL	:	Reinforcement learning
FESS	:	Flywheel energy storage system	SESS	:	Supercapacitor energy storage system
FIBBC	:	Floating-interleaved buck-boost converter	SL	:	Supervised learning
FLC	:	Fuzzy logic control	SO	:	Solid oxide
FNN	:	Feedforward neural network	SMC	:	Sliding mode control
GHP	:	Green hydrogen production	SMSS	:	Superconducting magnetic storage system
HESS	:	Hydrogen energy storage system	STSMC	:	Super-twisting sliding mode control
HOSMC	:	Higher-order sliding mode control	TSMC	:	Terminal sliding mode control
HTTS	:	High temperature thermal storage	UL	:	Unsupervised learning
IBBC	:	Interleaved buck-boost converter	VR	:	Vanadium redox
IRR	:	Internal rate of return	WEL	:	Water electrolyzer
LA	:	Lead acid	WT	:	Wind turbine
LCOE	:	Levelized cost of electricity	Zn-Br	:	zinc-bromine

1. Introduction

Fossil fuel consumption has raised significant global concerns due to severe ecological drawbacks and greenhouse gas emissions that accelerate climate change [1]. These fuels also contribute to water pollution and habitat destruction, and their unsustainability raises doubts about long-term availability and price stability [2]. Consequently, the global energy landscape is shifting toward renewable energy sources (RESs), such as photovoltaic (PV), solar thermal, wind turbine (WT), hydro, geothermal, and biomass, to reduce carbon emissions and achieve energy security [3-5]. Practically, governments and agencies worldwide have implemented regulations such as the Paris Agreement to boost RES adoption [6]. For instance, Japan has committed to carbon neutrality by 2050, marking a significant step beyond earlier targets [7].

While RESs like PV and WT provide abundant clean energy, their dependence on fluctuating weather conditions can pose stability challenges for modern power grids [8]. Accordingly, energy storage technologies (ESTs) help mitigate these issues by storing excess power during light-load conditions and releasing it when demand increases [9]. These ESTs may employ electrochemical, thermal, electromechanical, or electromagnetic methods [10-12]. Among them, hydrogen energy storage systems (HESS) derived from green hydrogen production (GHP), where hydrogen is generated from RESs using water electrolyzers (WELs), present a particularly promising solution for carbon emission reduction and power system stabilization [13]. Specifically, hydrogen offers high energy density, can be stored in gaseous or liquefied form, and is non-toxic, thus it enables flexible use across multiple applications [14, 15]. Moreover, it can be reconverted into electricity using fuel cells (FCs), signifying its role as a cornerstone of a carbon-neutral society [16].

In fact, incorporating WEL/FC-based systems within power grids can facilitate demand-supply balance by converting surplus energy into hydrogen, which is later used during peak demand or reduced renewable output [17, 18]. This dynamic flexibility aids frequency regulation, voltage control, and overall grid resilience [19]. However, efficient integration requires suitable DC-to-DC converter (DC converter) topologies and robust control methodologies to manage power flow. Non-isolated converters are often employed in smaller-scale applications, while isolated converters provide electrical isolation for high-power systems [20, 21]. Additionally, advanced control strategies, ranging from proportional–integral (PI) and fuzzy logic to neural networks, are critical for addressing nonlinear system dynamics and ensuring stable operation [22-25].

In this regard, several reviews have addressed individual aspects of GHP, such as technical principles, market potential, and challenges [26-28], the role of WELs in decarbonized power grids [29, 30], and WEL/FC-based configurations in AC/DC networks [31]. Other studies focus on FC/WEL control strategies [32], examine broader energy storage options [33], or perform techno-economic assessments of different RESs and WEL types [34-36]. Yet, a comprehensive discussion that integrates both technical and economic dimensions, covering WEL/FC designs, converter topologies, control schemes, and profit optimization for power grids, is still lacking.

To fill this gap, the present review provides a holistic evaluation of GHP systems, emphasizing their role in power regulation, grid stability, and economic performance. The key contributions can be summarized as follows:

a) A systematic comparison of various ESTs, highlighting why hydrogen-based solutions stand out.
b) An in-depth analysis of different WEL types, e.g., alkaline (ALWEL), proton-exchange membrane (PEMWEL), anion exchange membrane (AEMWEL), and solid oxide (SOWEL), and their best-fit applications.
c) A review of mathematical modelling approaches for WELs, with detailed formulations, particularly for PEMWEL.
d) An overview of DC converter topologies (isolated and non-isolated) and their control strategies for efficient power transfer with WELs and FCs.
e) A survey of practical WEL applications in modern power systems, focusing on stability and ancillary services.
f) Recent approaches to optimizing economic performance when integrating GHP and RESs.
g) Key insights into future research directions and challenges in achieving carbon-neutral power systems.

The remainder of the article is organized as follows: Section 2 discusses the concept, advantages, and disadvantages of various ESTs. Section 3 introduces the internal construction and chemical reactions of common WEL types. Section 4 reviews WEL modelling approaches and provides a detailed mathematical formulation for PEMWEL. Section 5 explores DC converter topologies for connecting fuel cells and WELs to the grid, while Section 6 highlights corresponding control strategies. Section 7 illustrates WEL applications in modern power systems, and Section 8 addresses recent efforts to optimize economic performance. Finally, Section 9 concludes with key findings and future perspectives. A graphical overview of the scope is shown in Fig. 1.

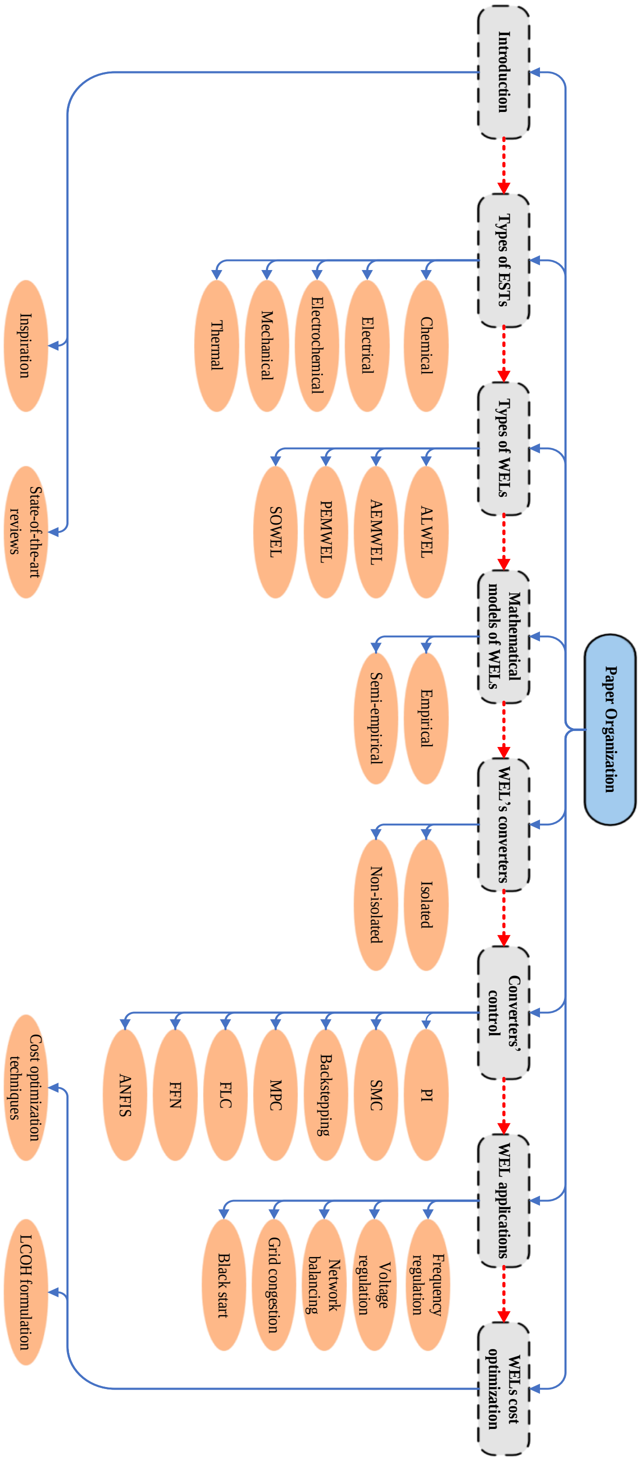


Fig. 1. Organization of paper scope

2. Overview of various energy storage technologies

Since the growing integration of RESs in power systems is characterized by a continuous substitution of synchronous generators with static inverters, significant instability issues have arisen due to power fluctuations [37, 38]. Such power electronic devices reduce the system's mechanical inertia making it vulnerable to instability attacks as a result of any supply-demand imbalance [39]. Actually, minimizing the mechanical inertia increases the system efficiency, however, it can vigorously trigger frequency oscillations leading to recurring tripping of under/over frequency relays. Thus, the operator may resort to shed the loads or automatic series outages may occur [40].

Indeed, ESTs offer an effective solution to overcome the aforementioned problems related to the high penetration of RESs in power networks [41]. Principally, an EST-based system stores surplus energy in a form different from its original one for a while then releases it upon a call to support the power balance [42]. Fig. 2 classifies various ESTs employed in power systems according to the type of stored energy [43]. Specifically, hydrogen-based energy storage system (HESS) represents chemical ESTs, and supercapacitor energy storage system (SESS) and superconducting magnetic storage system (SMSS) are examples of electrical ESTs. Besides, electrochemical ESTs refer to batteries, such as lithium-ion (Li-ion), lead-acid (LA), nickel-cadmium (Ni-Cd), sodium-sulfur (Na-S), zinc-bromide (Zn-Br), and vanadium redox (VR) batteries. Additionally, mechanical ESTs include compressed air energy storage (CAES), flywheel energy storage system (FESS), and pumped hydro storage system (PHSS), while thermal ESTs comprise cryogenic energy storage (CES), low temperature thermal storage (LTTS), and high temperature thermal storage (HTTS). Furthermore, the technical characteristics of such technologies are thoroughly described in Table 1, which are extracted from [44-47].

Particularly, HESS is a promising technology where hydrogen serves as the energy carrier. Due to its abundance and ecological benefits, hydrogen supports transportation, power generation, heating, and industry. However, its sustainability depends on the production process [48]. Hence, the authors in [49] introduced a quality-based methodology to classify diverse hydrogen production techniques with a color coding, as revealed in Fig. 3. Among the four methods, green and blue hydrogen gained a wide popularity for attaining carbon neutrality [50]. Explicitly, green hydrogen attracts research interest due to its reversibility in power systems [51]. In detail, Excess RES electricity is converted into hydrogen via WELs, while fuel cells regenerate electricity from stored hydrogen during peak demand [52].

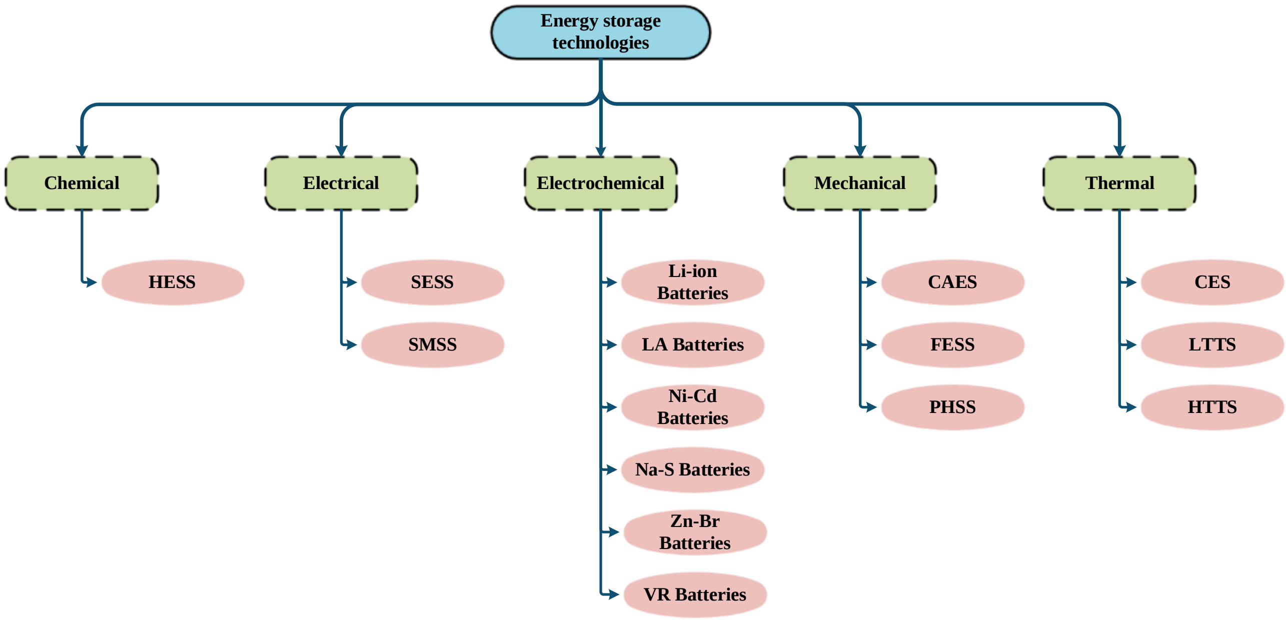


Fig. 2. Classifications of ESTs

Table 1. Practical features of some ESTs

EST	Commercial status	Installed power (MW)	Efficiency (%)	Capital cost ($/W)	Charging period	Discharging period	Time span, Cycles × 10^3 (years)
HESS	Growing	0-58.8	25-58	0.5-10	hr - months	sec - days	1-20 (5-20)
SESS	Growing	0-0.3	90-95	0.1-0.45	sec - hr	msec - hr	>100 (20)
SMSS	Growing	0.1-10	95-98	0.2-0.489	min - hr	msec - 8 sec	>100 (20)
Li-ion	Commercialized	0-100	85-90	0.9-4	min - days	min - hr	1-20 (5-15)
LA	Mature	0-40	70-90	0.3-0.6	min - days	sec - hr	2 (3-15)
Ni-Cd	Commercialized	0-40	60-65	0.5-1.5	min - days	sec - hr	2-3.5 (10-20)
Na-S	Commercialized	0.05-34	80-90	1-3	sec - hr	sec - hr	2.5-4.5 (10-15)
Zn-Br	Demonstration	0.05-10	75 (average)	0.7-2.5	hr - months	sec - 10 hr	>2 (5-10)
VR	Pre-commercialized	0.03-3	85 (average)	0.6-1.5	hr - months	sec - 10 hr	>12 (5-10)
CAES	Mature	5-1000	70-89	0.4-1	hr - months	hr - days	>13 (20-40)
FESS	Pre-commercialized	0.1-20	93-95	0.25-0.35	sec - min	msec - 15 min	>100 (>15)
PHSS	Mature	100-5000	75-85	2-4.3	hr - months	hr - days	>13 (40-60)
CES	Growing	0.1-300	40-50	0.2-0.3	min - days	hr - 8 hr	>13 (20-40)
LTTS	Growing	0-5	50-90	-	min - days	hr - 8 hr	- (10-20)
HTTS	Growing	0-60	30-60	-	min - months	hr - days	>13 (5-15)

*sec, min, and hr refer to second, minute, and hour, respectively.

