Renewable and Sustainable Energy Reviews 152 (2021) 111628

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications

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A R T I C L E I N F O

Keywords:
Renewable hydrogen
Stationary applications
Fuel cell
Energy storage
Technical feasibility
Cost-competitiveness

A B S T R A C T

The exponentially growing contribution of renewable energy sources in the electricity mix requires large systems for energy storage to tackle resources intermittency. In this context, the technologies for hydrogen production offer a clean and versatile alternative to boost renewables penetration and energy security. Hydrogen production as a strategy for the decarbonization of the energy sources mix has been investigated since the beginning of the 1990s. The stationary sector, i.e. all parts of the economy excluding the transportation sector, accounts for almost three-quarters of greenhouse gases (GHG) emissions (mass of CO_2-eq) in the world associated with power generation. While several publications focus on the hybridization of renewables with traditional energy storage systems or in different pathways of hydrogen use (mainly power-to-gas), this study provides an insightful analysis of the state of art and evolution of renewable hydrogen-based systems (RHS) to power the stationary sector. The analysis started with a thorough review of RHS deployments for power-to-power stationary applications, such as in power generation, industry, residence, commercial building, and critical infrastructure. Then, a detailed evaluation of relevant techno-economic parameters such as levelized cost of energy (LCOE), hydrogen roundtrip efficiency (HRE), loss of power supply probability (LPSP), self-sufficiency ratio (SSR), or renewable fraction (f_{RES}) is provided. Subsequently, lab-scale plants and pilot projects together with current market trends and commercial uptake of RHS and fuel cell systems are examined. Finally, the future techno-economic barriers and challenges for short and medium-term deployment of RHS are identified and discussed.

1. Introduction

Greenhouse gases (GHG) reduction is in the spotlight since the end of the XX century. Thus, an international response is being coordinated to cut down global emissions and limiting the increase in the global average temperature to 2 °C above pre-industrial levels [1–3]. The use of hydrogen is a proven alternative for the mitigation of global warming and comply with the United Nations Sustainable Development Goals. Moreover, its large-scale hybridization with Renewable Energy Sources (RES) represents a clean and sustainable solution to boost the required energy transition [4,5].

Historically, hydrogen has been considered as a valuable commodity gas and a chemical feedstock mostly in oil refining and for the production of fertilizers [6]. Nevertheless, it is also a clean and flexible energy carrier produced from primary energy sources, chemicals with hydrogen atom, e.g., methane, water, or also as a by-product of chlor-alkali plants. Moreover, there are other novel methods for hydrogen production being developed that use different sources for its generation: fossil fuels [7,8], biomass [9], wastes [10,11], bacteria [12], etc. Hydrogen can enhance the flexibility of the energy system matching energy supply to demand profiles [13]. Furthermore, it is time and location shifting: it allows from daily to seasonal storage, enabling local and global distribution. Additionally, its use is not restricted to electricity generation [14].

Hydrogen hybridization makes renewables contribution even more significant, avoiding the existing mismatch between demand and supply because of wind and solar resources intermittency [15]. It also enables sector coupling, allowing the conversion of generated power into different useable forms. This hybridization also permits energy storage through hydrogen and its distribution for every end-user [16]. The different ways of integrating hydrogen and RES across the energy sectors can be classified as follows:

- Power-to-power: water electrolysis transforms electricity into hydrogen, which is stored and re-electrified when needed using a fuel cell (FC). Hydrogen can be also used to run combined cycle gas turbines.

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https://doi.org/10.1016/j.rser.2021.111628
Received 28 April 2021; Received in revised form 4 August 2021; Accepted 27 August 2021
Available online 13 October 2021

Abbreviations

AC	Alternating Current
ACAES	Adiabatic Compressed Air Energy Storage
Bat	Battery
Bio	Biomass
BoP	Balance of Plant
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
$C_{ann,tot}$	Total annualized cost of the system, US$
CCSU	Carbon capture, storage, and utilization
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DC	Direct Current
DG	Diesel Generator
DMFC	Direct Methanol Fuel Cell
Eff	Efficiency
$E_{gen}(t)$	Generated energy at t period, kWh
$E_{grid,imp}$	Total imported energy from the grid, kWh
EL	Electrolyzer
E_{load}	Total consumed energy by the load, kWh
$E_{load}(t)$	Consumed energy by the load at t period, kWh
EMS	Energy Management Strategy
$E_{non,RES}$	Total non-renewable consumed energy by the load, kWh
ESS	Energy Storage System
FC	Fuel Cell
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
f_{RES}	Renewable fraction, %
GHG	Greenhouse gases
H_2	Hydrogen
HD	Hydraulic
HHV	High Heating Value
HRE	Hydrogen Roundtrip Efficiency, %
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LAES	Liquid Air Energy Storage
LCOE	Levelized Cost of Energy, US$/kWh
LHV	Lower Heating Value
LPSP	Loss of Power Supply Probability, %
MCFC	Molten Carbonate Fuel Cell
mCHP	micro-Combined Heat and Power
MPPT	Maximum Power Point Tracking
NH_3	Ammonia
NPC	Net Present Cost
NZEB	Nearly Zero Emissions Buildings
Off-G	Off-Grid
OPEX	Operational Expenditures
PAFC	Phosphoric Acid Fuel Cell
PCM	Phase Change Material
PEMFC	Proton Exchange Membrane Fuel Cell
PHS	Pumped Hydro Storage
PV	Photovoltaic
R&D	Research and Development
RCS	Regulation, codes and standards
Ref	Reference
RES	Renewable Energy Sources
RHS	Renewable Hydrogen-based Systems
RODP	Reverse Osmosis Desalination Plant
rSOFC	reversible - Solid Oxide Fuel Cell
SC	Supercapacitor
SMEs	Small-Medium Enterprises
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SSR	Self-sufficiency ratio, %
STC	Solar Thermal Collector
StH_2	Stored Hydrogen
TCS	Thermochemical Storage
TD	Tidal
TRL	Technology Readiness Level
UAE	United Arab Emirates
UK	United Kingdom
USA	United States of America
WT	Wind Turbine
WWTP	Wastewater treatment plant
η_{EL}	Electrolyzer efficiency, %
η_{FC}	Fuel cell efficiency, %

- Power-to-gas: electricity is converted to hydrogen via electrolysis. This hydrogen can be either directly transported, distributed, and stored, blended in the natural gas grid, or transformed into synthetic methane after a methanation step, needing, in this case, a low-cost carbon dioxide (CO_2) source [17,18].
- Power-to-fuel: electrolysis transforms electricity into hydrogen, which can be used as a fuel for FCEVs in the transportation sector. Hydrogen can also be converted into ammonia (NH_3) to be used as a fuel for ships, but it is a non-stationary application [19].
- Power-to-feedstock: transforms electricity to hydrogen for its usage as feedstock and to produce chemical compounds or synthetic fuels [20–22].

As for 2020, 75% of global GHG emissions (around 28.2 billion tons of CO_2-eq) associated with power generation [23] came from stationary applications according to the International Renewable Energy Agency (IRENA) [24]. Now, the most commonly employed fossil fuels for power generation are coal (0.93–1.05 kg CO_2-eq/kWh), natural gas (0.55 kg CO_2-eq/kWh), LPG (0.62 kg CO_2-eq/kWh), gasoline (0.69 kg CO_2-eq/kWh) and diesel (0.73 kg CO_2-eq/kWh) [25]. The carbon intensity associated to power generation in each country or stationary application depends on the kind and amount of fossil fuels used. For example, in the European Union, Sweden produces the cleanest energy (0.13 kg CO2-eq/kWh) due to its high penetration of wind and hydro power, while Poland has emissions of 0.73 kg CO2-eq/kWh due to the majority contribution of coal-fired power plants [26]. Therefore, it is necessary to raise the penetration of renewable energy sources in power generation. Specifically, the IRENA estimates that 94% of pollutants reduction will come from RES deployment and improvement measures in energy efficiency, needing an accelerated uptake of renewables [13]. Consequently, they are experiencing exponential growth, achieving a total capacity of over 2500 GW of RES installed globally in 2020 [27]. Nevertheless, this increase is not enough to achieve the target reduction of GHG emissions as energy demand is growing too. Currently, RES share only contributes to 10% of global final energy consumption, being necessary to increase this share three to six-fold by 2050 to secure Paris agreement goals [4], so further measures need to be taken [28].

Accordingly, several countries focus R&D activities on the deployment of hydrogen as the enabler of a clean energy system [29,30] by releasing different strategies and roadmaps with the support of manufacturers and hydrogen associations to decarbonize the stationary sector [31,32]. Based on the existing technical literature, this work classifies hydrogen consumption into four stationary applications: Large-scale power generation, industrial facilities, residential buildings, and different infrastructures. Table 1 gathers current and future activities on RES and renewable hydrogen-based systems (RHS) for stationary

Table 1
International strategies for RHS deployment in the stationary sector.

Continent/Country	RES	Stationary applications
Europe [16,33]	- RES use at EU and imported from mid-East and North Africa (2030).	- 40 GW EL capacity across EU (2030). - 40 GW EL capacity in bordering regions with 32.5 GW capacity for hydrogen exportation (2030). - New hydrogen and natural gas infrastructure upgrade for green hydrogen distribution. Large storage in salt caverns.
Germany [34]	- 20 TWh RES for green hydrogen production (2030). - Additional 5 GW RES capacity (2040).	- 5 GW EL capacity to cover 100 TWh power generation (2030). - 100 TWh green hydrogen capacity for steelmaking, refineries, and ammonia production (2050). - Utilization of mCHP units and RHS for domestic purposes with subsidies for end-users.
France [35]	- 40% RES production with shares up to 70% (2030).	- 1 GW EL capacity (2030). - Hydrogen blending equivalent to 1–2 TWh needs (2030). - 12% hydrogen contribution to cover energy demands from buildings (2050). - 10% hydrogen contribution to cover energy demands from industry (2050). - Large-scale projects for green steelmaking.
UK [36–38]	- 30 GW offshore wind (2030)	- 10,000 mCHP units for residential and buildings (2025). - More than 100 MW of large FC systems (2025). - Ongoing projects for 20% hydrogen blending in the natural gas grid. - Net-zero industrial clusters (2040).
Spain [39,40]	- 100% RES generation and 97% consumed by end-users (2050).	- 4 GW EL capacity as close as possible to end-users (2030). - 25% green hydrogen as commodity and energy carrier (2030). - Passive refurbishment and RHS deployment for old building stock. NZEB concept for new buildings.
Portugal [41,42]	- 80% RES in the electricity sector and 47% in final energy consumption (2030)	- 2 GW EL capacity installed by 2030. - 5% green hydrogen in industry sector consumption. - 15% hydrogen injection in natural gas network.
North America		
USA [43,44]	- RHS for 100% green energy (2050).	- Minimum 20% hydrogen blending in the natural gas grid in combination with 100% hydrogen networks. - 100% green hydrogen and/or hydrogen through CCSU for industry CHP, steelmaking, refineries, and biofuels.
Canada [45]	- 67% RES and 82% low-carbon intensity energy (RES and nuclear)	- 30% of final energy delivered by hydrogen FC systems and combined cycle turbines (2050). - Hydrogen 86% by volume of fuel supplied through blending and dedicated network (2050). - Green hydrogen exports to the USA, Japan, South Korea, China, and EU.
Asia		
Japan [15,46–48]	- RES and 17% energy conservation to cover 40% of electricity demands (2030).	- 5.3 million mCHP units for the residential and buildings sector (2050). - Large pilot projects for hydrogen ecosystem development. - Establishment of green hydrogen shipping routes in the Pacific (Australia, Brunei, USA, Canada, Chile, etc.).
South Korea [49–51]	- Nuclear phase-out, 20% RES production (2030)	- Over 300 MW stationary FC capacity. - 60 TWh capacity for power generation through FC systems and hydrogen combined cycle turbines (2050). - 20,000 mCHP units and 120 TWh capacity for buildings (2050) - 37.5 TWh capacity with industrial purposes.
China [52,53]	- Accounts for almost 30% RES capacity globally.	- RHS to reduce energy curtailments due to great distances between production and consumption areas. - Multi-MW pilot projects for power generation and district heating.
Oceania		
Australia [54,55]	- 11% of Australia suitable for green hydrogen production.	- GW-scale projects for power generation (2030). - RHS with off-grid purposes (2030). - Green hydrogen and commodities production/exports (2030).
Other countries with broad hydrogen-RES potential [15]	- Chile → High solar (Atacama Desert) and wind potential (Patagonia region). - Middle East countries → rich countries (Saudi Arabia, UAE, Qatar) with massive PV potential.	

applications of the most committed countries in the deployment of hydrogen technologies.