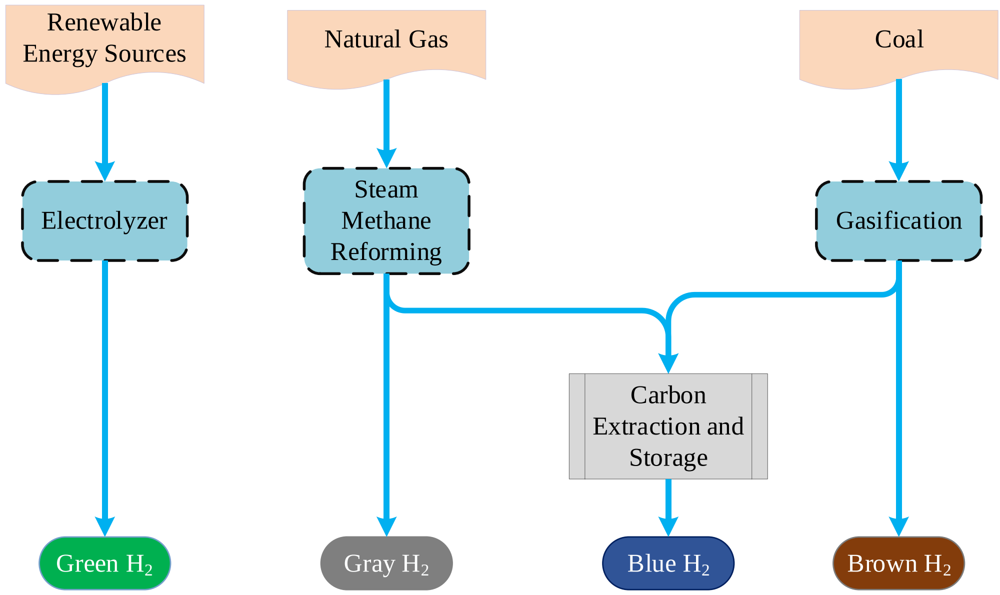


Fig. 3. Classification of hydrogen production systems

Besides, according to Table 1, HESS provides a longer-term energy solution than other ESTs, making it ideal for sustaining large loads during power outages. Its rapid response helps regulate power system frequency, mitigating RES intermittency effects. Additionally, modularity and scalability enhance its adaptability, while oxygen as a byproduct makes it an environmentally friendly option [53]. Recent studies suggest that integrating distributed RESs with HESS improves power reliability, resilience, and continuity. Table 2 highlights global HESS pilot projects, demonstrating its feasibility in power networks. However, high installation costs and the need for a robust hydrogen infrastructure remain key challenges [54].

Table 2. Global HESS ongoing projects

Ref.	Origin	RES' type	WEL		Hydrogen tank		FC	
			Type	Capacity (kW)	Pressure (bar)	Volume (Nm^3)	Type	Output power (kW)
[55]	Germany	PV	AL	100	30	5000	PAFC	80
[56]	Spain	PV	AL	5	10	24	PEMFC/PAFC	7.5/10
[57]	USA	PV	AL	6	5.7	30	×	×
[58]	Germany	PV	PEM	2	15	30	×	×
[59]	Germany	PV	AL	26	120	3000	PEMFC	5.6
[60]	Canada	PV/Wind	AL	5	120	40	PEMFC	5
[61]	Argentina	PV/Wind	AL	5	35	10	×	×
[62]	Spain	PV	PEM	1	70	30	×	×
[63]	Norway	Wind	PEM	1.5	14	16	×	×
[64]	France	PV	AL	3.6	0.4	10	×	×
[65]	Italy	PV	AL	3.4	4	10	×	×
[66]	USA	PV	PEM	3.35	15	5.4	PEMFC	2.4
[67]	Spain	PV	AL	15	25	2	×	×
[68]	Australia	×	PEM	100	163	14	×	×
[69]	UK	×	AL	250	NM	10	NM	100
[70]	UK	×	PEM	500	20	NM	×	×

"NM" and "×" refer to not mentioned and not existed in the reported article, respectively.

3. Advances in WEL technologies

A WEL utilizes a flow of electrons, injected from an external DC voltage source, to return water to its forming atoms, hydrogen (H_2) and oxygen (O_2) [71]. It basically comprises an electrolyte sandwiched by two electrodes (anode and cathode). So, passing an electrical current via water yields hydrogen at the cathode and oxygen at the anode [72]. Considering the electrolyte material, WELs have several types, such as ALWEL [73], AEMWEL [74], PEMWEL [75], and SOWEL [76]. To visualize the main differences of these types, Fig. 4 encloses their schematic diagrams. Technically, each type has distinctive characteristics, regarding operating temperature and pressure, efficiency, current density, input voltage, and lifetime, as indicated in Table 3 [77].

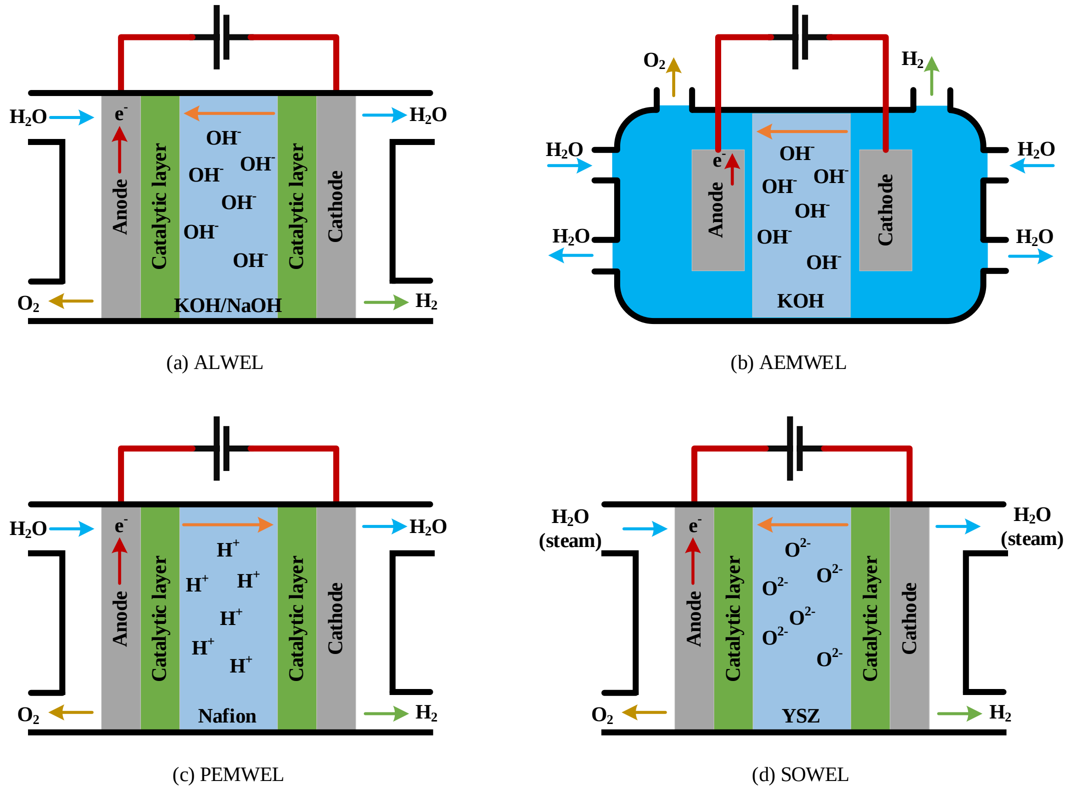


Fig. 4. Schematic diagram of WEL's types

Table 3. Practical features of various WEL's types

Feature \ Type	ALWEL	AEMWEL	PEMWEL	SOWEL
Electrolyte	KOH/NaOH	KOH	Solid polymer (Nafion)	yttria-stabilized zirconia (YSZ)
Carrier ion	OH^-	OH^-	H^+	O^{2-}
Temperature	65 – 100 °C	50 – 70 °C	70 – 90 °C	600 – 1000 °C
Pressure	2 – 10 bar	≤ 35 bar	15 – 30 bar	< 30 bar
Efficiency	62 – 84 %	50 – 70 %	67 – 82 %	≤ 100 %
Voltage/cell	1.8 - 2.4 V	1.85 V	1.8 - 2.4 V	0.95 – 1.30 V
Current density	0.2 – 0.4 A. cm^{-2}	0.1 – 0.5 cm^{-2}	0.6 – 2.0 cm^{-2}	0.3 – 1.0 cm^{-2}
Response time	Seconds	Seconds	Milliseconds	Seconds
Lifetime	< 90 × 10^3 hr	> 10 × 10^3 hr	< 40 × 10^3 hr	< 40 × 10^3 hr
Scalability	High	Reasonable	Reasonable	Reasonable
Applicability status	Mature	Commercial	Commercial	Under development
Electrochemical reactions				
At anode:	$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$	$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$	$H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$
At cathode:	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + 4O^{2-}$
Overall:	$2H_2O \rightarrow 2H_2 + O_2$	$2H_2O \rightarrow 2H_2 + O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$

According to Table 3, PEMWEL has the fastest response time among the other types. Hence, PEMWELs find extensive use in power system applications, especially where a swift response is essential for perceiving system stability. This motivates the authors to focus on modelling this specific type, thereby ensuring a more concise article. In this context, the reader is invited to check the following subsection for the PEMWEL mathematical model.

4. Electrical modelling of WELs

As mentioned earlier, the primary barrier to widespread commercialization of WELs in power systems is their capital cost. Thus, a precise and reliable assessment of their behaviour shall be implemented to identify any system defect before installing such expensive apparatuses [78]. Consequently, numerous researchers are seeking for properly deriving comprehensive mathematical models that can accurately simulate WELs' performance during various operating conditions [79, 80]. In fact, a robust and efficient model cannot only evaluate the WEL's response but also highlight the operational parameters that optimize and predict WELs' performance in a wide range of operating scenarios [81].

Given that WELs are multiphysics devices in which various chemical and thermal processes occur simultaneously during operation, deriving a single model to comprehensively describe all these phenomena is challenging. So, various electrical models have been introduced each varies depending on the deriving approach, the studied behaviour, and the mathematical formulation, as depicted in Fig. 5 [82, 83].

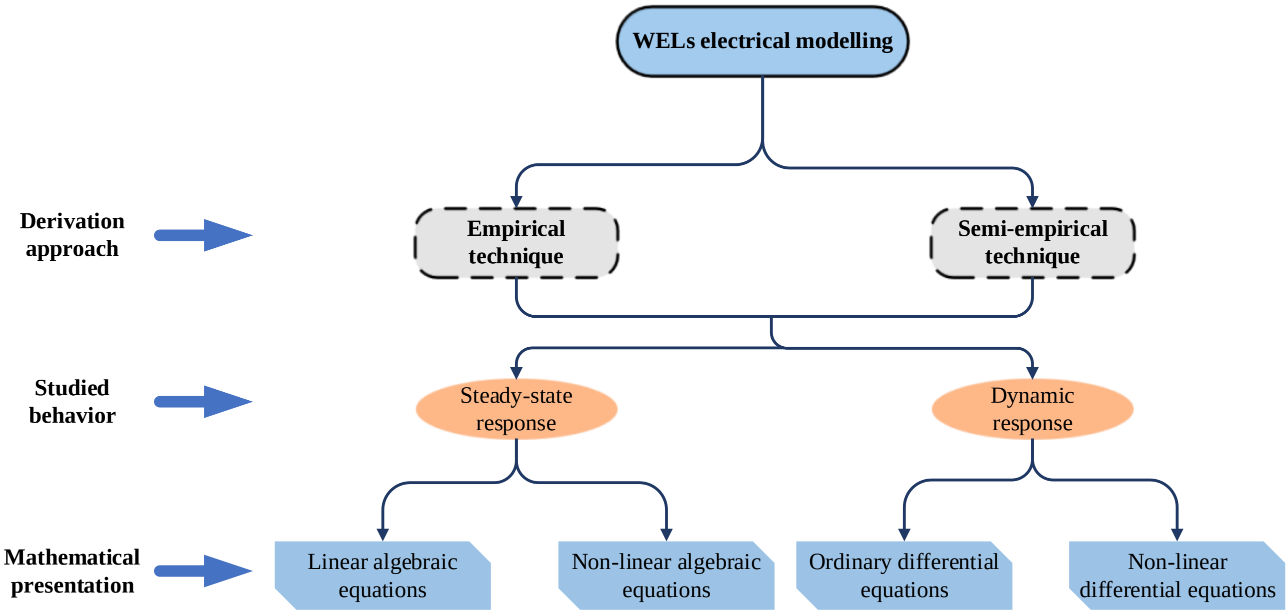


Fig. 5. Categorization of WELs' modelling

Among these approaches, the electrochemical model plays a significant role in accurately replicating the polarization characteristics (V-I curve) of PEMWELs [84]. This is achieved through the integration of chemical and physical parameters, including water content, hydrogen production rate, membrane material, and cell area [85]. As illustrated in the model's equivalent circuit shown in Fig. 6, the PEMWEL's input voltage is a resultant of a voltage source, representing the minimum required potential to start the chemical reactions, and a series of operational losses. More precisely, these losses encompass activation and concentration overpotentials, each depicted by a capacitor-resistor branch, alongside ohmic voltage drop originating from membrane and connection resistances. The model's results are illustrated through a V-I curve, as depicted in Fig. 7 [78, 86].

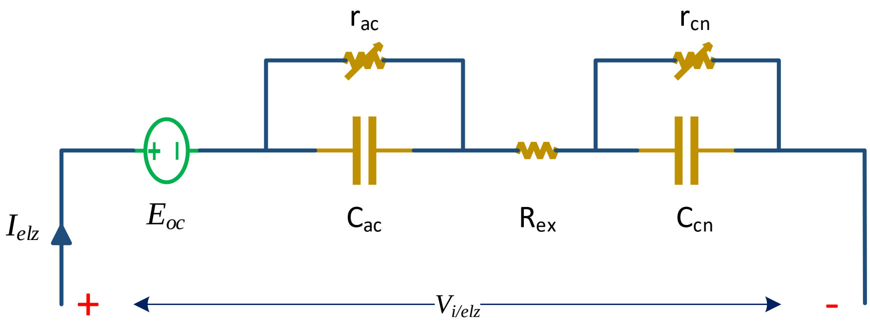


Fig. 6. Equivalent circuit of the electrochemical model

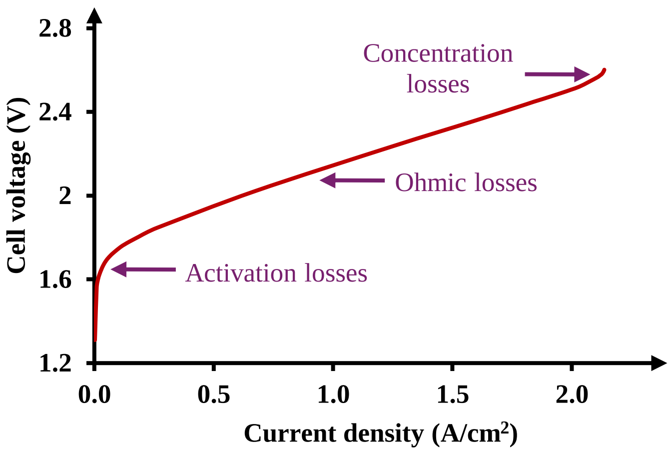


Fig. 7. Typical polarization curve of PEMWEL

As a single WEL cell is inadequate for meeting the demanded hydrogen production, multiple cells are linked together serially forming a stack, ensuring the required hydrogen output. Thus, input voltage of the WELs' stack $V_{i/st}$ in (V) can be mathematically described by (1).

$$V_{i/st} = N_{elz} \times V_{i/elz} \tag{1}$$

where, N_{elz} is the number of serially connected cells. $V_{i/elz}$ is the cell input voltage in (V) which is formulated by (2) [87].

$$V_{i/elz} = E_{oc} + V_{ac} + V_{\Omega} + V_{cn} \tag{2}$$

where, V_{ac}, V_{Ω}, and V_{cn} symbolize the activation, ohmic, and concentration voltage drops in (V), respectively. E_{oc} represents the minimum required voltage to initiate the cell in (V) and is given by Nernst equation, as in (3) [86].

$$E_{oc} = 5.1822 \times 10^{-3}\left[\Delta G + 0.0821 \cdot T_{elz} \cdot ln\left(\frac{P_H\sqrt{P_O}}{P_W}\right)\right] \tag{3}$$

where, the change in Gibbs-free-energy is represented by ΔG in (kJ/mol). T_{elz} refers to the WEL's operating temperature in (k). P_H, P_O, and P_W point out the pressure of hydrogen, oxygen, and water in (bar), respectively.

To describe the initial sluggish of the chemical reaction, the activation overpotential V_{act} is computed by (4).

$$V_{act} = 4.2545 \times 10^{-4} \cdot T_{elz}\left[\frac{1}{\delta_n}\sinh^{-1}\frac{J_{elz}}{2J_n^{\circ}} + \frac{1}{\delta_{th}}\sinh^{-1}\frac{J_{elz}}{2J_{th}^{\circ}}\right] \tag{4}$$

where, δ_n and δ_{th} symbolizes the charge transfer coefficients of anode and cathode, respectively. The WEL's current density is denoted by J_{elz} in (A/cm^2). The anode and cathode exchange current densities are indicated by J_n° and J_{th}° in (A/cm^2), respectively.

Furthermore, the linear region in the polarization curve, caused by the ohmic losses, can be expressed by (5) [88].

$$V_{\Omega} = J_{elz} \cdot (R_m + R_{ex}) \tag{5}$$

where, R_{ex} refers to the resistance due to the external leads in $(\Omega.cm^2)$. The membrane resistance is represented by R_m in $(\Omega.cm^2)$ and is computed by (6) [86].

$$R_m = \frac{l_m}{\sigma_m} \tag{6}$$

where, l_m is the thickness of the WEL's membrane in (cm). The membrane's resistivity, donated by σ_m in $\Omega.cm^{-2}$, is function of the WEL's temperature and the membrane's water content λ, as given by (7).

$$\sigma_m = (0.005139\lambda - 0.00326) \cdot \exp\left[4.1848\left(\frac{T_{elz} - 303}{T_{elz}}\right)\right] \tag{7}$$

At heavy current density, the chemical reaction encounters an impediment due to the high oxygen concentration at the membrane area. This is represented by the concentration voltage drop and expressed by (8).

$$V_{cn} = 4.2545\ \times 10^{-4} T_{elz} \cdot ln\left(\frac{J_{max}}{J_{max} - J_{elz}}\right) \tag{8}$$

where, J_{max} represents the maximum current density in (A/cm^2).

Finally, the produced hydrogen flowrate Q_H in (m^3/sec) is expressed by (9) [87].

$$Q_H = 4.2545 \times 10^{-4}\frac{J_{elz}.T_{elz}}{P_H} \tag{9}$$

While the electrochemical model discussed thus far primarily addresses PEMWELs, it is also instructive to examine alternative electrolyzer technologies, such as ALWELs, AEMWELs and SOWELs, and how their modelling approaches differ in response to unique operational conditions. An ALWEL is typically described by a base thermodynamic voltage plus activation, ohmic, and concentration overpotentials. The ohmic loss is higher than in PEM systems due to the alkaline solution's lower conductivity and the diaphragm thickness. Activation overpotentials, stemming from electrode kinetics, can be captured via resistor–capacitor (RC) or resistor–inductor–capacitor (RLC) branches, while concentration overpotentials account for gas bubble formation and mass transport limitations [89].

AEMWELs resemble PEMWELs in having a reference voltage source and similar loss terms, but the higher ionic resistance of AEM membranes amplifies ohmic losses. Activation overpotentials are modelled by RC branches, with differences in catalyst composition. Concentration overpotentials can become significant if water supply or gas evacuation is restricted. Evolving models also consider membrane carbonation and degradation to predict dynamic performance [90].

SOWEL modelling must integrate electrochemical and thermal dynamics due to elevated temperatures that alter reaction kinetics and material properties. Multiple overpotential terms, including activation, ohmic, and concentration, are typically included, with separate RC or RLC branches for different electrode interfaces. Temperature-sensitive ohmic resistance arises from the electrolyte and interconnects, while mass transport effects may require diffusion-limited current expressions. Long-term factors like electrode delamination or electrolyte cracking are also included in advanced models [91]. Table 4 compares the primary parameters, challenges, and representative equivalent circuit elements across different electrolyzer types.

Table 4. Comparative overview of modelling approaches across electrolyzer types

Item	ALWEL	PEMWEL	AEM	SOWEL
Overpotentials	• Activation • Ohmic • Concentration	• Activation • Ohmic • Concentration	• Activation • Ohmic • Concentration	• Activation • Ohmic • Electrode polarization
Ohmic loss drivers	• Diaphragm/electrolyte resistance.	• Membrane conductivity (hydration-dependent).	• Higher membrane resistance than PEM.	• High-temperature electrolyte/interconnect resistance.
Equivalent circuit structure	• Voltage source (thermodynamic). • Multi-branch RC (or RLC) networks for	• Similar multi-branch RC structure, with emphasis on	• Like PEM, but with higher ohmic resistance	• More complex. • Often featuring multiple RC (or RLC) branches to capture temperature-

	activation and concentration overpotentials.	membrane resistance and water management.	due to OH^- conduction.	dependent polarization effects.
Dynamic modelling complexity	• Moderate: gas bubble formation and mass transport influence transient response.	• High: rapid load-following capability requires time-varying membrane hydration modelling.	• Moderate to high: evolving designs require tracking membrane carbonation and electrode kinetics.	• High: must integrate thermal gradients, potential material degradation, and transient electrochemical responses.
Modelling challenges	• Ensuring accurate representation of diaphragm thickness, ion transport, and bubble formation.	• Capturing water management (membrane hydration) and load transients. • Catalyst degradation.	• Limited data on membrane durability. • Higher ohmic losses. • Evolving catalyst designs	• Elevated temperatures accelerate electrode/electrolyte degradation • Requires coupled thermal-electrochemical modelling.
Representative references	[89, 92]	[93, 94]	[90, 95]	[91, 96]

5. Power electronics for electrolyzers and fuel cells applications

Modern power systems incorporate large amounts of RESs along with conventional power plants, with distinct volage profiles. Thus, the integration of WELs and FCs in such systems necessitates an interface to link the system voltage to their operating and generated voltages, respectively [20]. Specifically, the DC converter serves as such an interface since most RESs generate high DC voltage, whereas WELs need a low DC voltage input [21]. Conversely, FCs are employed as a standby power source that can rapidly inject electrical power to the system when the power supplied by RESs is insufficient. However, the injected power is delivered at a lower voltage than the DC bus. Hence, a DC converter is also obligatory to step up the FC's output voltage. Another crucial feature of WELs and FCs is their inherently non-linear electrical response. Hence, a DC converter is essential to regulate the voltage regardless of the loading conditions [14]. Fig. 8 offers a schematic explanation for the configuration of WELs and FCs with RESs in a practical power network [32]. Indeed, a proper DC converter for WELs and FCs applications shall meet certain features, like low expenses, high conversion ratio and efficiency, substantial power density, minimized output current ripples and electromagnetic interference, and capability to operate reliably during switching failure [20, 97].

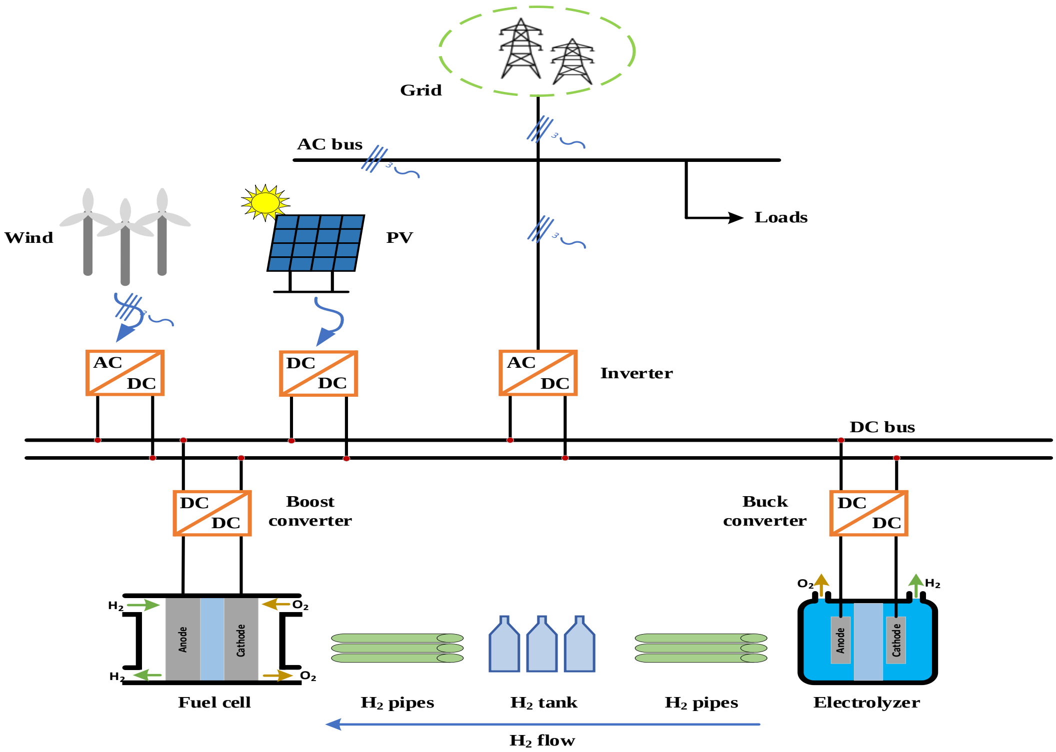


Fig. 8. Schematic configuration of WEL/FC-based power network

Particularly, the non-isolated and isolated DC converters dominate the WEL and FC applications throughout the literature [20, 21, 98-100]. Thus, Table 5 presents a summarized comparison of the key features of each category. In addition, the following subsection introduces an overview of their topologies.

Table 5. Basic comparison of DC converters

Converter's type / Index	Non-isolated DC converters		Isolated DC converters	
	Boost converter	Buck-boost converter	Flyback converter	Full-bridge converter
Electrical isolation	×	×	Via transformer	Via transformer
Conversion type	Step up	Step up/down	Step up/down based on the transformer turns ratio	Step up/down based on the transformer turns ratio
Power range	Low-medium	Low-medium	Low-medium	Medium-high
Complexity	Simple	Simple	Moderate	Complex
Efficiency	High	Moderate	Low	High
Cost	Low	Low-moderate	High	High
Electromagnetic compatibility	Low	Low	Moderate	High
Switching frequency	High	High	Moderate-high	High
Reliability	Vulnerable to single point of failure	Vulnerable to single point of failure	Moderate	High with reduced capacity

5.1. Non-isolated DC converters

Principally, non-isolated converters are extensively utilized in numerous applications involving low and medium DC voltages due to their affordability, simplicity, compact design, and ease of control [101, 102]. Typical examples of such converters are the conventional buck-boost converter (BBC)

[103], interleaved buck-boost converter (IBBC) [104], bidirectional buck-boost converter [105], and floating-interleaved buck-boost converter (FIBBC) [106].