Several works analyze and report the potential benefits of RES hybridization with different traditional storage methods like pumped hydro or compressed air [56] and optimization methodologies [57,58]. Other authors approach power-to-gas [59–61], power-to-fuel [62] or power-to-x projects (referring to every hydrogen use pathway) [63]. However, there are few reported studies of hydrogen FC systems and their hybridization with renewable energies to decarbonize stationary applications [64]. Therefore, this manuscript provides an in-depth review of RHS and their deployment in this sector.

This study explores and review the recent technical literature about RES, ESS, power-to-gas hydrogen generation, stationary applications of RHS, and power retrieval by FC technology. These components are integrated into many different topologies of hydrogen, carbon dioxide, and renewable power flow. A tabular techno-economic analysis presents the existing literature organized by configurations, size, power capacity, electrolyzer technology and RHS application type for the stationary sector [65,66]. Completing the analysis of the theme from a comprehensive perspective, a brief overview presents the global market and the main suppliers of RHS technology.

Hydrogen use as an energy carrier is relatively new. Therefore, different barriers apart from techno-economic boundaries arise to achieve broader deployment of hybrid systems. Thus, this article evaluates existing barriers and drawbacks (like current legal framework, environmental impact of hybrid systems, required infrastructure, safety concerns, and societal factors) and proposes further actions to reach the goal of decarbonization of the stationary sector. Finally, the most relevant outcomes obtained through the analysis of RHS are discussed.

2. Renewable hydrogen-based systems

A fast and wide deployment of renewable power generation, transmission, distribution and storage is a critical element in the strategy for decarbonization of the global economy in light of the GHG emission targets by 2050. Particularly, photovoltaic panels (PV panels) and wind turbines (WT) are the main renewable alternatives to slow down GHG emissions in the stationary sector. As for 2019, RES represent 72% of the total new capacity additions (considering both RES and fossil fuel-based power systems), being wind and solar power 90% of this newly installed renewable volume [27]. The highest PV power potential is reached in the tropics (corresponding to the north and south of Africa, Australia, and the Middle East) and desert areas of China, and Mongolia, while wind power densities increase with the latitude.

Concerning technology development, the knowledge collected over the years has led to a significant cost reduction of both technologies. PV CAPEX is below 1000 US$/kWp in almost 70% of the PV market [67], reaching a levelized cost of energy (LCOE) of 0.057 US$/kWh during 1st half of 2019 [68]. According to the US Department of Energy, wind LCOE will drop between 24% and 30% for onshore and both fixed-bottom and floating offshore technologies. Larger and developed rotors, taller towers, economies of scale, durability, reliability, and financing costs reduction are the main cost drivers [69].

Nevertheless, RES cannot operate on their own. The intermittency and shifting nature of solar, wind, or water renewable resources make it indispensable to couple them with dispatchable backup power generation or energy storage systems (ESS) to mimic baseload and load following power supply. In this sense, different ESS have been developed and tested across the years (pumped water, batteries, compressed air, flywheels, supercapacitors, thermal storage, etc.) [70]. Although these traditional ESS are fully developed and cost-competitive, they present different drawbacks such as large area requirements, negative environmental impact, materials availability, etc. [71]. In such a way, hydrogen technologies offer an environmentally friendly and flexible solution for energy storage, being adaptive and feasible for bulk energy quantities and small backup systems, with fast response time and full load operating times over 12 h as depicted in Fig. 1.

The hybridization of hydrogen and renewables will enable the mitigation of GHG emissions in different stationary applications with high pollution indexes such as power system plants, industry, residential, and building sectors. Besides, hydrogen versatility makes it appropriate to be coupled with other ESS such as batteries or supercapacitors. These ESS are usually employed for energy short-term storage, whilst hydrogen affords energy-saving seasonally. Hydrogen technologies can operate in standalone or grid-connected systems with or without fossil fuels-based backup generators like diesel generators (DG). In Fig. 2, we show the typical RHS power supply chain for stationary applications.

Renewable energies like solar, wind, hydraulic, geothermal, tidal, and biomass (accounted as renewable due to its feedstock carbon neutrality) are considered primary power supply sources. The RES surpluses are then employed to charge the energy storage system (consisting of batteries, supercapacitors, etc.) and to run the hydrogen chain: the electrolyzer uses the energy to generate hydrogen that is stored in vessels, pressurized tanks (needing an intermediate compressor), salt caverns, etc. The stored energy is released via direct electricity or hydrogen re-electrification in a fuel cell system when renewable energy is not enough to cover the demand. Furthermore, diesel generators and grid connections can be used as dispatchable backup energy sources to avoid power shortage, but they may imply CO_2 emissions. Microgrids with properly sized RHS and grid-tied converters may be remunerated for back feeding the power utility grid in compliance with the local legislation for self-consumption. Finally, hybrid systems are particularly interesting in remote areas with limited or no access to the grid.

The diversity of the stationary applications implies a wide range of hybrid systems sizes and configurations depending on renewables availability. From small backup installations to multi-MW power systems, RHS represent a reliable alternative to cut down CO_2 emissions. Focusing on the configuration, these systems are classified in this work in binary (one RES and one FC), ternary (two RES and one FC), or multi-source systems (three or more RES and one FC) as depicted in Fig. 3.

Three main categories are considered depending on the backup system employed, which are off-grid (Off-G) for standalone and self-sufficient systems, diesel generator (DG) for those including a fossil

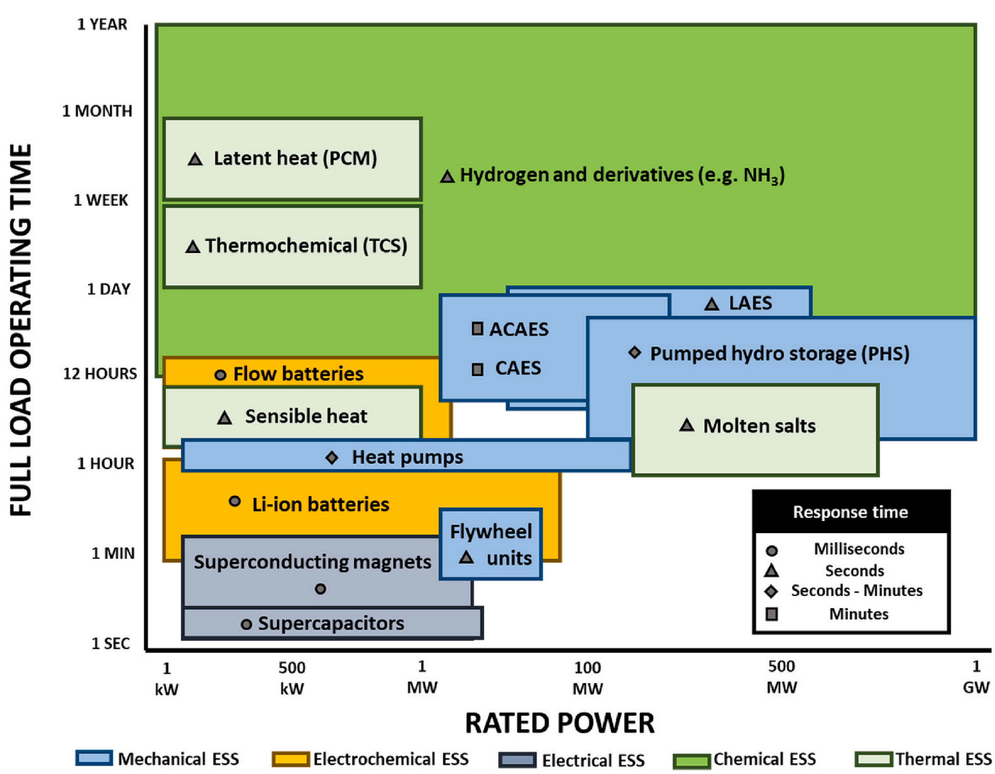

Fig. 1. Operating parameters of different energy storage systems. Abbreviations: ACAES (Adiabatic Compressed Air Energy Storage), CAES (Compressed Air Energy Storage), LAES (Liquid Air Energy Storage). Adapted from Ref. [71].

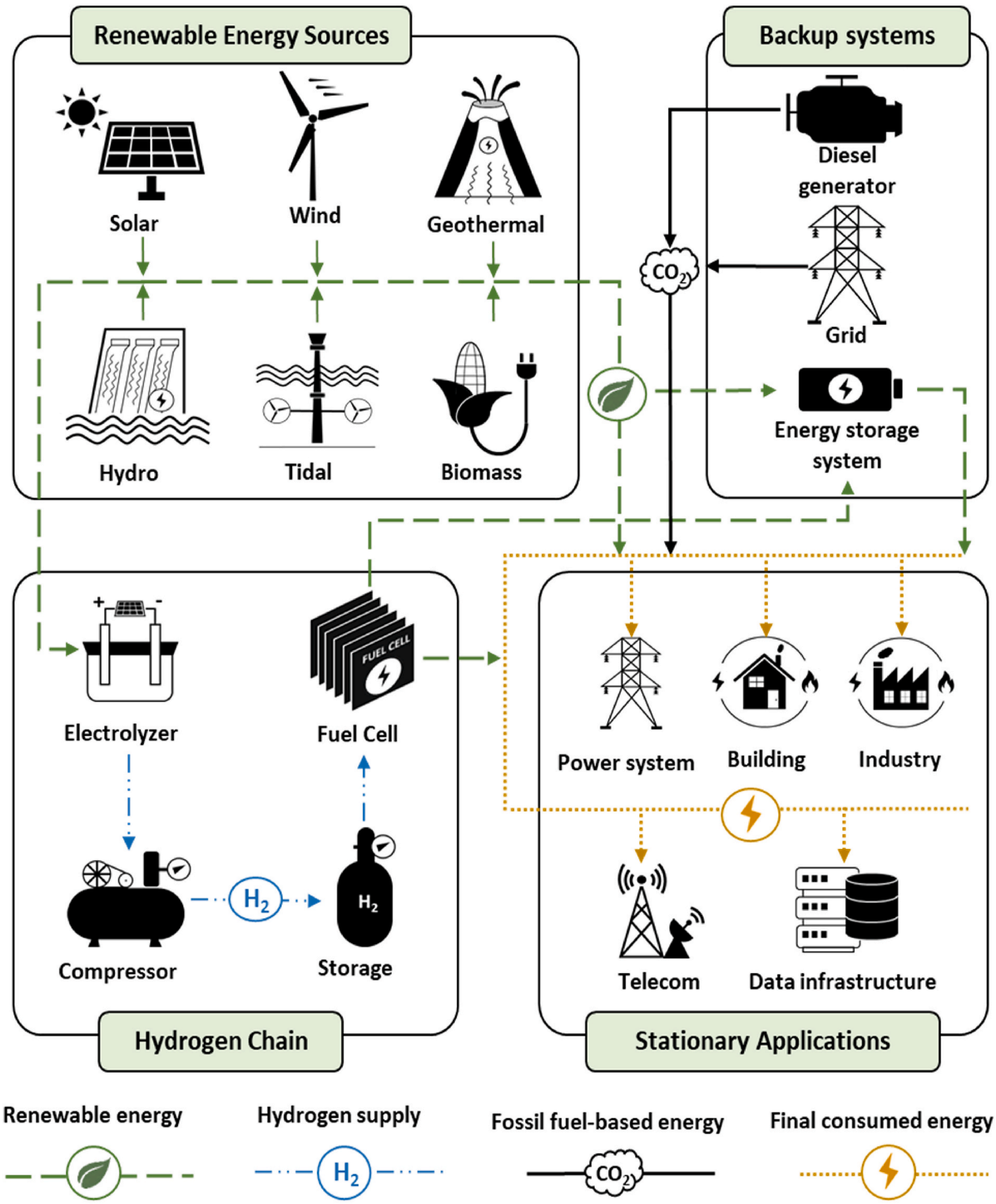

Fig. 2. RHS power supply chain for stationary applications.

fuel-based generator as energy backup, and grid-connected (GC) for the systems integrated into the grid. Besides, electrochemical devices (supercapacitors and batteries) and hydrogen technologies are accounted for as the main energy storage systems. Finally, the depicted components are connected to AC or DC power line depending on the type of current supplied and/or consumed (some components like the electrolyzer can be fed by the AC bus, if interfaced by an AC/DC converter, or the DC bus). The power system that electrically supports the components of the RHS is equipped with a multitude of power electronic converters (DC/DC, AC/AC, or AC/DC) to keep power stability in both AC and DC voltage.