Conventional BBCs are distinguished by their low cost and uncomplicated circuit connection. This augments their wide implementation in WEL-based power systems. However, such converters experience considerable ripples in output current, which can be mitigated by raising the inductor size or magnifying the switching frequency [102]. Nevertheless, increasing either of these parameters will inversely impact energy efficiency, as it will lead to higher core and switching losses. Another concern is that to attain a high step-up or step-down ratio, BBCs must operate at a significantly low duty cycle, which can potentially result in interrupted conduction mode. This directly affect the converter's output voltage connected to the WEL. Again, this issue is addressed by elevating the inductor rating leading to a higher loss, price, and size [103]. Moreover, conventional converters suffer also from reverse recovery power loss due to the diode's reverse recovery potential. Such loss is function of the initial current, operating temperature, and the change rate of the switching current [101]. Thus, a synchronous buck converter, an upgraded version of the conventional buck converter, is proposed in [107] to minimize the aforementioned loss. In this design, a power transistor replaces the freewheeling diode, as illustrated in Fig. 9.

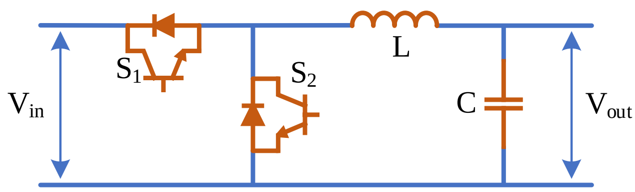


Fig. 9. Circuit diagram of synchronous buck converter

For the sake of obtaining a high step-down ratio, a quadratic buck converter is proposed in the literature [108]. In this configuration, two buck converters are serially connected through a single power transistor, as shown in Fig. 10. Since this type runs only with a single power switch, the converter lacks fault tolerance. Also, the power transistor encounters a high potential stress throughout the operation. Thus, the authors in [109] have introduced multiquadric buck converters to minimize the potential stress across the switches. Another technique to increase the step-down ratio is to use the tapped-inductor buck converter [110]. In this design, the conventional inductor is replaced by a tapped inductor with a single primary and single secondary winding, as depicted in Fig. 11. By this architecture, the step-down voltage ratio is controlled by changing the turns ratio of the tapped winding n_p/n_s along with the duty cycle D, as described in (10). Nonetheless, the winding leakage flux between both windings causes spikes across the switch.

$$\frac{V_{out}}{V_{in}} = \frac{D}{D + (1 + n_p/n_s)(1 - D)} \tag{10}$$

For the same reason, a switched inductor-switched capacitor buck converter is developed in [111] to magnify the voltage stepping ratio, as shown in Fig. 12. However, this design cannot guarantee continuous operation in faulty conditions as it only includes one power switch.

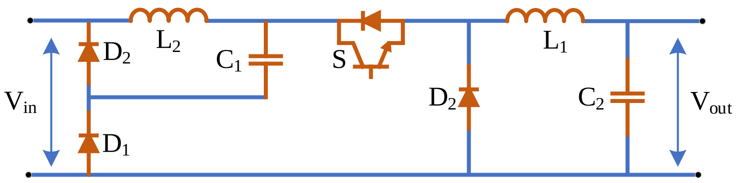


Fig. 10. Circuit diagram of quadratic buck converter

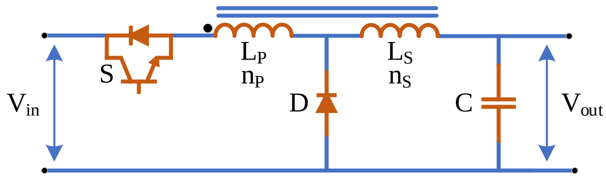


Fig. 11. Circuit diagram of tapped-inductor buck converter

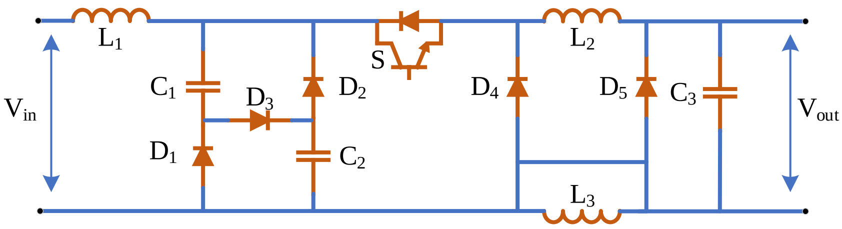


Fig. 12. Circuit diagram of switched inductor-capacitor buck converter

When aiming to amplify the delivered power, the IBBC and FIBBC are the best alternatives to the traditional BBC because the current is divided through separate legs. Basically, both configurations are formed by connecting multiple BBCs via a common DC bus. For instance, the 3-legs IBBC, whose circuit is shown in Fig. 13, offers optimal solution for minimizing output current distortion and magnifying energy efficiency [112]. Another merit is that the power delivered from/to a WEL/FC through IBBCs remains unaffected by the failure of a single power switch. Nevertheless, in the case of 3-legs IBBC, such a failure causes a 50% increase in current stresses on the unfaulty legs compared to the normal operation. This overstress, accompanied by excessive temperature, can severely affect the switches' reliability. Multi-leg IBBCs have also been studied in the literature for WEL/FC applications. For example, the authors in [113] designed a 1200W silicon-based Multi-leg IBBC for

FC operation. The results demonstrate a substantial reduction in current ripples by nearly 100%, along with an energy efficiency of approximately 90%, while operating at a switching frequency of 25 kHz.

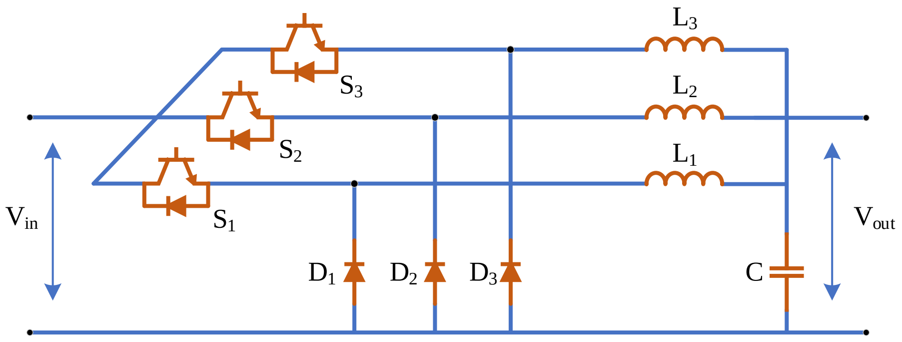


Fig. 13. Circuit diagram of 3-legs IBBC

5.2. Isolated DC converters

Isolated DC converters are the optimal choice for high-voltage WELs/FCs, as they incorporate an intermediate AC domain utilizing a high-frequency transformer, as illustrated in Fig. 14 [100]. Particularly, the transformer plays a vital role in ensuring a low voltage input and a low current to the output side converter [114]. The AC phase is considered as an over current protection stage for the FCs [115]. Practically, it can be composed of various configurations including half-bridges [116], full-bridges [117], or multi-port interleaved bridges [118]. Conversely, a diode rectifier along with a multi-stage voltage source inverter represent the DC phase of such converters. Generally, flyback [119], half-bridge [120], full-bridge [121], forward [122], and push-pull [120] are among the commercial versions of isolated converters. Specifically, the literature claims that the best appropriate types for FCs are the half and full-bridge converters due to their galvanic isolation, the high frequency of the transformer minimize its size, their high voltage stepping ratio, and their smooth switching cycle that improves their efficiency [122].

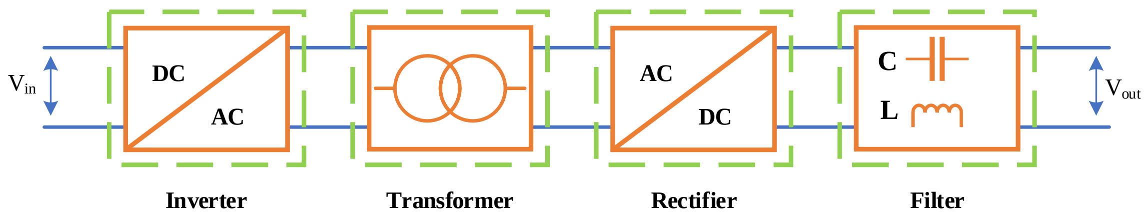


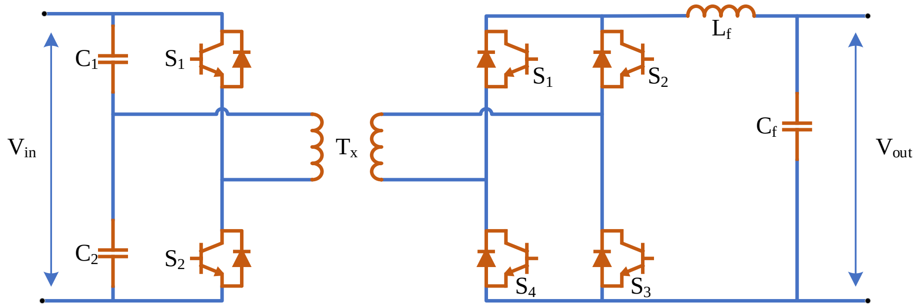
Fig. 14. Schematic configuration of isolated DC converter

For example, an isolated half-bridge DC converter engaged with a smooth switching technique is introduced in [123] for an WEL application to diminish the switching losses, as captured in Fig. 15(a). In fact, this configuration is characterized by regulation simplicity, and applicability to achieve significant voltage ratio which is a must for WEL/FC systems, as described in (11).

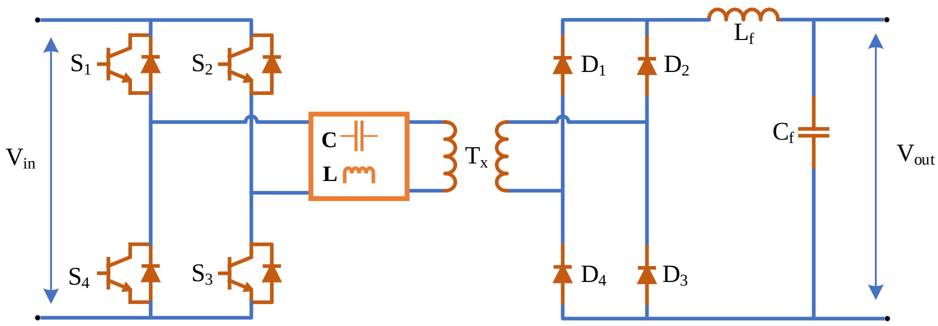
$$\frac{V_{out}}{V_{in}} = \frac{D}{2n} \tag{11}$$

where, n is the transformer turns ratio.

On the other hand, it experiences high power loss due to the large turns ratio of the transformer which causes high magnetic flux resulting in excessive leakage reactance. Besides, it lacks the ability to operate in the event of a switch failure. Furthermore, the reader can browse [124] for investigating the full-bridge version utilized in WEL systems whose circuit diagram is depicted in Fig. 15(b). Primarily, its main advantage over the half-bridge isolated converter is its superior conversion efficiency. Moreover, a filter can also be integrated with it to eliminate current spikes on the power electronics.



(a) Half-bridge DC converter



(b) Full-bridge DC converter

Fig. 15. Circuit diagram of isolated DC converters

6. Control methodologies of WELs/FCs DC converters

An essential factor in optimizing WEL/FC-based systems is the converter control methodology, which ensures precise and efficient DC converter operation. Controllers regulate output voltage and current, mitigate power oscillations, and prevent adverse effects on WEL/FC performance [21]. Moreover, optimal control design enhances energy efficiency, minimizes converter losses, and extends component lifespan. To reiterate, buck converters step down DC bus voltage to power WELs, while boost converters raise FC output voltage to the required DC level [84]. For clarification, Fig. 16 illustrates the integration of controllers with DC converters. Control methods vary by technique, including analytical (e.g., PID, root locus, lead-lag compensators), model-based (e.g., sliding mode, fractional order), and data-trained approaches (e.g., neural networks, fuzzy logic, model predictive control) [32]. However, only specific types have been recognized in the literature as effective tuners for DC converters in WELs/FCs-based power systems. Thus, the following subsections offer discussive illustrations on such types.

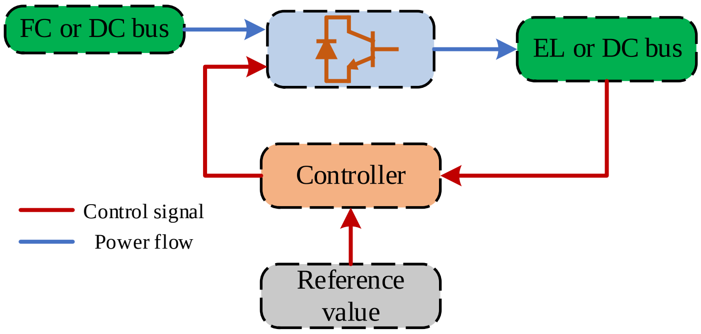
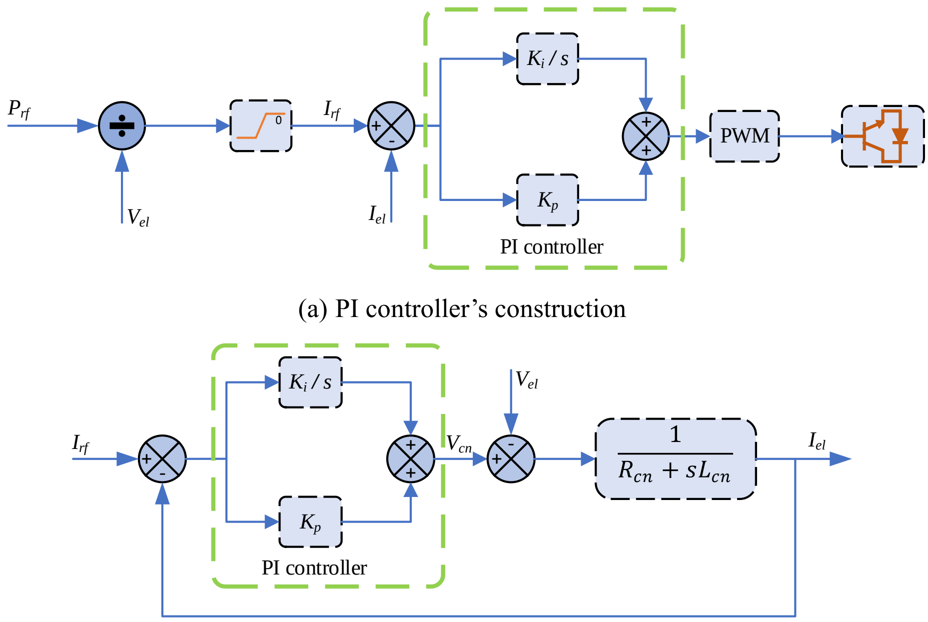


Fig. 16. Generic configuration of DC converter's controllers in WEL/FC-based networks

6.1. Proportional-integral controller

The proportional-integral (PI) controller is widely used due to its effectiveness and simple mathematical formulation. It operates by minimizing the deviation between the actual and desired values, combining two key components: the proportional term (k_p), which adjusts the output based on the current error, and the integral term (k_i), which accumulates the error over time to eliminate steady-state deviations [21, 84]. Accordingly, several studies have demonstrated the effectiveness of PI controllers in regulating the output voltage of DC converters, ensuring that WELs receive a consistent and appropriate power supply, even when the grid voltage fluctuates [32, 125].