This section aims at analyzing the applicability of hybrid systems from theoretical studies and experimental prototypes to large pilot projects, and even available commercial devices coupling fuel cells and renewable energies for different stationary applications.

2.1. *Sizing and optimization strategies: techno-economic analysis*

Previously to the implementation of experimental plants, theoretical studies serve as a useful tool to analyze the influence of different techno-

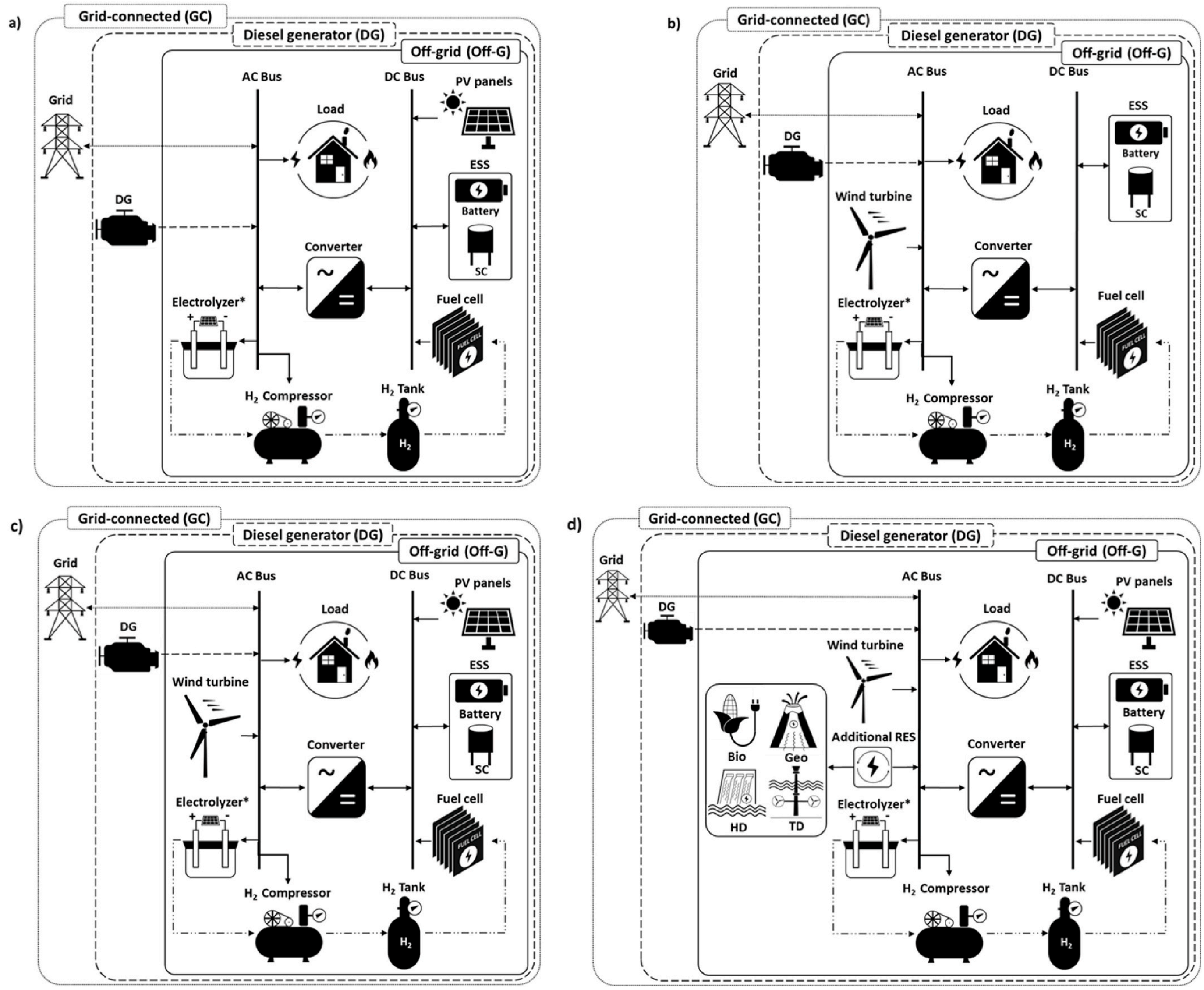

Fig. 3. Binary PV/FC (a), binary WT/FC (b), ternary PV/WT/FC (c), and multi-generation RHS (d). * Electrolyzer includes AC/DC rectifier.

economic parameters. The variables involved in the design of hybrid RHS are:

- Load demand to be supplied, variability, and application.
- Capital, operation, and replacement costs of the equipment, levelized cost of energy (LCOE), and net present cost (NPC) of the project.
- Availability of RES, power grid for external interconnection, non-salty water for electrolysis, and land for system deployment.
- System configuration: topology (binary/ternary systems, on/off-grid, backup systems, etc.), technology (fuel cell, electrolyzer, energy storage system, efficiencies, etc.), and electricity share among generators.
- Loss of power supply probability (LPSP), self-sufficiency ratio (SSR), the renewable fraction (f_{RES}), energy management strategy (EMS), dynamic response to fluctuations, energy excesses, or simulation parameters.
- Storage safety concerns, applicable regulations, codes, and standards.

The published theoretical studies report various simulations aiming at covering the load demand. Moreover, these simulations focus on different techno-economic parameters among which the following stand out: LCOE, hydrogen roundtrip efficiency (HRE), LPSP, SSR, and f_{RES}.

$$LCOE = C_{ann,tot} / E_{load} \tag{1}$$

$$HRE = \eta_{EL} \cdot \eta_{FC} \tag{2}$$

$$LPSP = \frac{\sum_{t=1}^{T} (E_{load}(t) - E_{gen}(t))}{\sum_{t=1}^{T} E_{load}(t)} \tag{3}$$

$$SSR = 1 - \frac{E_{grid,imp}}{E_{load}} \tag{4}$$

$$f_{RES} = 1 - \frac{E_{non,RES}}{E_{load}} \tag{5}$$

where $C_{ann,tot}$ is the total annualized cost of the system, E_{load} is the total load consumption, and η_{FC} are the electrolyzer and FC efficiencies respectively, $E_{load}(t)$ and $E_{gen}(t)$ are the consumed and generated energy in every time step, $E_{grid,imp}$ is the total energy imported from the grid and $E_{non,RES}$ is the total non-renewable energy consumed.

In this work, renewable hydrogen-based systems are divided into three different groups according to their dimension: small-scale (load demands between 0 and 50 kWh/day or FC rated powers ranging from

0 to 25 kW), medium-scale (load demands from 50 to 500 kWh/day or installed FC powers from 25 to 100 kW) and large-scale schemes (load demands or FC rated powers over 500 kWh/day and 100 kW respectively).

Regarding their configuration, binary systems (one RES and one FC) secure a good trade-off between system simplicity, autonomy, and economic feasibility in locations with abundant solar irradiation or high wind densities. This means that with the proper design and sufficient renewable resources, system self-sufficiency can be achieved, so that the primary renewable energy is sufficient to cover the load and sufficient energy (in the form of hydrogen or batteries) can be stored from excess RES energy. On the contrary, they present higher energy excess for off-grid systems with seasonal energy storage and lower flexibility since there is only one RES available.

Ternary solutions (two RES and one FC) are commonly applied in locations with specific limitations such as remote areas or detached buildings. The electronics involved and the integration complexity of these configurations imply raising the investment. Nevertheless, the coupling increases systems resiliency in case of failures or low availability of renewable resources. It also contributes positively to reduce energy excess for off-grid loads and micro-grids due to solar and wind energies complementarity.

Tables 2 and 3 gather the publications that address small-medium and large-scale RHS for different stationary applications, focusing on the optimal off-grid scheme reported in every publication. The optimal off-grid configuration is selected either directly from each manuscript or among multiple simulated scenarios within the work. References are classified from the largest to the smallest load covered and FC rated power. The table includes different characteristics of the renewable energy source, hydrogen chain size (fuel cell, electrolyzer, stored hydrogen, and the pressure), energy stored in ESS, the backup technology employed (off-grid, diesel generator, and grid-connected), load type, location, application, levelized cost of energy and hydrogen roundtrip efficiency.

The most employed modeling tools in the analyzed bibliography are HOMER Pro, TRNSYS, MATLAB-SIMULINK, GAMS, and iHOGA software codes. Table 4 collects main advantages and disadvantages between energy modeling software along with some case studies as examples of utilization. It summarizes main advantages and disadvantages of each software; along with several examples of case studies developed using every tool.

Binary RHS based on PV frequently appear as an alternative for small-medium scale residential communities [77–79], commercial and research buildings [72,83,84], single-family housing [93,96–98] or telecom stations [104]. These systems allow not only to cover electricity demands but also to obtain heat storable in water tanks from waste heat produced during FC operation or using solar thermal collectors like those in the report of Assaf et al. [99,100].

Likewise, ternary hybrid configurations are mainly used for residential and different buildings: nursing homes [80], laboratory buildings [128], or office buildings [124]. Other publications evaluate the deployment of ternary systems due to high RES availability. For instance, Duman et al. [76] simulated a PV/WT/FC facility located on the Turkish west coast. This region has great potential for both PV and WT with solar irradiation levels over 1500 kWh/m^2-year and average wind speeds between 7 and 9 m/s.

Authors like Ghaffari et al. [118] performed a sensitivity analysis on the LPSP and f_{RES} to assess their impact on the final system dimensions and net present cost. For the scenario of LPSP = 0%, halving f_{RES} from 0.8 to 0.4 reduces PV panels by 60%, requiring 15 times fewer FC units and 9 times less electrolyzer and hydrogen tank capacity. Moreover, for the maximal $f_{RES} = 0.8$, slightly increasing the LPSP to 0.05% reflects a reduction of almost 40 kW in the installed DG capacity.

The presence of batteries impacts the installed RES power for similar off-grid loads as noticed in Takatsu et al. [91] and Castañeda et al. [93], where a 10.5 kWh battery capacity in the last case reduces by 40% the PV power needed. These cases also demonstrate the location effect (Japan and Spain). Takatsu et al. reports lower electrolyzer capacity thanks to auxiliary hydrogen obtained through steam methane reforming. Besides, Castañeda et al. [93,94] study two different RHS to cover a residential load of 11 kWh/day in Spain, comparing the performance of both binary and ternary schemes. The optimal binary system consists of 6 kW PV, 1.2 kW FC, 3 kW electrolyzer, 3 kg stored hydrogen, and 10.5 kWh battery capacity. Conversely, the optimal ternary facility comprises 1.5 kW PV and 1.5 kW WT rated power respectively, the same FC capacity of 1.2 kW, 2 kW electrolyzer, 1 kg stored hydrogen, and a battery bank of 5.3 kWh. Thus, when a WT is integrated with the system, it leads to a reduction of half of the RES power required and threefold of hydrogen storage capacity, as well as downsizing the electrolyzer and battery bank by 33% and 50% respectively.

Large-scale PV and WT farms are usually deployed far from urban areas. Massive investment are normally needed for the construction of high voltage transmission systems to deliver high levels of power quality to distant customers, as required by the electrical regulatory agencies and standards. RHS associated with FC can improves the service availability to the customers by locally doing peak shaving and valley filling of the RES intermittent power. RHS is particularly convenient to customers in remote areas with precarious access to the grid.

Solar stands out over wind for binary large-scale systems covering different stationary loads that imply the presence of buildings like academic centers [135,151], industrial facilities [133,148], or residential and commercial applications [137,141,144]. However, Chade et al. and Abdin et al. [140,156] evaluated WT/FC configurations in Iceland and Canada due to high wind densities.

Conversely, ternary schemes are often reported in remote areas like those simulated by Kalinci et al., Luta et al., and Samy et al. [142,145,146] or cities as in Abdin et al. [156] with land restrictions to deploying large-scale PV plants. However, transportable and more accessible fossil-fuelled generators can be used in isolated areas to ensure energy supply continuity, like in Phan et al. and Cozzolino et al. [134,153] who tested them in combination with RHS in islands. Mohseni et al. [154] studied an alternative multi-source system as part of a green hydrogen power supply chain and a large remote area in New Zeeland.

Despite grid access is a constraining factor in certain locations due to the required investment and engineering complexity, several publications evaluate grid-connected configurations to supply large residential applications. Daraei et al. [132] defined a grid-integrated PV/HD/Bio configuration to power 275,000 homes, including a 1.7 MW compressor in the modeling, while HassanzadehFard et al. [149] studied a smaller PV/WT based system to provide electricity to a microgrid of 300 households in Hawaii with backup hydrogen supply via steam methane reforming. Similarly, Ceran et al. [143] proposed a large residential application with hydrogen compression and Jahangir et al. [136] designed a large-scale PV/WT plant to cover the demand of a sports complex.

The location has a major impact in the final configuration. Hutty et al. [139] conducted a simulation to supply 92 households in different locations (southeast England and Texas) with an achieved self-sufficiency ratio (SSR) of 90% and considering compression needs. Despite Texas' consumption is threefold the requirements of England, the needed PV power is bigger in the latter (1.61 MW) than in Texas (1.49 MW) due to the higher solar irradiation available. Moreover, if we compare the results with the ones reported by Luta et al. [145] for a remote community with a daily consumption of 1080.5 kWh/day in South Africa, a decrease of three times on RES capacity required (0.66 MW PV/WT) is appreciated. However, the FC power required is proportional to the load. Therefore, the FC capacity in Texas is almost three times (0.8 MW) the one required for UK and South Africa (0.35 and 0.3 MW respectively). Likewise, Coppitters et al. [152] reported a maximal SSR of 59% for a residential micro-grid of 2500 housing. The remaining load is covered by importing electricity from the grid.

Renewable hydrogen-based alternatives must reach economic

Table 2
Small-medium scale theoretical RHS for stationary applications.

Configuration					Off-G/DG/GC	Load (kWh/d)	Application/Country	LCOE ($/kWh)	HRE (%)	Ref., year
RES (kW)	FC	EL	StH_2 (kg)	Bat (kWh)						
PV (190)	5	5	40	800	Off-G	484.9	University (Turkey)	1.051	37.5	[72], 2012
PV (170)	50	50	50	600	DG	470	Residential (Italy)	–	31.5	[73], 2020
PV(75) - Bio(15)	10	10	15	60	Off-G	361	Residential (Iran)	0.24	34	[74], 2020
PV(82) - WT (225)	50	25	13.9		DG	347.3	Residential/Industrial (Norway)	–	31.5	[73], 2020
PV(40) - Bio(50)	50	25	27.8		DG	264.7	Residential (Italy)	–	31.5	[73], 2020
HD (900)	50	25	27.8	30	DG	239	Residential (Greece)	–	31.5	[73], 2020
PV (66)	9	15	70		Off-G	236	RODP (Egypt)	0.062	76.5	[75], 2019
PV(40.7) - WT (20)	20	20	40		Off-G	165.6	Residential (Turkey)	0.309	28	[76], 2018
PV (105)	20	40	20		Off-G	165.2	Residential (Turkey)	0.612	71.8	[77], 2019
PV (71)	5	3	2	500	Off-G	140.75	Residential (Malaysia)	0.355	–	[78], 2017
PV (25.9)	–	–	–		Off-G	117.2	Residential (Germany)	–	30	[79], 2017
PV(30) - WT (20)	20	50	100		Off-G	110	Nursing home (Turkey)	1.306	25	[80], 2019
PV (39.6)	5	5	204.8		Off-G	102	Hospital (Turkey)	0.626	28.6	[81], 2016
PV (39.6)	5	5	204.8		Off-G	102	Hospital (Turkey)	0.377	32.4	[82], 2017
PV(57.1) - WT (10)	25	30	25		Off-G	100.6	Residential (Turkey)	0.502	28	[76], 2018
PV (40)	4	10	20		Off-G	60	Laboratory building (Iran)	0.924	–	[83], 2018
PV (5)	3	–	–	36	Off-G	56.5	Research building (India)	0.203	–	[84], 2017
PV (6.6)	1	1	0.1	48	DG	48.1	(Spain)	–	42.5	[85], 2007
PV(8.1) - WT (3)	5	6	130 bar	92.2	Off-G	38.4	–	–	29.6	[86], 2015
PV(8.1) - WT (3)	5	6	4.6	92.2	Off-G	38.4	(Italy)	–	–	[87], 2014
PV (–)	20	–	–		Off-G	34.9	Residential/RODP (Algeria)	–	–	[88], 2011
PV (10)	1	2	6	25	Off-G	31.8	Remote (China)	–	–	[89], 2019
PV (21)	4	5	170	20	Off-G	19.9	Residential (Finland)	–	–	[90], 2021
PV (8.6)	–	–	–		Off-G	13	Residential (Germany)	–	30	[79], 2017
PV (10)	1.5	1.5[a]	5		Off-G	12	Residential (Japan)	0.54	–	[91], 2020
PV(3.4) - WT (3)	2.9	4.2	70	17.6	Off-G	11.3	Residential (Greece)	1.2	–	[92], 2019
PV (6)	1.2	3	3	10.5	Off-G	11	Residential (Spain)	–	43.5	[93], 2013
PV(1.5) - WT (1.5)	1.2	2	1	5.3	Off-G	11	Residential (Spain)	–	–	[94], 2012
PV(2.4) - WT (1.5)	1.2	3	–	7.3	Off-G	11	Residential (Spain)	–	–	[95], 2013
PV (5)	1	0.25	–	33	Off-G	10	Residential (Iran)	–	–	[96], 2015
PV (16)	5	7.2	55		GC	7.3	Residential (Spain)	3.65	20.7	[97], 2019
PV (18)	2.25	3.5	10		GC	6.8	Residential (Iraq)	0.195	35.2	[98], 2020
PV (3.5[b])	0.33	2.5	16.3		Off-G	5, 165 L/day	Residential (Australia)	–	41.1	[99], 2016
PV (3.6[b])	0.59	1.8	16.3		Off-G	5, 165 L/day	Residential (Australia)	0.342	65.3	[100], 2019
PV (1)	2	1	10		Off-G	1.43	Irrigation (Bangladesh)	0.0893	37.3	[101], 2017
PV (171)	47.2	–	33.4		Off-G	45 kWp	Residential	–	–	[102], 2020
PV (5)	4	0.1	1000	4.8	Off-G	4.7 kWp	Remote (India)	0.245	–	[103], 2017
PV (9.7)	1.7	10	1.8	12	Off-G	2 kWp	Telecom	–	–	[104], 2015
PV(40) - WT (60)	40				–	Variable	–	–	–	[105], 2014
PV (25)	25			8	Off-G	Variable	–	–	–	[106], 2013
PV (32)	12		–		–	Variable	–	–	–	[107], 2020
PV(2) - WT (5)	6		–	25	Off-G	Variable	Laboratory	–	–	[108], 2015
WT (6)	6			20	Off-G	Variable	Laboratory	–	–	[109], 2018
PV(2.4) - WT (4)	1.9	2.8	827.4/200 bar		Off-G	Variable	Laboratory (Canada)	–	–	[110], 2014
PV (1.1)	1.3	0.3		5	Off-G	Variable	Laboratory	–	–	[111], 2013
WT (0.6)	1.2				Off-G	Variable	Laboratory	–	–	[112], 2014
PV(1.6) - WT (1.5)	1.2	3	–	7.3	GC	Variable	Laboratory (Spain)	–	37.3	[113], 2014
PV(1.62) - WT (1.5)	1.2	0.48	–	8.91	Off-G	Variable	Laboratory (Spain)	–	32	[114], 2015
PV(0.75) - WT (1)	1.2				GC	Variable	Telecom	–	–	[115], 2012
PV(2.3) - WT (1.9)	–				Off-G	Variable	–	–	–	[116], 2014
PV (720)	53	10	93	1040	Off-G	–	(Nigeria)	0.85	–	[117], 2015
PV (167)	30	92	54		DG	–	Remote (Iran)	–	–	[118], 2020
PV(–) - WT (–)	28.7	137	82.7		Off-G	–	Residential/Commercial (Iran)	0.853	37.5	[119], 2021
PV(33) - WT (50)	18	50	60 bar	10	Off-G	–	Residential (USA)	–	31.5	[120], 2008
PV (115)	14	52	24		DG	–	Residential (Iran)	–	–	[121], 2019
PV(10) - HD (20)	10	10	20		Off-G	–	Remote (Ecuador)	0.4	–	[122], 2020
PV(12.8) - WT (20)	10				Off-G	–	–	–	–	[123], 2005
PV(20) - WT (13.5)	3	4	300 bar	76	Off-G	–	Office building (Argentina)	0.604	–	[124], 2019
PV(3.1) - WT (4)	3	3	–		Off-G	–	Residential (Mexico)	0.55	44.4	[125], 2014
PV(1.2) - WT (9)	3	3	–		Off-G	–	(Iran)	–	37	[126], 2014
PV(200) - WT (40)	2	2	–	3747	Off-G	–	Residential (Malaysia)	1.108	42.5	[127], 2013
PV(0.47) - WT (2)	2	2	–		GC	–	Laboratory building (Iran)	–	–	[128], 2015
PV (60)	–	500 kWh-StH_2/Bat			GC	–	Residential (Italy)	–	–	[129], 2021

(continued on next page)

Table 2 (*continued*)

Configuration					Off-G/DG/GC	Load (kWh/d)	Application/Country	LCOE ($/kWh)	HRE (%)	Ref., year
RES	FC	EL	StH_2	Bat						
(kW)			(kg)	(kWh)						
PV(−) - WT (10)	–	–	100 kWh	–	Off-G	–	Residential (Iran)	–	–	[130], 2020
PV(2.2) - WT (2.25)	–	–	–		Off-G	–	(Egypt)	–	–	[131], 2006

Abbreviations: StH_2 (Stored Hydrogen), Bat (Battery), SC (Supercapacitor), MH (Metal Hydrides). Off-G (Off-Grid), DG (Diesel Generator), GC (Grid Connected), LCOE (Levelized Cost of Energy), HRE (Hydrogen Roundtrip Efficiency).

[a] Includes hydrogen obtained through steam methane reforming.

[b] Includes solar thermal collector (STC).

competitiveness to become a realistic alternative to fossil fuels for stationary power supply. Green hydrogen already represents a clean alternative with water and heat as only wastes, while grey hydrogen generation by steam methane reforming produces 9–11 kg of CO_2-eq emissions per H_2 kg generated. However, production costs for grey and green hydrogen are 0.6–1.9 and 3.7–6.1 US$ per H_2 kg as for 2020 [157].