In this regard, the authors in [126] proposed a novel PI tuner for an ALWEL-based network, as shown in Fig. 17(a). It's worth indicating that V_{el}, I_{el}, P_{rf}, and I_{rf} represent the WEL's actual voltage and current, as well as the desired preset power and current, respectively. On the other hand, R_{cn} and L_{cn} denote the buck converter's resistance and inductance, respectively. Additionally, they developed a tuning technique for the PI controller's parameters of the ALWEL, eliminating V_{el} by assuming it remains constant throughout the entire operation. They disregarded the internal dynamic response of the WEL by treating it as a linear resistor. Furthermore, an average switching approach is introduced for the WEL current control loop, as illustrated in Fig. 17(b). Finally, the authors assert that their design enhances the controllability of the DC link voltage by implementing the WEL current control as an inner control loop within the outer DC voltage control loop.



(a) PI controller's construction

(b) Small signal current control loop of WEL

Fig. 17. PI controller for WEL-based systems

Another contribution, as presented by the authors in [127], involved the development of two cascaded PI controllers to refine the current control signal more smoothly. Essentially, the inner loop regulates the WEL's current based on the reference signal generated by the outer loop, as revealed in Fig. 18. They employed the state-space representation to derive the transfer function of the WEL.

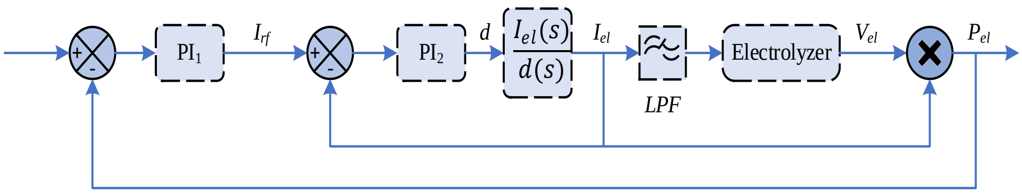


Fig. 18. Series PI controller for WEL-based systems

In contrast to previous efforts, the authors in [128] have taken into account the actual dynamic performance of the ALWEL. They applied control theory to model the WEL by using a step input and subsequently derived the corresponding second-order transfer function. Their proposed model is considered as an electrical circuit where it includes inductance L_{el} and capacitance C_{el}. These parameters represent the time delay due to a step input applied to ALWEL. However, L_{el} may be assumed zero for PEMWEL since it has a swift response compared to ALWEL. Physically, C_{el} defines the double-layer capacitance, R_m symbolizes the mass transport losses, and R_i refers to the nonlinear losses due to the material and external leads. The aforementioned state-space modelling, the proposed electrical model incorporates two state variables that characterize the controller's response, as described in (12) and (13) by neglecting R_{cn}.

$$(L_{el} - L_{cn})\frac{dI_{el}}{dt} = dV_{in} - V_{el} \tag{12}$$

$$C_{el}\frac{dV_{dl}}{dt} = I_{el} - \frac{V_{dl}}{R_m} \tag{13}$$

where, V_{in} and V_{dl} are the input voltage of the converter and the EL's electrical double layer voltage in (V), respectively.

As a result of (12) and (13), two PI controllers are necessary for both the outer voltage control and the inner current control in ALWEL. Nevertheless, only a single PI controller is employed in PEMWEL, as the electrical double layer is nearly neglected, thereby eliminating the need for the outer voltage control loop, as shown in Fig. 19.

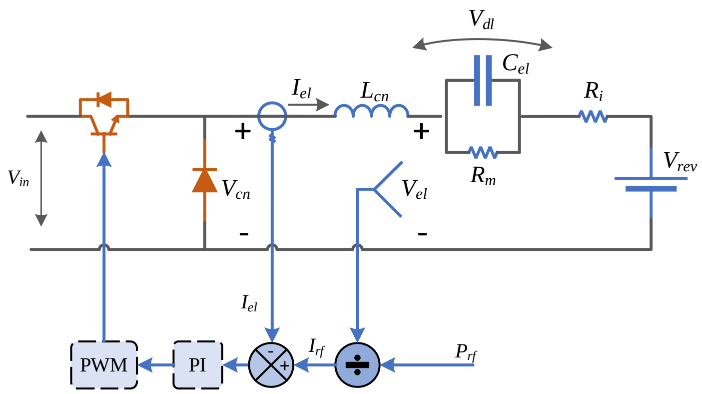


Fig. 19. PI controller for ALWEL based on control theory

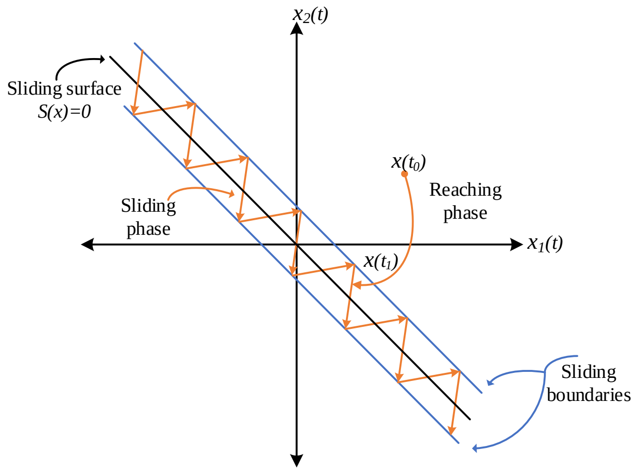
6.2. Sliding mode controller

Sliding mode control (SMC) is a nonlinear control technique that operates by forcing the system to follow a desired trajectory, known as a sliding surface or sliding manifold, in the state-space. The system is driven toward this surface using a high-gain control law, where it slides along the surface toward the desired equilibrium point, as revealed in Fig. 20(a). The main principle behind SMC is to switch control actions based on the system's state in relation to the sliding surface, allowing the system to converge to its target behaviour despite uncertainties or disturbances [129].

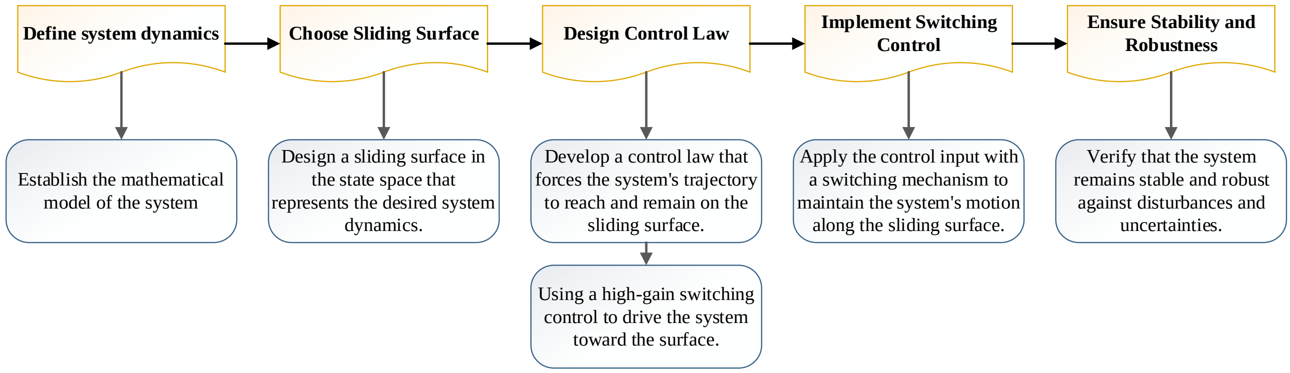
One of SMC's most significant advantages is its ability to handle systems with nonlinearities, unknown dynamics, and external disturbances, as concluded from its conventional structure seen in Fig. 20(b). However, SMC typically experiences chattering caused by the high-frequency switching in sliding mode, which can result in mechanical vibrations or excessive switching in power electronics [43,58]. Thus, recent SMC variants have been developed, like higher-order sliding mode control (HOSMC), terminal sliding mode control (TSMC), and super-twisting sliding mode control (STSMC) [130, 131]. In WEL-based systems, SMC provides precise control of DC converters by optimally regulating input voltage and current, maintaining efficient hydrogen generation. Thanks to its swift dynamic response, SMC can ensure system stability despite load variations and disturbances. Moreover, its capability to deal with heavy nonlinear systems, like WELs, magnifies its robustness in sustaining the desired operating scenarios. In this context, the reader is invited to visit [132] for investigating practical applications of SMC in WEL/FC-based systems.

6.3. Backstepping controller

Principally, backstepping control offers a systematic design approach that utilizes a series of virtual controllers to stabilize complex systems. Specifically, the backstepping controller is constructed step by step using a recursive procedure, which ensures stability at each stage. Hence, it outperforms conventional techniques in managing nonlinear behaviours and unwanted disturbances [133]. Accordingly, backstepping control has several applications in DC converters, where it accurately controls output voltage and current to minimize energy loss and enhance stability over a wide range of loading conditions [134]. Furthermore, due to its capability to handle abrupt system changes and parameter uncertainties, backstepping control can address additional integrated control targets, such as power management and current limitation. Thus, the backstepping tuner has been employed to address various control challenges in FC-based power systems. For example, a backstepping controller is proposed in [135] to ensure smooth tracking of the maximum allowable power generated by the PEMFC, thereby extending its operational lifetime.



(a) Typical trajectory of a standard SMC



(b) Practical steps for designing an SMC

Fig. 20. Basic structure and concept of SMC

6.4. Model predictive controller

The popularity of Model Predictive Control (MPC) in WEL/FC-based power systems arises from its effectiveness in managing multivariable control systems with constraints and optimizing performance in real-time applications [136]. Particularly, MPC can predict the future response of WEL/FC operating variables, such as voltage, current, and hydrogen production/consumption, by utilizing their dynamic model. It updates the control inputs based on a continuously optimized objective function, subject to practical constraints, such as power and hydrogen production/consumption boundaries. This promotes MPC in applications involving WELs/FCs linked to RESs, where unpredictable variations in power supply may occur. Its robustness and precision in predicting system responses within preset boundaries contribute to maximizing the efficiency of WELs/FCs, thereby extending their operational lifetime. Moreover, MPC can adapt to additional control objectives, including hydrogen storage limitations, downstream applications, and power network stability [137, 138].

Practically, an MPC comprises four principal phases: prediction technique, optimization methodology, receding horizon, and feedback. The prediction technique is employed to foresee the system's upcoming states, while the control task is handled by the optimizer to diminish the fitness function without violating the system's constraints. The receding horizon approach implements only the first control action from the optimized sequence, advancing the horizon with each time step. Finally, the model is updated according to the latest measured data using the feedback strategy. Fig. 21 illustrates the basic block diagram of a practical MPC, showing how these phases work together to achieve efficient control [139].

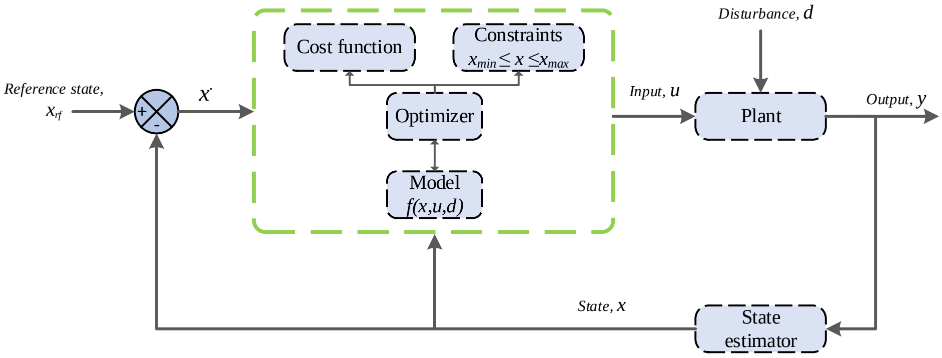


Fig. 21. Schematic block diagram of MPC

6.5. Fuzzy logic controller

Owing to its ability to address the vagueness and inaccuracy inherent in sophisticated dynamic systems, fuzzy logic controller (FLC) has recently recognized as a potent control method in WEL/FC-based systems. In contrast to conventional controllers, FLC doesn't necessitate a precise mathematical model of the system, rather, it utilizes human-like reasoning to derive decisions predicated on imprecise information [140]. Fig. 22 showcases the three primary phases of implementing an FLC: fuzzification, rule evaluation, and defuzzification. Initially, it transforms distinct inputs, such as error signals, into fuzzy sets that denote varying degrees of membership within linguistic categories. Subsequently, it analyses these inputs through the application of specific rules to ascertain the suitable control action. Ultimately, the fuzzy output is reverted back to a distinct control signal. This methodology is particularly efficacious for the management of intricate, nonlinear systems without the necessity for exact mathematical models [141].

In WEL-based systems where variables such as input power, voltage and current can fluctuate due to RESs, FLC is of great advantage. It allows smooth control of the operation of the WEL by adjusting parameters to maintain optimal hydrogen production under changing conditions. FLC is perfect for online applications because of its adaptability in handling nonlinearities and disturbances, which guarantees the WEL runs effectively and within safe bounds. To further improve system performance and reliability, FLC can be easily integrated with other control strategies, such as PI or MPC. Because of its versatility and durability, FLC is a preferred option for handling the complexity of WEL-based power systems, especially when integrating RESs [142].