Based on low and high heating values (LHV and HHV), 33.3 to 39.4 kWh are obtained per H_2 kg generated. Therefore, hydrogen roundtrip efficiency is key to harvest the largest amount of energy feasible and it strongly influences the achieved LCOE. Several small and medium-sized configurations report hydrogen roundtrip efficiencies values under 40%, being Rezk et al. [75] and Assaf. et al. [100] the only publications with higher HRE (76.5 and 65.3% respectively), while large-scale facilities show values above 48% except in the report of Samy et al. [147] whose HRE is 34%. The compression stage also contributes to raising the investment as it involves great energy consumptions, and additional safety and infrastructure requirements. Only Cano et al., Rullo et al., Trifkovic et al., Daraei et al., and Ceran et al. [86,110,124,132,143] incorporate compressors into their models, pressurizing the hydrogen up to 300 bar.

System components CAPEX have a great influence on the economics of the project. Therefore, Table 5 compiles real capital expenditures and the maturity level of main equipment reported by international agencies and associations like IEA, IRENA, US Department of Energy, Hydrogen Council, Fuel Cell and Hydrogen Joint Undertaking Programme (FCH JU), etc. The CAPEX/kWh of FC and electrolyzers decreases for large-scale RHS due to economy of scale. Moreover, it classifies FC systems per stationary application according to the technology readiness level (TRL). The TRL 0–3 classification corresponds to idea conception and technical formulation, 4–5 to prototyping, 6–7 to prototype validation under real operating conditions and 8–9 to production and commercialization.

With global residential electricity prices ranging between 0.005 and 0.365 US$/kWh, several references achieve LCOE similar to grid prices [160,161]. Fig. 4 depicts a comparison between residential electricity prices per country and the levelized cost of energy reflected by the different RHS per country evaluated in this study. In general, it can be appreciated that renewable hydrogen-based configurations do not reach the average rate of each country. However, there are publications reflecting cost of energies below the maximum reported residential electricity price in Germany, which require a more detailed analysis for possible application in other countries. Furthermore, these systems show a downward trend in terms of energy prices in the face of increasingly higher electricity rates, mainly in the most developed countries, due to penalties for CO_2 emissions.

Therefore, Fig. 5 depicts a cost breakdown of main equipment within references showing a cost of energy below 0.365 US$/kWh (dotted and dashed line in Fig. 4) that are compared with CAPEX collected in Table 5. Hence, it is aimed at assessing the influence of prices and configurations considered in published manuscripts in comparison with the costs contemplated by international organisms and the influence of installing diesel generators or connecting the system to the grid in the final LCOE. It also establishes a comparison between publications analyzing multiple scenarios to evaluate the influence of installing backup generators or importing energy from the grid in the LCOE. References are classified as off-grid (Off-G, no backup employed), grid-connected (GC), or diesel generator (DG). The legend shows the LCOE reported in every reference and the backup system if any. Blue boxes represent the range of reported costs by international agencies (real prices). Moreover, Fig. 5 includes a comparison of the LCOE obtained in different scenarios within the same reference in order to check the difference between completely self-sufficient systems and those that need an ancillary generator or electrical connection.

Most of the small-medium scale off-grid references underestimate different hydrogen chain components: Das et al. and Khadem et al. considered low fuel cell costs [78,101], Rezk et al. [75] used electrolyzer and tank CAPEX below lower limits reported by international organisms. Singh et al., Khadem et al., Khemariya et al., and Rad et al. [74,84,101,103] also reported low tank prices. Likewise, large-scale configurations analyzed in Ansong et al. and Ghenai et al. [133,135,137] underrated tank CAPEX (0.5US$/kg H_2 stored) and Rezk et al. [148] estimated capital costs below international prices for every hydrogen chain device. Hassan et al. [98] and Jahangir et al. [136] tested grid-connected systems with undervalued tank costs and with a low contribution of the FC due to the price of the energy imported from the grid respectively, lowering hydrogen chain size and final energy prices. This undervaluation of hydrogen-related technologies implies oversized storage tanks, fuel cells, and electrolyzers, allowing larger amounts of energy stored and reducing the required RES power.

However, Duman et al. [76] achieved competitive LCOE (0.309 $/kWh) with components CAPEX comparable to the reported ones or Assaf et al. [100] that secured a cost of energy of 0.342$/kWh, both with off-grid systems. Other publications from Dawood et al. and Samy. et al. [141,147] have obtained competitive LCOE with 100% self-sufficient large-scale systems and equipment prices in the range of the internationally reported capital expenditures.

The comparison of multiple scenarios where Off-G, DG, and GC scenarios are simulated demonstrates that the gap in terms of cost-competitiveness between RHS and other alternatives is being reduced. Das et al. and Dawood et al. [78,141] compared 100% energy supply with diesel generators and off-grid RHS, being off-grid solutions around 0.30$/kWh cheaper than DG-based ones. Ghenai et al. and Duman et al. [76,135] showed minor LCOE differences (the latter for the regular occupancy scenario).

Nevertheless, additional efforts are required to close the current existing difference. Future CAPEX reductions reflect promising LCOE for renewable hydrogen-based strategies. Particularly, in Ozden et al. [82], a sensitivity analysis is conducted varying PV capital investment between 1600 and 5000 US$/kW, obtaining a cost of energy of 0.377 and 0.706 US$/kWh for the same hydrogen technologies prices, which are the main cost-drivers.

Moreover, Heras et al. [162] have recently evaluated a future Spanish energetic scenario, where solar and wind energy in combination with fuel cells, electrolyzers, compressors, and metal hydride tanks replace coal and nuclear plants. Compared to the base assumption, the

Table 3
Large-scale theoretical RHS for stationary applications.

Configuration					Off-G/DG/GC	Load (kWh/d)	Application/Country	LCOE ($/kWh)	HRE (%)	Ref., year
RES (MW)	FC	EL	StH_2 (kg)	Bat (kWh)						
PV(1000) - HD/Bio(51)	350	900	130 GWh		GC	6,570,000	Residential (Sweden)	–	34.8	[132], 2020
PV (50)	15	30	$25\cdot10^6$	3600	DG	350,000	Mine (Ghana)	0.242	–	[133], 2019
PV(5.5) - WT (2.36)	0.5	3	500	20,948	DG	18,000	Island (Philippines)	0.696	–	[134], 2019
PV (1.08)	0.2	0.05	100	406	Off-G	6540	University (UAE)	0.099	52	[135], 2019
PV(0.6) - WT (0.25)	0.1	0.1	100	2990	GC	5136.9	Sports complex (Iran)	0.114		[136], 2021
PV (0.52)	0.75	0.25	900		Off-G	4500	Residential (UAE)	0.145	63	[137], 2020
WT (0.81)	0.1	0.1	90		DG	3214	Residential (Saudi Arabia)	0.253	–	[138], 2019
PV (1.49)	rSOFC (0.8)		53 MWh		GC	2986	Residential (USA)	–	34.8	[139], 2020
WT (0.7)	0.15	0.3	850		Off-G	2400	Remote (Iceland)	0.434	48.5	[140], 2015
PV (0.95)	0.1	0.25	200/350 bar	300	Off-G	2000	Residential (Australia)	0.342	60	[141], 2020
PV(0.3) - WT (0.66)	0.1	0.2	500		Off-G	1776.4	Remote (Turkey)	0.836	32	[142], 2015
PV(0.14) - WT (0.16)	0.07	0.18	–		GC	1205.5	Residential	–	–	[143], 2019
PV (1.35)	0.08	400	80	123 (SC)	Off-G	1200	Commercial (South Africa)	4.78	–	[144], 2019
PV(0.31) - WT (0.35)	0.3	0.11	100		Off-G	1080.5	Remote (South Africa)	–	–	[145], 2018
PV (1.61)	rSOFC (0.35)		42.2 MWh		GC	1052	Residential (UK)	–	34.8	[139], 2020
PV(0.22) - WT (0.14)	0.15	0.32	–		Off-G	840	Remote (Egypt)	0.45	45	[146], 2020
PV (0.15)	0.14	0.29	0.36 MWh		Off-G	594	Remote (Egypt)	0.334	34	[147], 2019
PV (0.24)	0.03	0.13	25	311	Off-G	522	RODP (Saudi Arabia)	0.117	76.5	[148], 2020
PV(0.77) - WT (0.9)	0.91	0.44	70[1]		GC	–	Residential (USA)	–	45	[149], 2020
PV(4700 panels) - WT (1.8)	0.75	0.6	–		Off-G	–	Island (Tunisia)	–	–	[150], 2016
PV (4.5)	0.6	2.9	5700		Off-G	–	University (Algeria)	2.225	63.4	[151], 2018
PV (21.2)	0.5	2.3	16.7 MWh	8400	GC	–	Residential (Belgium)	0.456	–	[152], 2020
PV(1.1) - WT (1)	0.3	0.7	150	72	DG	–	Island (Italy/Tunisia)	0.522	–	[153], 2016
PV(0.33) - WT (0.36) HD (0.24) - Bio(0.19)	0.24	1.11	663	29,079 (SC)	Off-G	–	Remote (NewZeland)	–	24	[154], 2020
PV(0.26) - WT (0.52)	0.2	0.71	103		Off-G	–	Remote (Egypt)	0.43	37.5	[155], 2020
PV(0.47) - WT (1.5)	0.1	0.35	500	396	Off-G	–	City (USA)	0.52	42.5	[156], 2019
PV(0.35) - WT (1.5)	0.1	0.35	700	496	Off-G	–	City (Australia)	0.53	42.5	[156], 2019
PV(0.67) - WT (1.5)	0.1	0.35	800	565	Off-G	–	City (USA)	0.61	42.5	[156], 2019
PV(0.45) - WT (1.5)	0.1	0.65	800	572	Off-G	–	City (Australia)	0.63	42.5	[156], 2019
WT (3)	0.1	0.65	1000	1951	Off-G	–	City (Canada)	0.88	42.5	[156], 2019

Abbreviations: StH_2 (Stored Hydrogen), Bat (Battery), SC (Supercapacitor), MH (Metal Hydrides). Off-G (Off-Grid), DG (Diesel Generator), GC (Grid Connected), LCOE (Levelized Cost of Energy), HRE (Hydrogen Roundtrip Efficiency).

Table 4
Comparison of different energy modeling tools.

Software	Use & objective function	Advantage	Disadvantage	Case studies
HOMER Pro	Techno-economic optimization. Minimize LCOE and net present cost.	- User friendly. - Capable of modeling RES and non-RES systems. - Optimization and sensitivity analysis ability. - Considers degradation of the components. - Full report of emissions. - Possibility of introducing real hourly consumption data or creating a synthetic load profile. - Support from NASA meteorological databases. - MATLAB link for dispatch strategy design.	- Economic priority over technical characteristics. - Lack of specific FC module. - Unlike AI optimization techniques. - Hydrogen storage does not consider neither hydrogen pressure nor tank volume required. - Hydrogen compressor module not included. - MATLAB link for self-defined dispatch strategies does not support hydrogen modules.	[72,74–77,133,135–137]
TRNSYS	Modeling and simulation Analysis of system performance	- Flexible software based on the case study. - Complete library of components with large and complex modules for a faster design.	- Complex software, especially for new users. - Poor graphical user interface.	[81,82,99]
MATLAB-SIMULINK	Modeling, simulation and optimization. Self-defined objective function.	- Flexible software based on the case study. - Multi-objective optimization and sensitivity analysis. - Definition of different simulation algorithms and comparison between them. - Transient behavior of the system. - Self-defined graphical user interface.	- Modeling complexity, especially for new users. - Lack of dedicated hydrogen modules.	[93,94,100,108,109,126,154]
GAMS	Modeling, simulation and optimization. Self-defined objective function	- Flexible software based on the case study. - Multi-objective optimization and sensitivity analysis. - Definition of different simulation algorithms and comparison between them.	- Modeling complexity, especially for new users. - Lack of dedicated hydrogen modules. - Complex programming language. - Ancillary solver required. - Poor graphical user interface.	[102]
iHOGA	Techno-economic optimization. Minimize LCOE and net present cost.	- Software uses time steps for calculations–Reliable accuracy. - User friendly. - Job creation optimization ability.	- Only capable of modeling PV, wind, hydrogen and hydro systems. - Converters, generators and grid network cannot be modeled. - Only PRO version has sensitivity analysis ability.	[85,96]

future scenario envisions PV panels efficiency increase from 17.5% to 22% and CAPEX reduction from 1050$/kW to 600$/kW, WT capital costs downsizing of 200$/kW. Fuel cell efficiencies raise to 70% with a needed investment of 910$/kW, and electrolyzer performance improves from 54 to 50 kWh/kg H_2 with a cost of 400$/kW. Under these hypotheses and considering the extra energy needed to split hydrogen from metal hydrides, an electricity cost of 0.11$/kWh is achieved, reducing the investment threefold. Furthermore, it is reflected a reduction in the number of PV panels from 205 million to 151 million units and in the wind turbines from 8000 to 1540 generators. Therefore, hybrid configurations demonstrate economic feasibility in the mid-term for larger energetic demands.

The conclusions drawn from the analysis of simulated RHS are as follows:

i. A clear predominance of PV as the main RES over wind turbines or others is reflected from small to large-scale systems for both binary and ternary schemes, with load demands between 1.43 and 6,570,000 kWh/day (corresponding to an irrigation system and 275,000 households respectively).
ii. Residential and buildings prevail as main applications for small-medium systems. These applications encourage the PV/FC combination as they enable the installation of PV panels in roofs or facades.
iii. Remote areas without grid access are the most studied ones for large-scale schemes. Wind turbines and panels are recommended for large loads such as islands, cities, or detached residential communities providing a more continuous electricity supply. However, their production highly depends on air density, rotor height, or turbulent flows caused by obstacles and other surrounding buildings.
iv. The location impacts the final optimal configuration by reducing system size for those that have abundant renewable resources available. Besides, in locations with similar RES potential, increasing energy storage capacity reduces final PV or WT dimensions.
v. For similar load demands and locations, the use of ternary systems reduces RES and storage capacities in comparison with binary configurations.
vi. The reduction of loss of power supply probability (LPSP) and the increase of renewable fraction (f_{RES}) and self-sufficiency ratio (SSR) enlarge the system size and investment needed. Reduced hydrogen roundtrip efficiencies (HRE) have the same impact on the configuration dimensions and economics.
vii. Despite some publications undervalue hydrogen-related technologies CAPEX, off-grid renewable hydrogen-based strategies already present competitive LCOE in some cases with promising results in mid and long-term scenarios.

2.2. Proof of concept: lab-scale experimental plants

Some simulations do not consider relevant variables, which effectively have a great impact on the system and the achieved LCOE. Indeed, the integration level and balance of plant (BoP) development also influence the final costs [163,164]. Therefore, the study of experimental systems marks the transition between theoretical simulations and the deployment of larger-scale projects, boosting RHS progress through real experiences. Therefore, Table 6 collects a list of publications analyzing lab-scale prototypes aimed at improving different parameters such as system performance, energy management strategies (EMS), or reliability and using the aforementioned classification criteria for theoretical studies.

Most of the listed publications consider off-grid schemes to cover the

Table 5
Reported CAPEX prices by international agencies, maturity level of main hybrid systems components and technology readiness level (TRL) of FC systems per stationary application.

Component	Technology	Reported CAPEX Prices (US$/kW)	Maturity level [20]	Stationary application	TRL [158]
Photovoltaic		**250–1050** [67]	Mature	**Electricity grid services**	7–8
Wind Turbine		**1300–4600** [69]		**Off-grid power/isolated microgrids**	6–8
	On-shore	1300–1800	Mature	**Industrial use**	
	Off-shore	3500–4600	Mature	District heating	7
Fuel Cell		**1600–6000** [20,66]		Biogas in FCs	8
	PEMFC	1600–4000	Early market	**Residential use (mCHP)**	8–9
	SOFC	3000–4000	Demonstration	**Commercial buildings**	6–7
	PAFC	4000–5000	Mature	**Back-up power**	8
	MCFC	4000–6000	Early market	**Gen-sets**	7–8
Electrolyzer		**500–5600** [15]			
	Alkaline Electrolyzer	500 - 1400	Mature		
	PEM Electrolyzer	1100–1800	Early market		
	SOEC Electrolyzer	2800–5600	Demonstration		
Hydrogen tank	Low-pressure – High-pressure	**700–1000 US$/kg** [159]	Mature		

load demand without using backup generators. Silva et al. [165] developed an experimental facility to power a remote microgrid at the Brazilian Amazon, while Marino et al. [166] compared conventional lighting and LED lamps to assess the system performance, potential size reduction, and the curtailed energy. Yunez-Cano et al. [167] integrated a PV/FC system with an electrolyzer and metal hydride storage tank to satisfy a mobile house demand in Mexico for an uninterrupted period of up to 2 days. In Cordiner et al. and Bartolucci et al. [171,172], telecom stations from different locations in Italy include a PV/FC system along with batteries for on-field trials. These systems operate with different energy management strategies to compare the PV utilization factor, hydrogen production, and FC energy flow to sort the best one for every location. The facilities include a vessel to store the hydrogen produced through water electrolysis at 30 bar (only 4 out of 9 locations have electrolyzer) and a bundle of bottles refilled externally at 200 bar to avoid electricity shortfalls and ensure supply continuity (in all the cases).

Nevertheless, the interaction in the electricity grid is of interest in terms of integration, required electronics, grid imports and exports, etc. In Carbone et al. [170] different load scenarios are considered to test and validate an experimental PV/FC plant for the campus lighting. Thus, the lighting modeled as a constant load works with two patterns: daylight load (load is activated from dawn to sunset) and nightlight load (load from sunset to dawn). Endo et al. [175] study a medium-scale containerized solution with TiFe-based metal hydrides storage in Japan, achieving a reduction of up to 99% on the thermal management operations of MH tanks. Furthermore, these improves the overall efficiency of the system (power-to-power/heat) up to 60% based on high heating value (HHV). Finally, Boulmrharj et al. [176] developed an mCHP experimental solution to increase energy efficiency in buildings, and Stewart et al. [174] evaluated different power dispatch strategies in the frame of the Ecological House project in Italy.

Additionally, other reported articles have analyzed the influence of EMS in laboratories. For instance, Karami et al. [178] improved electronic controllers to maximize renewable penetration. Likewise, Alam et al. [169] used a PV and load emulator, small FC/electrolyzer systems, metal hydride storage tank (typically used in lab-scale plants due to the higher storage capacity in reduced volumes compared to pressurized vessels), sensors, and controllers to analyze the system dynamic response. The scheme implemented in Calderón et al. [180] monitors the power generation of the PV/WT/FC configuration; it registers hydrogen production and stores it in metal hydride cylinders. It also includes a programmable logic controller to adjust the EMS. Other lab-scale prototypes in Benlahbib et al. and Brka et al. [177,179] use power electronic sources to emulate RES and loads, testing variable load consumptions and different weather conditions.

Several conclusions are obtained from the performed analysis:

i. Prototype renewable hydrogen strategies are implemented in different applications such as lighting, residential, telecom stations, or laboratory benches.
ii. Off-grid configurations prevail over grid-connected ones. The latter are considered in some publications to evaluate the integration of RHS in the electricity mix. Additionally, the early development of the prototypes implies the need for ancillary support in some off-grid schemes, for instance, hydrogen refilled externally.
iii. The references gather on-field trials, where the prototype systems performance is assessed in the final location; or lab trials that use power sources to emulate loads and renewable production profiles along with the hydrogen-related technologies to develop the energy management strategy.
iv. The evaluated lab-scale systems focus on technical development. The articles that analyze the economics reflect high LCOE, so larger-scale designs are required to overcome cost challenges.

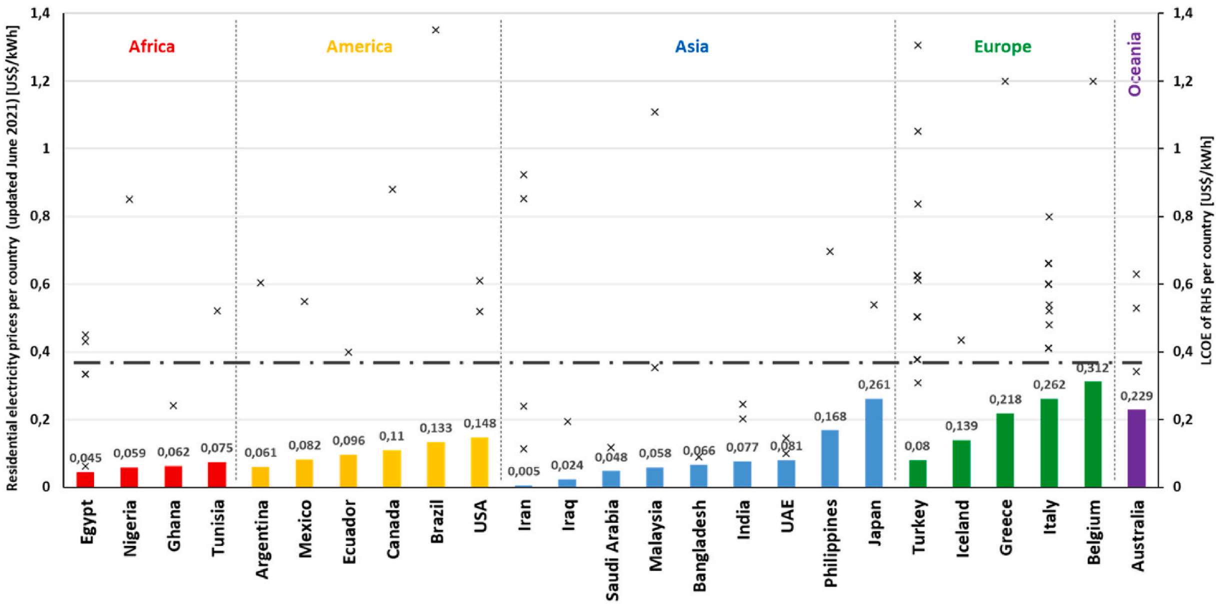

Fig. 4. Comparison between residential electricity prices and LCOE of renewable hydrogen-based schemes analyzed per country. Dotted and dashed line represents the maximum reported residential electricity price (0.365 US$/kWh) in Germany.

2.3. Towards RHS wide deployment: pilot plants and projects

Table 7 collects several real implementations within the stationary sector that include both RHS and FC systems. The projects are divided according to their application in power systems (providing grid balancing services and energy injection), industrial (like steel plants, refineries, or wastewater treatment plants), residential and other applications (such as telecom stations, mountain huts, hospitals, and other facilities). These pilot plants are sorted from largest to smallest FC rated power inside each category, giving technical characteristics of the configurations.

Although power systems and industrial pilot projects are not the targets of small-medium scale RHS due to the great quantities of hydrogen, heat and power involved within the process, projects like ELY4OFF have developed a scale prototype using PV panels and Proton Exchange Membrane FC (PEMFC) to provide the Aragonese Hydrogen Foundation facility with 100% green electricity [181–183]. Another relevant project is the BIG HIT [184–186], which implements a complete hydrogen supply chain using wind and tidal energy at the Orkney Islands in the north of Scotland. The generated hydrogen pursues different applications like electricity injection or heat and power generation for harbor buildings. The hydrogen produced on one island is stored and distributed using ferries and trucks between the islands. Both projects have been funded by the FCH JU.

Industrial systems like SOFCOM [187,188] or ECOELECTRICITY [189] use biogas and syngas obtained within daily activities of a WWTP and a biomass plant respectively. Therefore, FC systems are implemented to get heat and power for their processes.

Regarding residential applications, installing a hybrid system in a single housing or a remote residential community differs from the integration possibilities in a city. Thus, the studied projects have been divided into projects funded by public programs, and projects from private companies and individual end-users.