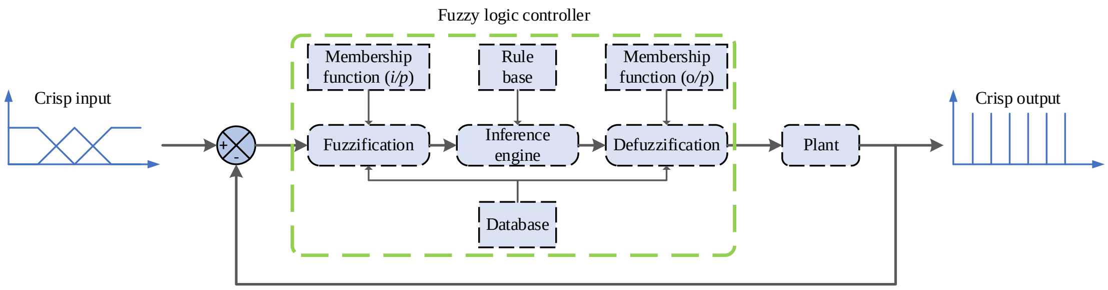


Fig. 22. Schematic block diagram of FLC

6.6. Neural network controller

Without any loops, a feedforward neural network (FNN) processes data in a single direction, from input to output. It is made up of an input layer that takes in data, one or more hidden layers that use activation functions and weighted transformations, and an output layer that generates the final prediction. In order to reduce errors during training and enable the network to learn intricate patterns and produce precise predictions, the network uses backpropagation to modify its weights. Over time, the network's performance can be enhanced and generalized through this process [143]. FNNs are employed to model and regulate the challenging behaviour of WELs/FCs because they resemble the human brain's capacity for learning and generalization from data. In these systems, particularly when connected to RESs, FNN can learn the best control strategies for managing variables like voltage, current, and hydrogen mass flowrate under variable load and power conditions. For example, a novel FNN-based maximum power point tracking controller is proposed in [144] to optimally tune the duty cycle of the DC converter connected to a PEMFC stack. The FC's voltage V_{fc} and current I_{fc} serve as the input data, while the converter's duty cycle represents the output. Fig. 23 illustrates the proposed FNN structure. The integration of the FNN with the DC converter ensures zero current ripple, optimizing the performance of the system.

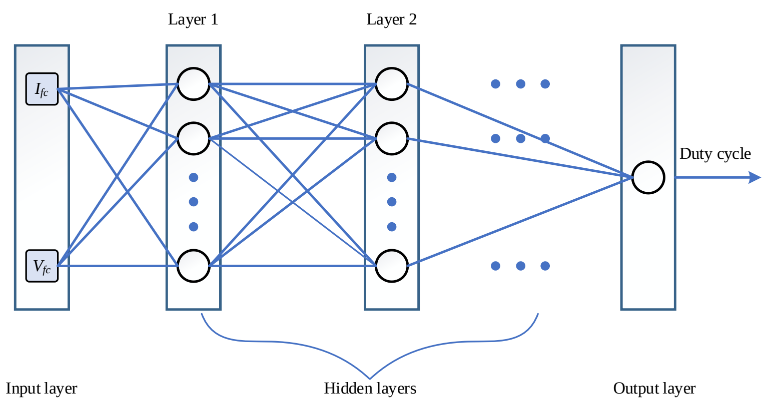


Fig. 23. Schematic architecture of FNN

6.7. Adaptive neuro-fuzzy inference controller

Fuzzy logic and neural networks are combined in an adaptive neuro-fuzzy inference system (ANFIS), which allows it to learn and adjust to changing operating conditions. It functions by transforming input data into fuzzy sets, assessing relationships, and optimizing the membership functions and rules using neural network learning. ANFIS modifies these settings during training in order to reduce errors. Lastly, it transforms fuzzily output values into sharp ones [145]. ANFIS is an optimal solution for dynamic and nonlinear systems because of its integration of neural learning and fuzzy logic, which enables it to adapt over time. Because of its flexibility, ANFIS can continuously modify control parameters to achieve the highest efficiency levels, thereby optimizing the performance of WEL/FC. ANFIS can be used in FC systems to control output power and increase cell lifetime, and in WEL systems, it aids in maintaining ideal hydrogen production rates under a range of load scenarios [146].

Finally, Table 6 offers a comprehensive comparison of the previously discussed control techniques in terms of operation theory, stability, learning and adaptation capabilities, ability to handle nonlinear systems, tuning effort, computational burden, and suitability for real-time applications. Furthermore, an extensive summary of the recent state-of-the-art literature on the practical application of these techniques in WEL/FC applications is thoroughly covered in Table 7.

Table 6. Detailed comparison of recent controllers in WEL/FC systems

Index \ Controller's type	PI	SMC	Backstepping	MPC	FNN	ANFIS
Control concept	Linear, proportional-integral feedback control	Discontinuous, nonlinear, sliding surface control	Recursive, nonlinear control	Optimization-based, predictive control	Neural network-based learning and prediction	Combination of fuzzy logic and neural networks
Nonlinear systems	Limited capability	Excellent for highly nonlinear systems	Excellent	Can manage nonlinearities via model-based prediction	Can approximate nonlinearities with sufficient training	Effectively deal with nonlinearities via hybrid approach
Tuning burden	Relatively easy, requires tuning of P and I gains	Requires designing the sliding surface and control law	Moderate, involves recursive design for each subsystem	Difficult, requires dynamic model and constraints tuning	High, involves designing and training the neural network	High, involves tuning both fuzzy rules and neural network parameters
Stability	Moderate robustness, affected by parameter variations	Very robust to system uncertainties	High robustness due to recursive stability checks	Robust when models and constraints are well-defined	Limited robustness, dependent on training data	Good robustness, adapts to uncertainties
Computational complexity	Low, easy to implement	Moderate to high, especially with chattering reduction	Moderate, step-by-step design increases complexity	High, due to solving optimization problems in real-time	High, requires training and backpropagation	High, requires both fuzzy system design and neural network training
Chattering	No	Prone to chattering but can be mitigated with modifications	No	No	No	No
Real-time application	Suitable	Challenging due to chattering and high-frequency switching	Suitable with proper design	Requires powerful processors for real-time implementation	Using fast processors and good training	Possible but computationally challenging
Learning ability	No	No	No	No learning, but adapts by predicting future response	Learns through data training	Adaptive via learning from data and fuzzy rules
Performance due to disturbances	Moderate, may require additional tuning	Excellent, due to high robustness	High, effectively compensates disturbances	Good, with proper model and constraint definition	Depends on training data; may require retraining	Good, adapts to disturbances through learning

Table 7. Summary of recent literature in control techniques for practical WEL/FC applications

Ref.	Grid mode	RES's type	EST	WEL		FC		DC converter		Control method	Remarks
				Type	Capacity (kW)	Type	Capacity (kW)	Type	DC bus voltage (V)		
[147]	Off	WT	×	PEM	0.4	×	×	Buck and full bridge	150-220	PI	The proposed integration of the buck and full-bridge converters effectively achieves a high conversion ratio, making it suitable for medium and high-power ELRs. Additionally, the PI controller successfully eliminates current ripples and maintains stability during sudden load variations.
[148]	Off	PV	BESS	NM	NM	×	×	Buck-boost	37	PI-enhanced FLC	The authors propose a novel MPPT for a standalone PV system using a PI-improved FLC. The suggested controller outperforms conventional incremental conductance-based MPPT by extracting the maximum PV power. Additionally, it ensures a stable DC bus voltage, regardless of variations in solar irradiance or load conditions.
[149]	Off	WT Tidal	BESS	NM	50	PEM	40	Traditional buck	600	HOSMC	A two-level control methodology is introduced for optimal energy management and MPPT of the RESs, while also stabilizing the DC bus voltage by regulating the power flow of the battery, FC, and WEL. The proposed HOSMC achieves a minimal steady-state error of 0.005% and an overshoot of 0.07%.
[150]	Off	×	BESS SESS	NM	1.5	NM	13	Traditional buck	400	STSMC	A modified STSMC is designed for optimal wireless power transfer by supressing windup impacts due to integral deviation accumulation and smoothing the transition

											to the desired current values. The grey wolf optimizer is utilized for optimal extraction of the controller's parameters. The proposed control method has the minimum settling and rise times of 0.4356 s and 0.0364, respectively.
[151]	Off	WT	BESS	NM	10	PEM	13	Traditional buck	700	TSMC	An upgraded version of global TSMC-based energy management system is developed based on the battery's state-of-charge and hydrogen level in the tank to enhance the battery and FC lifetime over diverse operating conditions. Moreover, the controller affirms its capability to regulate the DC bus due to sudden load or weather changes.
[152]	Off	PV	×	PEM	NM	×	×	Quadratic buck	37	SMC	The authors address the indirect coupling of PV and WEL through a DC converter using SMC to optimally tune its duty cycle. The findings reveal that energy utilization ramps up to 77.6% when employing the SMC for tuning the converter's duty cycle.
[153]	On	WT	BESS SESS	NM	NM	NM	NM	Traditional buck	400	SMC	In this attempt, an SMC is employed for optimal managing the power flow of grid-connected WT along with WEL, FC, BESS, and SESS seeking a stable power supply system for electric traction applications.
[154]	Off	×	×	PEM	0.4	×	×	Traditional buck	100-200	Backstepping TSMC	A novel application of adaptive backstepping TSMC for voltage regulation of the DC converter is addressed. Numerically, at unexpected variation of operational scenarios, the controller attains the lowest settling time and percentage overshoot of 0.025 and 17.5%, respectively.
[155]	Off	PV	BESS	×	×	Virtual	NM	Dual input triple output buck	30	Integral backstepping	The authors elaborate on designing an integral backstepping controller for extracting largest allowable PV power, stabilizing the common bus voltage, and controlling the battery's state-of-charge. For further validation, the stability of the proposed controller is evaluated using Lyapunov method.
[156]	Off	×	×	×	×	PEM	100	Buck/boost	12	Backstepping SMC	This work proposes a backstepping SMC for a standalone system comprising PEMFC stack feeding adjustable resistive load through buck/boost DC converter. The suggested controller significantly minimizes chattering of the traditional one, ensuring a stable operation regardless the injected disturbances.
[157]	Off	PV	×	AL	10	PEM	10	Buck/boost	300	Distributed economic MPC	This article introduces an innovative distributed mathematical modelling of the DC converters controlled by three separated controllers for optimal techno-economic operation of PV, FC, and WEL. Furthermore, the authors proposed a communication strategy for the three controllers to achieve supply-demand power balance, regulated DC bus voltage, and cost-effective operation.
[158]	Off	PV WT	BESS	AL	1	PEM	1	Bidirectional	230	MPC	A two-layer control approach is addressed in this work for a sustained power flow to the loads and an ensured high-quality for the microgrid's variables. Specifically, the MPC represents the supervisory control layer that determine the desired values for the primary control layer leading to zero error in the reference values. Besides, it ensures that FC, BESS and WEL operate safely within their practical constraints for extending their lifetime.
[159]	Off	PV WT	×	PEM	0.4	×	×	Stacked interleaved buck	100-200	Double-loop PI	The proposed controller of the stack interleaved buck DC converter precisely allocate the optimal power delivered to the PEMWEL along with stabilizing the converter output voltage and minimizing its output current ripples. Moreover, the authors have addressed the state space modelling of the converter, along with the dynamic modelling of the converter.
[160]	Off	PV	BESS SESS	PEM	1.26	PEM	1	Traditional buck Interleaved boost	80	PI	An isolated microgrid comprising PV, along with ESTs, supplying a DC load and hydrogen production system. A PI controller is utilized to regulate the inner current control loop.
[161]	Off	×	×	PEM	0.4	×	×	Three-level interleaved buck	100-200	PI	This attempt reveals optimal design of a PI controller relying on the small signal analysis of the three-level interleaved buck converter, enhanced by experimental setup. The introduced work ensures an accurate control of the produced hydrogen quantity for optimal DC bus voltage balancing in the presence of RESs.

[135]	Off	×	×	×	×	PEM	0.5	Four-phase interleaved boost	26	Backstepping STSMC	A novel control methodology is presented for tuning four-phase interleaved boost converter linked to PEMFC stack. Specifically, it involves backstepping controller for the inside loop, while STSMC is for the outside loop. The designed approach guarantees a stabilized DC bus voltage within diverse levels, robust capability of withstanding strong sudden disturbances, and effective suppression of the FC's current ripples.
[162]	On	PV WT	×	PEM	10000	×	×	Traditional buck	500	MPC	An innovative modelling of a grid-connected offshore hybrid RESs-based network is thoroughly discussed for optimal power dispatch between the grid and PEMWEL for cost-effective hydrogen generation. The MPC is applied to the WEL's buck converter, based on the allocated hydrogen production strategy, for optimal economical hydrogen production.
[163]	Off	PV	×	AL	10	×	×	Traditional buck	70	Centralized economic MPC	The proposed methodology engages the energy allocation system with the local feedback control for an optimal individual controller. The findings reveal that the centralized economic MPC outperforms the others in attaining the minimum rout mean square error between the desired and actual powers of 0.1267.
[164]	Off	PV WT	BESS	PEM	1	PEM	1	Traditional buck	NM	Economic MPC	The authors introduce a novel sizing technique involved with optimal energy management system based on an economic MPC. The studied problem is considered as a dual-level optimization task comprising an inner and outer control loop. Particularly, the optimal sizing of the RESs is tackled by the outer loop, while the inner loop optimally manages the energy flow for each component.
[165]	On	PV	BESS	PEM	3	PEM	3	Traditional buck	NM	Dynamic programming MPC	In order to overcome the inaccurate prediction of loads and RES's share and the slowness of the programming techniques over large timescale, the authors propose an energy management approach based on MPC and dynamic programming concepts. The outcomes show that a balanced power flow is achieved, the FC and BESS operate within rated power scales, and the error signals are almost brought to zero.
[166]	Off	WT	BESS	NM	NM	NM	NM	Traditional buck	NM	FNN	An FNN is proposed to optimally control the wind output power and the battery's state-of-charge by tunning the FC and WEL outputs according to the battery's parameters, such as charging/discharging energy. The suggested FNN controller optimally manages the battery's state-of-charge leading to improving its lifetime and significantly diminishes the transient time.
[167]	Off	WT	×	PEM	0.4	×	×	Three-level interleaved buck	100-200	Improved SMC	The key contribution of this work is utilizing a three-level interleaved buck DC converter which has an electrical withstand capability against switches failure, high voltage step-down ratio, and insignificant output current ripple. Additionally, the proposed controller experiences a swifter response and higher stability in case of parameters' uncertainties with respect to the conventional PI controller.
[168]	Off	PV WT	BESS	NM	10	NM	10	Traditional buck/boost	800	ANFIS	The authors proposed a control methodology base on ANFIS for the operation of a hybrid AC/DC microgrid. The DC bus is connected to PV, FC, and WEL, while the WT and BESS are linked to the AC bus. An interconnected converter is placed between the two buses to control the power exchange according to the DC bus voltage and AC bus frequency. The suggested controller succeeds in reducing the output power and voltage transients of the BESS and minimizing the voltage deviations at the AC bus at changeable loads.
[169]	Off	PV	BESS	×	×	PEM	6	Bidirectional buck/boost	500	ANFIS	The authors introduce an ANFIS-based methodology for controlling bidirectional buck/boost DC converters in an isolated DC microgrid. The findings signify the superiority of ANFIS compared to PI and FLC controllers in terms of achieving the minimum voltage overshoot of 10%.

[170]	Off	PV	BESS	×	×	PEM	1	Conventional boost	300	ANFIS	Alongside modelling the dynamic behaviour of PEMFCs, the authors propose an ANFIS-based MPPT tuner for a DC microgrid. The addressed controller optimizes the converter’s output voltage and current for enhancing the voltage stability.

7. Power system integration of WEL-based systems

7.1. WEL's applications in modern power systems

The rapid expansion of RESs in modern power systems has raised stability concerns due to their intermittent nature, especially in PV and WT systems [3, 171]. Unlike conventional power plants, RES output fluctuates with weather conditions, causing frequency and voltage instability [172, 173]. On the other hand, WELs offer a dual benefit, producing green hydrogen while providing ancillary grid services. By adjusting their operation, they help balance supply and demand, regulate frequency and voltage, and enhance grid resilience [26, 29-32]. Thus, the following subsections explore these services, emphasizing their role in optimizing power system performance and supporting a sustainable energy transition.

7.1.1. Frequency regulation

Maintaining a stable frequency is crucial for reliable operation and protecting connected equipment. Frequency fluctuations occur when supply and demand are unbalanced, causing deviations from the nominal 50 Hz or 60 Hz [174]. In response to these alternations, WELs help stabilize frequency by adjusting their power consumption. During over-generation, they increase hydrogen production by consuming excess electricity, reducing frequency to normal levels. Conversely, during under-generation, they decrease power consumption, freeing capacity to balance the grid, as shown in Fig. 24 [175, 176].

Moreover, WELs are scalable devices capable of adapting to several network configurations and sizes. For instance, in distribution systems where the integration of RESs is rapidly increasing, small-scale WELs can be deployed to provide secondary frequency control. Accordingly, an online simulation of engaging a generic front-end controlled 120 kW WEL for providing frequency compensation is reported in [29]. The findings highlight the capability of the PEMWEL to provide an immediate and appropriate response, thereby significantly reducing frequency errors. On the other hand, placing larger-scale WEL systems at key locations such as transmission hubs or substations can significantly enhance grid stability and frequency control over a larger area. By optimal situating these WELs at specific points in the transmission network, they can effectively stabilize grid frequency and address larger-scale disturbances. Their rapid response to varying grid conditions aids in mitigating fluctuations and reinforcing overall system reliability. In this context, the authors in [177] conducted an efficacy assessment of utilizing PEMWELs in conjunction with PEMFCs for primary frequency control. This evaluation was based on accurate forecast data derived from an actual grid scenario in the Netherlands for the year 2030. The outcomes affirm that PEM devices can effectively compensate frequency deviations with respect to conventional generators under identical reserve capacity.

However, there are major obstacles that hinder the huge penetration of WELs in power systems. For instance, the swift dynamic response still only characterizes specific WEL's types, such as PEMWELs [30]. Furthermore, the WELs' capital cost of installation and maintenance are still high. Thus, numerous research attempts are trying to tackle these problems individually [22].

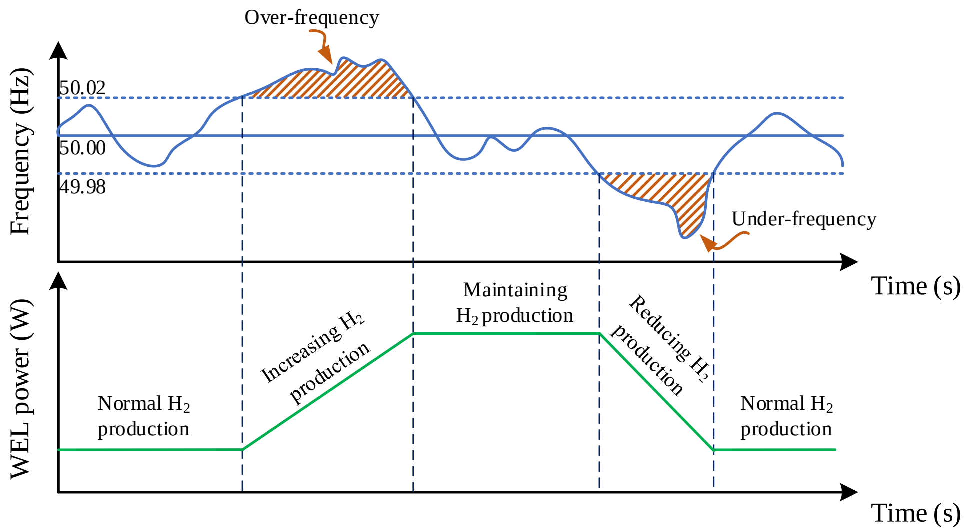


Fig. 24. WEL's contribution to frequency regulation

7.1.2. Voltage regulation

WELs also play a key role in voltage regulation, ensuring stable grid operation [178]. While traditionally considered DC loads consuming only active power, advancements in power electronics, such as grid-forming inverters, now enable WELs to control both active and reactive power [128, 179]. By adjusting inverter settings, WELs can absorb reactive power to lower voltage during overvoltage conditions or inject reactive power to raise voltage when needed. This regulation is achieved without disrupting hydrogen production, enhancing grid stability and flexibility [29, 32, 180].

Consequently, the authors in [181] propose a novel fleet control of grid-connected WELs to mitigate the penetration effect of PV into distribution systems. Their outcomes signify how the implemented fleet control can effectively reduce voltage oscillations, mitigate overvoltage issues, and stabilize the intermittent operation of control devices caused by the discontinuous nature of PV generation. This enhances overall grid stability and ensures smoother operation in systems.

Furthermore, the authors in [182] have fully defined the electrochemical model of a 0.5 MW AWEL involving its inherent dynamic response and nonlinearity. The studied WEL was connected to the grid through a phase-shifted full-bridge active front-end converter. The ultimate goal was to mitigate the voltage harmonic distortion and optimize the system behaviour under diverse operating conditions including severe voltage deviations. According to the simulation outcomes, the proposed system successfully minimized the harmonic contents to match the Danich electricity grid code.

Another attempt is presented in [183] for analysing the gride code requirements for linking mega-scale WEL to the power network. Specifically, the authors have introduced a detailed model for a grid-integrated WEL via triple-phase h-bridge converter. Moreover, they developed a low voltage ride-through methodology. The integrated system has proved its efficacy in supplying sufficient reactive power to compensate voltage deviations.

7.1.3. Network balancing

Basically, network balancing ensures equilibrium between electricity supply and demand [29]. WELs contribute by acting as flexible loads, adjusting power consumption based on grid conditions. During excess generation from PV and WT, WELs increase hydrogen production, preventing renewable curtailment and reducing grid overload [180]. On the other hand, during high demand or low RES output, WELs reduce or pause consumption, freeing power for critical loads and easing grid strain [184]. This flexibility helps stabilize supply-demand balance while enabling hydrogen storage for later energy or industrial use, enhancing profitability, resilience, and renewable integration [185].

In this regard, the authors in [186] discussed how WEL plants can maximize the profit share of a WT-driven hydrogen production system interconnected to gride services. Particularly, they simulated practical grid services along with actual data of the energy price and wind energy profile from certain countries like Norway, France, Spain, and Italy. The findings highlight the capability of WELs to maximize economic profit through participation in applicable grid services by utilizing the unexploited capacity of generated hydrogen.

7.1.4. Grid congestion

Grid congestion occurs when transmission or distribution networks are overloaded, restricting efficient power flow, especially in high-RES areas where infrastructure struggles to handle peak generation. Traditional solutions focus on grid expansion and modernization, while smart grids with ESTs offer real-time monitoring, demand-side management, and enhanced RES integration, providing a flexible approach to congestion management [3, 16, 29, 173].

WELs help alleviate congestion by acting as controllable loads in congestion-prone areas. They absorb surplus electricity, converting it into hydrogen for storage, preventing bottlenecks and renewable curtailment. Their dynamic operation allows real-time energy flow control, reducing grid strain while maximizing RES utilization. Additionally, WELs lower the need for costly infrastructure upgrades, making green energy integration more efficient and economically viable [128, 187].

In this context, the authors in [188] conducted a techno-economic assessment of a GHP system connected to a medium-voltage grid, supplemented with RESs. The case study was implemented in the Netherlands, considering price-aware electricity customers who adjust their consumption based on fluctuating electricity prices. Besides, the proposed economic-incentive optimization methodology involves single leader, grid utility, and several followers, including RESs' owners and electricity consumers. Specifically, the utility allocates the time-variant congestion tariffs at each individual busbar, accordingly, the followers adjust their power generation or dissipation to minimize the fitness function, which is the operational cost. Herein, WELs demonstrate their ability not only to adapt to dynamic pricing strategies but also to contribute to the grid's profit share. By responding to fluctuating electricity prices, WELs can optimize their operation, consuming energy when prices are low and generating hydrogen efficiently.

For the same purpose, the authors in [189] discussed how WELs could effectively support the network management, configuration, and congestion in Germany. They proposed a generalized optimization approach comprising electricity price's variations and congestion management for diverse operating modes and strategies. Particularly, different WELs' operating scenarios, distinct WELs' installed capacities, and various industrial carbon-neutrality strategies are comprehensively evaluated. The outcomes underscore that WELs demonstrate superior performance in addressing power congestion issues, particularly when implemented within a distributed-industries framework.

7.1.5. Black start

Black start refers to restoring power to a grid after a shutdown without external energy sources. Conventional power plants require external power to restart, making grid re-energization challenging. Black start-capable units, typically small self-sufficient generators, play a key role in this process [190]. Although WELs are still underexplored for black start, they can serve this function when coupled with hydrogen storage and FCs. Stored hydrogen can be converted back into electricity, supplying the initial power needed to restart larger generators and gradually restore the grid. Their independent operation, quick response, and sustainability make WELs valuable for grid recovery. As RES penetration increases, reliance on fossil-fuel-based black start resources may become impractical, positioning WELs as a green and efficient solution for power system restoration [191].

A systematic summary of recent attempts to utilize WELs in various power system applications is presented in Table 8. Several assessment criteria have been used to evaluate the effectiveness of WEL control methodologies in achieving goals such as frequency and voltage regulation, power balancing, and grid congestion management. Commonly employed criteria include the integral absolute error (IAE), integral time absolute error (ITAE), integral square error (ISE), integral time square error

(ITSE), and mean square error (MSE), all of which measure the deviation between reference and actual values for frequency, voltage, or power.

7.2. Advanced grid strategies for hydrogen integration

As concluded from the previous subsection, GHP via WELs presents significant benefits for power systems in terms of long-term energy storage and ancillary services. However, fully realizing these advantages requires not just technological innovation in WELs but also advanced grid management. Consequently, this section explores how flexible network topology, dynamic thermal rating (DTR), and other distributed energy resources (DERs) can synergize with GHP to enhance overall system reliability and resilience.

Flexible network topology adjusts circuit breakers and tie lines in real time to redistribute power flows resulting in congestion reduction and greater renewable penetration [192, 193]. Furthermore, DTR raises transmission limits based on real-time ambient conditions, allowing operators to channel otherwise-curtailed renewable energy toward WELs. This reduces hydrogen costs by boosting WEL utilization and deferring major infrastructure upgrades. Accordingly, short-term measures like topology reconfiguration and DTR pair effectively with hydrogen's longer-term buffering capacity which create a robust approach to handling intermittent RESs.

Other DERs, such as batteries, offer high-power but short-duration buffering, while hydrogen excels at longer timescales [194]. Hence, coordinating these technologies helps manage both immediate fluctuations and prolonged renewable deficits. For instance, batteries stabilize frequency or voltage quickly, while hydrogen addresses seasonal imbalances. On the other hand, DTR optimizes power flow so that grid operators can dispatch smoothly excess wind or solar to WEL.

Case studies show that network reconfiguration and DTR can jointly reduce wind curtailment, bolster grid stability, and improve economic returns [192-194]. Achieving this synergy, however, demands investments in sensor technology, real-time monitoring, and advanced control algorithms. Thus, ongoing research targets multi-objective optimizations that integrate WEL dispatch with grid reconfiguration to ensure cost-effectiveness and decarbonization without compromising reliability. As technology matures and costs decline, coupling hydrogen with flexible grids is poised to become a key pillar of future resilient power systems.

7.3. Hierarchical and distributed energy management in hybrid grids

The integration of GHP into modern power systems requires advanced energy management strategies to optimize efficiency and ensure stability. Thus, hierarchical and distributed energy management frameworks can play a key role in coordinating WELs, energy storage, and DERs in hybrid AC/DC grids [195, 196]. Particularly, hierarchical energy management operates across multiple levels. At the supervisory level, long-term hydrogen production is optimized based on market conditions and load forecasts. The network management layer balances AC/DC power flows, WELs, and storage assets to improve grid flexibility. Finally, device-level control autonomously adjusts power converters and WEL operation in real time [197]. This structured approach can optimize energy use, reduces congestion, and enhances grid resilience.