Projects funded by public programs (like the aforementioned FCH JU) are making efforts to develop micro-cogeneration units (mCHP) to get heat and power. Using different fuels, these units obtain hydrogen to provide households with heat and power with overall efficiencies over 90%. CALLUX [190] and ENEFIELD [191–193] set the basis of this technology in Europe with over 1000 units deployed during the project lifetime, while PACE [194,195] continues with the commercial roll-out and installation of more than 2800 units. According to these projects, the wide deployment of mCHP units in Europe will potentially avoid 62 billion € in grid reinforcement. In Japan, the ENEFARM program [196,197] has installed over 270,000 mCHP systems between 2009 and 2018, with activities still ongoing to achieve 5.3 million units by 2050. Within this project, several manufacturers are developing increasingly efficient units ranging between 0.7 and 250 kW.

Finally, the REMOTE project [73,198,199] combines different RES (PV, WT, hydraulic, and biomass) with hydrogen systems. Originally, the project was aimed at providing energy to 4 micro-grids in different locations in Europe: north and south Italy, Norway, and Greece covering load demands from residential loads available on-site to industries or small-medium enterprises (SMEs). However, following the recent outgoing of two Italian partners, the two demonstration projects in Italy have been discarded and replaced by a new pilot project in the Canary Islands (Spain) for the energy supply of a farm.

Additional R&D activities on RHS arise from private companies or end-users interested in developing case studies. Their main objective is achieving 100% clean electricity and heat consumption within the demonstrative daily operation. For instance, the PHI SUEA HOUSE project [200] in Thailand or SOCIAL HOUSING in Vagarda (Sweden) [201,202] belong to different residential communities with PV/FC in two very different locations. Other projects aim at becoming more efficient and independent through the combination of PV panels, geothermal energy via heat pump, FC, and different ESS, for buildings self-consumption in combination with passive refurbishment measures applying the NZEB concept [203]. This is the case of a private villa in Gothenburg (Sweden) [204] that employs PV/Geo/FC systems, with 144 kWh Li-ion batteries and 324 kg of hydrogen stored for short and seasonal storage respectively.

Besides, the HYDROGEN HOUSE PROJECT accounts for a 40 kW PV facility in combination with 20 kW of hydrogen FC and batteries [205]. Although it began as a private initiative in New Jersey (USA), currently, it belongs to a public partnership and focuses on education. In 2020, the project started the second phase, substituting the FC for a more developed one with 4–6 kW rated power and the lead-acid battery bank by a Li-ion one. WT and geothermal energy, along with high-pressure storage tanks were also added.

Similarly, hydrogen is a very interesting option to cover fully or partially the load demands from critical infrastructures like hospitals,

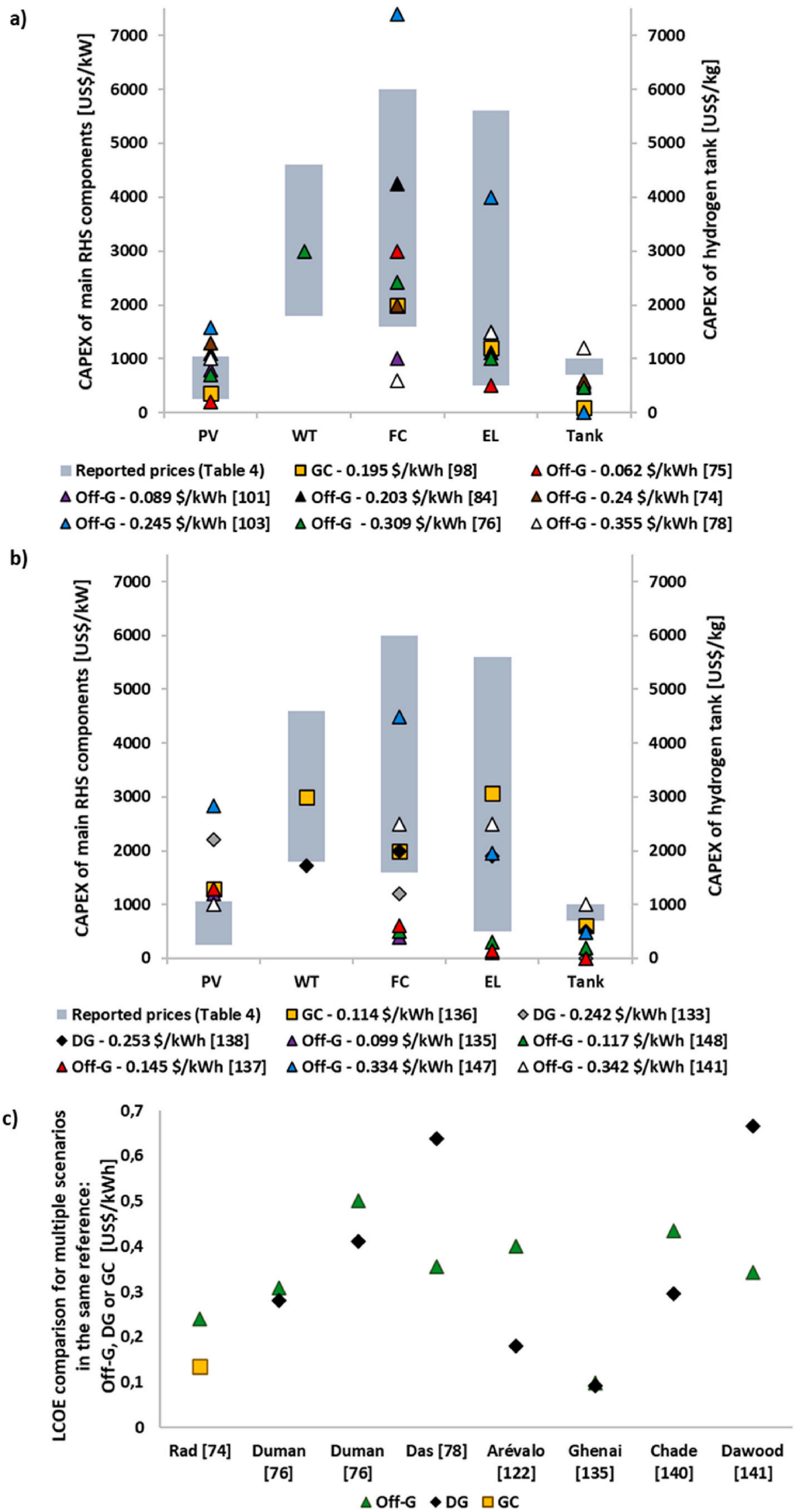

Fig. 5. CAPEX comparison of small-medium scale **(a)** and large-scale **(b)** RHS with competitive LCOE. **(c)** LCOE comparison in multiple scenarios in the same reference (triangles are employed for components costs from Off-G configurations, squares for GC systems, and diamonds for DG).

Table 6
Experimental RHS prototypes.

Configuration					Off-G/DG/GC	Load (kWh/d)	Application/Country	LCOE ($/kWh)	HRE (%)	Ref., year
RES (kW)	FC	EL	StH_2 (kg)	Bat (kWh)						
PV (8.8)	1	2	0.41	10.6	Off-G	23.8	Residential (Brazil)	1.351	–	[165], 2013
PV (9.7)	1.7	10	100	12	Off-G	15.6	Lighting (Italy)	0.8	24	[166], 2019
PV (9.7)	1.7	10	80	12	Off-G	13.2	Lighting (Italy)	0.8	24	[166], 2019
PV (3)	1.3	1.66	0.35 (MH)		Off-G	2–6	Residential (Mexico)	–	65	[167], 2016
PV/WT (6[a])	1.5	1	MH	4.4	GC	2.5 kWp	Residential (Spain)	–	–	[168], 2015
PV (5[a])	2.5	2.75	MH	19.2	Off-G	2 kWp	Laboratory (India)	–	–	[169], 2020
PV (5)	1	0.6	–	–	GC	1.5 kWp	Lighting (Italy)	–	–	[170], 2019
PV (5)	1.7	–	–	30.7	Off-G	1.31 kWp	Telecom (Italy)	–	–	[171], 2017
PV (5)	1.7	5	–	30.7	Off-G	1.28 kWp	Telecom (Italy)	0.48	–	[172], 2019
PV (5)	1.7	5	–	30.7	Off-G	1.28 kWp	Telecom (Italy)	–	–	[171], 2017
PV (2.5)	1.7	–	–	15.4	Off-G	0.87 kWp	Telecom (Italy)	0.54	–	[172], 2019
PV (3)	1.7	–	–	18.2	Off-G	0.87 kWp	Telecom (Italy)	–	–	[171], 2017
PV (5)	1.7	–	–	30.7	Off-G	0.72 kWp	Telecom (Italy)	–	–	[171], 2017
PV (5.5)	2.5	5	–	30.7	Off-G	0.65 kWp	Telecom (Italy)	0.66	–	[172], 2019
PV (2.5)	1.7	5	–	15.4	Off-G	0.65 kWp	Telecom (Italy)	–	–	[171], 2017
PV (5.5)	2.5	–	–	30.7	Off-G	0.35 kWp	Telecom (Italy)	–	–	[171], 2017
PV (50.2)	14.5	2.1 Nm^3/hr	1.34	100	GC	–	Research building (Italy)	0.41	30	[173], 2020
PV (11)	5	11	MH	144	GC	–	Residential (Italy)	0.6	–	[174], 2009
PV (20)	3.5	26	MH	20	GC	–	Residential (Japan)	–	34.5	[175], 2021
PV (2)	1.2	0.8	0.4	–	GC	–	Laboratory (Morocco)	–	31.5	[176], 2020
PV/WT (5[a])	6.2			–	Off-G	Variable	Laboratory (Algeria)	–	–	[177], 2020
PV (1.2)	1.2		–	2.2	Off-G	Variable	–	–	–	[178], 2014
PV/WT (0.14[a])	1.2		–	0.4	Off-G	Variable	Laboratory (Australia)	–	–	[179], 2015
PV(0.1) - WT (0.1)	0.04	0.25	MH	1	Off-G	Variable	Laboratory (Spain)	–	25.3	[180], 2010

Abbreviations: StH_2 (Stored Hydrogen), Bat (Battery), SC (Supercapacitor), MH (Metal Hydrides). Off-G (Off-Grid), DG (Diesel Generator), GC (Grid Connected), LCOE (Levelized Cost of Energy), HRE (Hydrogen Roundtrip Efficiency).
[a] Includes programmable load emulator for renewables.

remote facilities, data centers, or even to provide electricity in shows. This is the objective of the EVERY WH2ERE project [206,207] which provides energy in shows through transportable gensets with FC and stored hydrogen.

The power supply of telecom stations is also crucial nowadays. Therefore, they have been the subject of different studies aimed at avoiding energy shortfalls. FCpoweredRBS [171,172,208,209] uses a PV/FC system to ensure supply continuity, while ONSITE [210] proposes a containerized solution of FC and batteries. NH34PWR project [211] has designed a novel concept FC compact solution that obtains hydrogen from ammonia in developing countries. Likewise, mountain huts-related projects like SUSTAINHUTS [212,213] and COL DU PALET [214,215] use binary systems based on hydropower and PV respectively to partially cover huts load demand.

Concerning large-scale configurations with FC nominal capacities over 100 kW, many projects focus on coupling wind farms (onshore and offshore) and PV parks with electrolyzers for bulk hydrogen generation. Projects like NORTH2 aim at producing 800,000 T/year of hydrogen deploying a PEM electrolyzer with a 3–4 GW offshore wind farm in the Netherlands. The electrolyzer will be placed in a decommissioned drilling platform [216]. In Saudi Arabia, 4 GW wind and PV park along with electrolysis will produce 650 T/day of green hydrogen which will be converted into ammonia to end markets globally and then converted back to hydrogen [217].

Otherwise, we focus on the complete hybridization or in the standing FC systems providing grid and power services. In South Korea, Gyeonggi Green Energy FC park is powering 140,000 households each year and recovering heat for district heating using a Molten Carbonate FC (MCFC) [218]. Likewise, the Daesan Green Energy FC plant supplies electricity for 160,000 houses with a Phosphoric Acid FC (PAFC) [219].