In contrast, distributed energy management shifts decision-making to interconnected control nodes, enhancing scalability and adaptability. Using cloud-edge-device cooperation, cloud intelligence performs system-wide optimization, edge computing manages local grid conditions, and device controllers can adjust hydrogen production in response to real-time demand [196]. This approach can improve direct DC coupling for WEL, reduces conversion losses, and ensures efficient RESs utilization.

A key advantage of hierarchical and distributed energy management frameworks is their ability to coordinate hydrogen storage with other energy assets. For example, the synergistic operation between hydrogen and electric vehicle (EV) fleets can enhance grid flexibility, as EVs can act as mobile storage units, supporting short-term demand response, while hydrogen provides deeper storage capabilities for extended grid balancing [197]. This layered approach to energy resource coordination strengthens grid resilience, particularly in networks with high renewable penetration.

Table 8. Summary of recent WEL's applications in power systems

Ref.	Applications				Technical specs					Controller	Computational specs		
	Frequency regulation	Voltage regulation	Grid balance	Grid congestion	Grid configuration	Conventional sources	RESs	ESTs	WEL/FC		Optimizer	Objective functions	Performance indices
[178]	✓	✓	×	×	Two-area	•Deisel •Thermal	•PV	×	✓	IPD with one plus integral	Tunicate search algorithm	•ISE	•Overshoot •Undershoot •Settling time
[174]	✓	×	×	×	Hybrid power systems	•Deisel	•PV •WT	•BESS •FESS	✓	Nonlinear PI	Dandelion optimizer	•IAE •ITAE •ISE •ITSE	•Overshoot •Undershoot •Settling time
[175]	✓	×	×	×	Multi-micro grid	•Deisel •Thermal	•PV •WT	•BESS	✓	Fractional-order fuzzy PID	Modified harris hawks algorithm	•ITAE	•Overshoot •Undershoot •Bode plot
[184]	✓	×	✓	×	Hybrid power systems	•Deisel	•WT	•BESS	✓	PID with filter	Genetic algorithm	•ITAE	•Overshoot •Undershoot •Settling time •Peak time
[176]	✓	×	×	×	Two-area	•Deisel •Thermal	•WT	•BESS •FESS	✓	I, PI, PID	Smell agent Optimizer	•ISE	•Overshoot •Undershoot •Settling time
[185]	✓	×	✓	×	Hybrid power systems	•Deisel	•PV •WT	•BESS •FESS	✓	PI	Grey wolf optimizer	•ITAE	•Overshoot •Undershoot •Steady-state error
[198]	✓	×	×	×	Two-area	×	•PV •WT	•BESS •FESS	✓	2-degree of freedom fuzzy PID	Modified multiverse algorithm	•IAE •ITAE •ISE	•Overshoot •Undershoot •Settling time
[199]	✓	×	×	×	Isolated microgrid	•Deisel •Biogas	•PV	•BESS	✓	Cascade double-input interval Type 2 FLC	Enhanced salp swarm optimizer	•ITAE	×
[200]	✓	×	×	×	Isolated microgrid	•Deisel	•PV •WT	•BESS •FESS	✓	Fractional order type-II fuzzy PID	Modified grey wolf optimizer	•ITAE	•Overshoot •Undershoot •Settling time
[201]	✓	×	×	×	Isolated microgrid	•Nuclear	×	•BESS	✓	PID	Ant colony optimizer	•IAE •ITAE •ISE	•Overshoot •Undershoot •Settling time
[187]	×	×	×	✓	On-grid	NM	NM	NM	✓	×	×	×	×
[202]	✓	×	×	×	On-grid	×	•PV	•BESS	✓	•Day-ahead model •Intra-day model	NM	Optimal operation schedule of WEL	×
[179]	✓	✓	×	×	Shipboard microgrid	•Deisel	•PV •WT	•BESS	✓	Time-varying fractional order PID	Improved sine cosine algorithm	•ISE	•Overshoot •Undershoot •Settling time

[203]	✓	×	×	×	Isolated microgrid	×	•WT	•BESS	✓	MPC	NM	•Frequency deviation	•Regulation time
[204]	✓	✓	×	×	Isolated microgrid	×	•PV •WT	•BESS	✓	Intillegent MPC	Neural network	•MSE	•Peak PV and WT ramp
[205]	✓	×	×	×	On-grid	×	•WT	×	✓	Dynamic frequency regulation	Analytical	×	•Frequency rate of change •Nadir •Steady-state error
[128]	✓	×	×	✓	On-grid	×	×	×	✓	PI	Analytical	×	×
[180]	✓	×	✓	×	Isolated microgrid	×	NM	×	✓	MPC	NM	•Frequency deviation	•Overshoot •settling time
[206]	✓	×	×	×	On-grid	×	×	×	✓	PI	NM	NM	•Overshoot •Nadir •Steady-state error
[207]	✓	✓	×	×	On-grid	×	•PV	•SESS	✓	PI	NM	NM	×
[208]	×	✓	×	×	Isolated microgrid	×	•WT	×	✓	Fractional-order PID	Enhanced firefly optimizer	•IAE	•Overshoot •settling time
[209]	✓	×	×	×	Two-area	Deisel	•PV	•BESS	✓	PID	Artificial neural network algorithm	•ITAE	•Overshoot •Undershoot •Settling time

8. Economic perspectives of GHP

Fundamentally, conducting a thorough economic feasibility assessment is a crucial step in determining the viability and practicality of any project [210]. In fact, the cost of GHP in power systems is influenced by several factors, making it a complex and multi-faceted topic. The cost is primarily driven by the price of electricity, which accounts for a significant portion of the total production cost, often ranging between 50-70%. The WEL's efficiency is another critical factor, as higher efficiency reduces energy consumption and, consequently, the cost of hydrogen. WEL's capital cost, which includes the cost of the equipment, installation, and maintenance, also plays a significant role. WEL's type (e.g., PEM, AL, or SO) affects both efficiency and capital costs, with PEMWELs typically having higher costs but better adaptability to variable renewable energy inputs [211-213].

In addition, there are several external elements affecting the overall cost of GHP. These include government policies, subsidies, and carbon pricing, which can incentivize or penalize certain energy production methods. Technological advancements in WELs and RESs, as well as grid infrastructure improvements, can also reduce costs over time. Moreover, the cost of transporting and storing hydrogen, which can vary depending on the distance and method used, plays a substantial role in determining the final cost to the end-user. Ultimately, the integration of green hydrogen in power systems is expected to become more cost competitive as renewable energy prices decline, technology improves, and economies of scale are achieved [214, 215].

Numerically, the levelized cost of hydrogen (LCOH) is a metric used to evaluate the overall cost of producing hydrogen over the lifetime of a project. It's similar to the levelized cost of electricity (LCOE) and provides an average cost per kilogram of hydrogen produced, accounting for all expenses such as capital investment, operation, maintenance, and fuel costs, as formulated in (14) [216-218].

$$LCOH = \frac{C_{cex} + \sum_{t=1}^{n}(C_{om}^{t} + C_{elc}^{t}) \times (1+r)^{-t}}{\sum_{t=1}^{n} M_{H}^{t} \times (1+r)^{-t}} \tag{14}$$

where, the capital expenditure, initial investment cost for the WEL system, ($) is represented by C_{cex}. C_{om}^{t} and C_{elc}^{t} are the operational and maintenance cost and electricity cost used for hydrogen production in year t, respectively. M_{H}^{t}, r, and t symbolize the amount of hydrogen produced in year t (kg), discount rate (the cost of capital or interest rate), and project lifetime (years), respectively. It's worth mentioning that load factor, stack degradation rates, and energy tariffs, especially if the WEL relies on intermittent renewables, are the key inputs for LCOH calculations.

In this context, several studies have focused on reducing the LCOH through the optimal design and configuration of WEL-based power systems. These efforts aim to enhance the economic viability of

GHP by optimizing system components, improving energy efficiency, and reducing overall costs. Table 9 summarizes some of the recent efforts in this regard.

Table 9. Analysis of published attempts to minimize hydrogen production costs

Ref.	Grid mode	RESs	ESTs	WEL				H_2 Tank capacity (kg)	Location	LCOH ($/kg)
				Type	Capacity (kW)	Capacity factor (%)	Efficiency (%)			
[219]	On	PV	BESS	PEM	900	NM	15.35 (Overall)	270	Canada	4.76*
[211]	Off	PV	BESS	PEM	NM	NM	90	10.97	Spain Italy	6.71-7.82*
[212]	Off	PV	×	PEM	NM	90	61	×	NM	6.22
[213]	Off	PV	×	AL	4500	20	NM	NM	Korea	9.55
			BESS			22	Graphed			11.67
[214]	Off	WT	×	AL	4800	NM	80	×	Germany	4.84*
[215]	Off	WT	BESS	NM	NM	NM	75	3375	China	3.073-3.155
[216]	On	PV	×	NM	30	10	<75	30	Turkey	1.78-3.40
[217]	Off	WT	BESS	AL	250	NM	85	2022	NM	33.70
[218]	Off	WT	BESS	NM	750	NM	59	900	Australia	28.10
[220]	Off	PV	×	PEM	1000	NM	NM	×	Poland	14.13-15.06*
[221]	Off	WT	×	PEM	185	NM	8.72 (Overall)	×	Badakhshan	3.887-10.827
[222]	Off	PV/WT	×	AL	7.5	NM	62.8	NM	Egypt	4.54-7.48
[223]	On	WT	×	PEM	3700-4400	60	85	11.45-12.75 (10^3)	Croatia	17.1-27.2
[224]	Off	PV/WT	BESS	PEM	250	NM	NM	700	Canada	21.9-37.7
[225]	Off	PV/WT	BESS	NM	1500	NM	76.9	2000	India	3.00-3.22
[226]	Off	PV	BESS	AL	70000	28	85	×	Australia	3.1
[227]	Off	WT	×	PEM	NM	NM	50.7	×	Algeria	6.1-6.8
[228]	On	PV	×	PEM/AL	62/49	NM	NM	×	Germany	6.83-8.10
[229]	On	PV	×	PEM	800	NM	NM	1200	Oman	6.8
[230]	Off	Solar thermal /Geothermal	×	PEM	NM	NM	NM	NM	Iran	NM
[231]	Off	WT	×	AL PEM SO	NM	97 97 97	NM NM NM	NM	Chile	1.78-2.45 2.61-3.47 3.52-4.11
[232]	Off	PV/WT	×	AL	7.5	NM	77	NM	Egypt	3.73-4.656

*Converted to $ (browse the article for the original currency).

"Overall" denotes that the value corresponds to the total efficiency of the GHP system, accounting for all contributing sources.

Beyond LCOH, other financial indicators, such as net present value (NPV), internal rate of return (IRR), and payback period, offer a broader investment perspective [233]. Specifically, NPV determines whether the discounted sum of future cash flows is positive or negative, IRR identifies the discount rate at which NPV is zero, thus reflecting project profitability, and the payback period estimates the time required to recoup initial expenditures. When used in conjunction with LCOH, these metrics capture project-specific risk tolerance, making the analysis more robust for stakeholders and potential investors.

On the other side, given the uncertainties involved, sensitivity analyses are often performed to identify how changes in parameters, such as electricity price, WEL capital expenditure, efficiency, and policy incentives, impact GHP feasibility [213]. Scenario analyses can also explore various market conditions or policy frameworks, illuminating how GHP economics might evolve under different assumptions (e.g., high vs. moderate renewable deployment). These methodologies help pinpoint cost drivers and guide strategic planning, risk mitigation, or policy-making efforts [234].

9. Conclusion and future insights

In this article, a thorough review is presented to emphasize the transformative potential of green hydrogen as an EST through the integration of WELs into modern power grids. A key aspect highlighted in this work is the significance of the electrochemical model of WELs in understanding their internal dynamics, which enables accurate performance predictions, effective control design, and the optimization of hydrogen production processes. Furthermore, WELs have demonstrated their potential to enhance grid stability and reliability as a result of their diverse applications, from frequency and voltage control to grid congestion management and black start capabilities. It's worth highlighting that PEMWELs have the fastest dynamic response, enabling rapid adaptation to grid demand fluctuations, real-time supply balancing, and mitigating intermittent RES impacts. On the contrary, ALWELs boast lower capital costs, extended lifespans, and reduced degradation rates, making them an excellent choice for large-scale capacity projects. Moreover, the review underscores the importance of advanced control techniques, such as PI, FLC, FNN, and ANFIS, for optimizing DC converters connected to WELs/FCs. With ongoing research efforts focused on reducing hydrogen production costs, the future of green hydrogen in energy systems appears promising. This review not only sheds light on current technological advancements but also paves the way for future innovations in sustainable energy systems.

Herein, various future perspectives are presented to accelerate the shift towards GHP systems, aimed at enhancing power system stability and facilitating the large-scale penetration of RESs.

1. Enhancing the precision of WEL mathematical models can lead to more accurate real-time operations and control strategies. Accordingly, novel mathematical models shall be developed to combine the whole operation aspects of GHP system, including hydrogen fluid dynamics in pipelines and storage medium.
2. Future advancements in WEL efficiency can significantly lower hydrogen production costs and enhance their role in power systems. For instance, developing more efficient and durable catalysts, such as using platinum-group metals or non-precious metal alternatives, can reduce energy losses and enhance reaction rates during electrolysis. GHP efficiency can also be enhanced by further

developments in PEM and AEM for augmenting ion conductivity. Moreover, better utilization of the generated heat during hydrogen production phase can improve the overall efficiency by directing it to preheat water or serve other thermal processes.

3. The integration between advanced converters topologies and control approaches can optimize power system stability. For example, the concept of grid-forming converters can provide ancillary services to power systems, like frequency and voltage regulation due to their rapid response to power fluctuations. Thus, they can optimally synchronize the hydrogen production with the grid's demands.
4. Recent evolution of AI-based controllers can further facilitate the utilization of GHP systems in dynamic grid support. Particularly, different machine learning control techniques, such as supervised learning (SL), unsupervised learning (UL), reinforcement learning (RL), and deep learning (DL), can significantly enhance the rapid integration of WELs. SL algorithms can predict energy demand patterns according to recorded historical data, while UL models determine the operation characteristics and abnormalities in WEL performance. Besides, RL techniques support dynamic operation of WELs in response to power oscillations by offering on-time decision-making capabilities. Lastly, DL approaches are appropriate for complex analyses of large datasets regarding GHP processes.

Conflicts of interest

There is no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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