Due to land availability restrictions, FC systems are usually hybridized with WT or a PV/WT combination with grid service purposes. HAEOLUS project proposes a solution to store hydrogen and cover the heat and power demands of a microgrid in the Norwegian Arctic [220,221]. Similarly, the DON QUICHOTE project [222,223] harvests energy from an MW-sized PV/WT plant and feeds an electrolyzer to generate hydrogen, which is compressed up to 350 bar for storage. Then, the PEMFC injects the generated electricity.

However, there is a changing trend concerning industrial systems, with current and future projects aligned with the utilization of waste streams with high hydrogen content or hydrogen as a by-product of the target finished goods to get heat and power for industry and even for grid injection [224].

Accordingly, projects like CLEARgen DEMO [225,226] or POWER-UP [227] benefit from waste hydrogen within refinery activities to power their plants. DEMOSOFC [228–232] and SOFCOM [187,188] projects use biogas or even produce bio syngas with CCSU from wastewater treatment plants (WWTP). Another alternative for these WWTP is to employ regenerated water to produce green hydrogen in combination with renewables. This is the case of a future project in Spain that will use regenerated water to obtain hydrogen using PV and biogas as renewable resources [233].

Nonetheless, large-scale hybrid systems are good opportunities for the industrial sector. For instance, GRINHY2.0 [234,235] introduces a novel rSOFC with a PV/WT plant supplying the electricity and the heat obtained. Waste steam from the steelmaking factory is used for rSOFC working on electrolyzer mode. On the contrary, when running on FC mode, the rSOFC generates heat, power, and oxygen for the process, as well as electricity for grid injection.

The amount of integrated large FC systems in the residential and building sector is continuously growing. Through projects like ELECTROU [236] which is going to deploy a multi-MW FC system to power supply Kings Cross neighborhood in London, the residential sector aims at cutting carbon emissions mainly associated with heat needs.

Table 7
Small-medium and large-scale pilot projects for power systems, industrial facilities, residential, buildings, and other infrastructures.

Configuration									Pilot project	Duration	Application/Country
Small-medium scale pilot projects											
WT (1,800) - TD (4,000)	PEMFC	75	80	PEM	1.5	–	200 bar		BIG HIT [184–186]	2016–2022	Power system (Scotland)
PV(10) - WT (110)	PEMFC	5	–	ALK-PEM	40–7	41–57	18/400 bar		WIND2H2 [244–246]	2008–2009	Power system (USA)
PV (62)	PEMFC	5	–	PEM	50	86	23/20 bar 7/350 bar	36	ELY4OFF [181–183]	2016–2019	Power system (Spain)
	SOFC	2–10	53	Biogas – Biosyngas					SOFCOM [187,188]	2011–2015	WWTP (Italy/Finland)
	SOFC	3	–	Biogas					ECOELECTRICITY [189]	2016–2019	Biomass plant (Spain)
PV(–) - WT (–)	PEMFC	100	–	PEM	80	–	–		REMOTE [73,198,199]	2018–2021	Residential (Spain)
PV(82) - WT (225)	PEMFC	50	50	PEM	25	63	13.9		REMOTE [73,198,199]	2018–2021	Residential (Norway)
	PEMFC-SOFC	0.7 to 100	95 (CHP)						ENEFARM [196,197]	2009 -	Residential (Japan)
HD (900)	PEMFC	50	50	PEM	25	63	27.8		REMOTE [73,198,199]	2018–2021	Residential (Greece)
PV (109)	PEMFC	30	90 (CHP)	ALK	$60Nm^3$/hr	–	4560/300 bar	187	SOCIAL HOUSING [201,202]	- 2022	Residential (Sweden)
PV (40)	–	20 (FC/Bat)	–	–	–	–	–	–	HYDROGEN HOUSE PROJECT [205]	2006 -	Residential (USA)
PV (–)	PEMFC	6.2	–	–	–	–	30 bar		OFF-GRID FACILITY [247]	- 2016	Residential (Switzerland)
	PEMFC-SOFC	0.7 to 5	95 (CHP)						CALLUX [190]	2008–2016	Residential (Germany)
	PEMFC-SOFC	0.7 to 5	95 (CHP)						ENE.FIELD [191–193]	2012–2017	Residential
	PEMFC-SOFC	0.7 to 5	95 (CHP)						PACE [194,195]	2016–2021	Residential
PV (101.1)	PEMFC	4	–	AEM	9.6	–	7.5/30 bar	192	PHI SUEA HOUSE [200]	2013–2016	Residential (Thailand)
PV (10)	rSOFC	3	–	rSOFC	3	–	–		INNOVATHUIS [248]	–	Residential (Netherlands)
	SOFC	0.4 to 3	–						RoRePower [249,250]	2019–2022	Residential
	SOFC	1–2	60						SOFT-PACT [251]	2011–2015	Residential (UK)
	SOFC	1.5	–						TRISOFC [252,253]	2012–2015	Residential (UK)
PV(20) - STC(13)	PEMFC	1.5	–	ALK	11	–	324/300 bar	144	OFF-GRID PRIVATE VILLA [204]	–	Residential (Sweden)
PV(31) - Geo(100)	–	–	–	–	–	–	–		OFF-GRID FACILITY [254]	–	Residential (Switzerland)
	PEMFC	25–100	52				350 bar		EVERY WH2ERE [206,207]	2018–2023	Gensets
PV (126)	PEMFC	28	–	–	–	–	–	500	STONE EDGE FARM [255,256]	2013 -	Winery (USA)
	SOFC	10	85 (CHP)						ONSITE [210]	2013–2017	Telecom (Italy)
PV (–)	PEMFC	2.5	–	AEM	2.5	–	5		COL DU PALET [214,215]	- 2015	Mountain hut (France)
PV (4–10)	PEMFC	1.7–2.5	–	ALK	5	–	30 & 300 bar	7.7 to 30.7	FCpoweredRBS [171,172,208,209]	2012–2015	Telecom (Italy)
HD (30)	PEMFC	1.6	–	PEM	3	–	3.3/50 bar	73.1	SUSTAINHUTS [212,213]	2016–2021	Mountain hut (Spain)
	PEMFC	1.2	–	Ammonia-fuelled			–		NH34PWR [211]	2010–2013	Telecom (Namibia)
	PEMFC	1.2	–	Ammonia-fuelled					TOWER POWER [257]	2011–2014	Telecom (sub-Sahara Africa)
Large-scale pilot projects											
RES (MW)	**FC Type**	**(MW)**	**Eff. (%)**	**EL Type**	**(MW)**		**StH_2 (kg)**	**Bat (kWh)**			

(*continued on next page*)

Table 7 (*continued*)

Configuration								Pilot project	Duration	Application/Country
						Eff. (%)				
	MCFC	59	–	Biogas				GYEONGGI GREEN ENERGY FC PARK [218]	2012–2014	Power System (South Korea)
	PAFC	50	–	By-product of petrochemical complexes				DAESAN GREEN ENERGY FC PLANT [219]	2017–2020	Power System (South Korea)
WT (45)	PEMFC	0.12	89	PEM	2.5	–	1613.4	HAEOLUS [220,221]	2018–2021	Power Systems (Norway)
PV (0.8) - WT (1.5)	PEMFC	0.12	–	ALK	0.156	–	(350 bar)	DON QUICHOTE [222,223]	2012–2018	Power Systems (Belgium)
	PEMFC	0.1	–	By-product of a Chlor-alkali plant				GRASSHOPPER [258,259]	2018–2020	Power Systems (Netherlands)
	PEMFC	1	–	Waste hydrogen				CLEARgen DEMO [225,226]	2012–2020	Refinery (Martinique)
	MCFC	0.8	–	Waste hydrogen				MCFC-CONTEX [260]	2010–2014	Coal Plant (Spain)
WT (30)	rSOFC	0.72	52	rSOFC	0.72	84		GRINHY2.0 [234,235]	2019–2022	Refinery (Germany)
	ALK	0.5	–	Waste hydrogen				POWER-UP [227]	2013–2017	Refinery (Germany)
	SOFC	0.174–0.094[a]	53	Biogas				DEMOSOFC [228–232]	2015–2020	WWTP (Italy)
	MCFC	1.6–1[a]	–					ELECTROU [236]	2018–2023	Residential (UK)
	PEMFC - SOFC	0.1 to 0.25	95 (CHP)					ENEFARM [196,197]	2009 -	Residential (Japan)
	DMFC	1.4	–					HARTFORD HOSPITAL [237]	- 2013	Hospital (USA)
	SOFC	0.75	–					MORGAN STANLEY OFFICE [238]	- 2016	Office Building (USA)

Abbreviations: HD (Hydraulic), Bio (Biomass), ALK (Alkaline), AEM (Anion Exchange Membrane), CHP (Combined Heat and Power), MCFC (Molten Carbonate FC), PAFC (Phosphoric Acid FC), DMFC (Direct Methanol FC), rSOFC (Reversible SOFC).

[a] Thermal rated power.

Additionally, private buildings like HARTFORD HOSPITAL [237] or MORGAN STANLEY OFFICES in New York [238] already opt for large FC systems to decarbonize their energy consumption.

Conversely, other projects aim at injecting hydrogen into the natural gas grid, achieving this way greater hydrogen blending or installing dedicated hydrogen networks with the corresponding GHG reduction. This is the case of the GREEN HYSLAND project in Mallorca (Spain) [239], where 16.4 MW PV plant and 10 MW EL will be coupled to produce green hydrogen to be blended into the natural gas grid. Besides, specific hydrogen pipelines are going to be installed to supply an industrial state, hydrogen filling stations, etc., enabling 100% green hydrogen generation and distribution to end-users.

This project, along with BIG HIT [184–186] or PHI SUEA HOUSE PROJECT [129] belongs to the HYDROGEN VALLEY PLATFORM [240] that has been created by Mission Innovation global initiative [241] in collaboration with FCH JU [242] to enable a large-scale deployment. With an investment of over 30 billion €, the platform collaborates globally to implement hydrogen-related facilities, creating green hydrogen supply chains and infrastructures for different economic sectors. Likewise, the manufacturer Toyota has recently announced the Woven City project [243], a “living laboratory” boosted by renewable energies (mainly PV) and hydrogen fuel cells at the base of Mountain Fuji in Japan. This city provides a real sustainable environment for 2000 inhabitants based on RHS systems for both stationary and transport.

The most relevant outcomes obtained through the evaluation of pilot projects are:

i. Small-scale systems are the main selected alternative for residential and buildings, where micro-cogeneration FC units are being boosted due to lower complexity and space requirements.
ii. Medium-scale schemes contribute to the decarbonization of micro-grids, residential communities, and other remote applications using renewable hydrogen-based schemes.
iii. Large-scale pilot projects focus on the decarbonization of the electricity grid and industrial applications using multi-MW fuel cells to get heat and power and benefiting from waste streams with high hydrogen content. The waste heat produced can be used for district heating or within industrial processes.

2.4. Current market penetration: commercially available devices

Small-medium scale commercial devices focus on combined heat and power FC systems for residential, commercial, and other buildings, being mainly fuelled by natural gas, LPG, or biofuels. These solutions are easier to integrate and more compact than RHS alternatives, which need extra room to place PV panels, wind turbines, or storage tanks. Now, they involve high capital investments despite the declining trend experimented in the last decade [15].

Hence, micro-cogeneration appliances aim at securing capital expenditures similar to conventional natural gas or propane boilers for both PEMFC and SOFC-based systems at 2030 [65]. Additionally, countries like Germany or Japan are partially subsidizing both hybrid systems and mCHP, boosting their use among users [46,201]. Suppliers like BDR Thermea, Bosch, Sunfire, or Viessmann through ENEFIELD and PACE projects [49], or Toshiba, Panasonic, Denso, Fuji, and Kyocera through ENEFARM [196,197] have developed a wide variety of compact solutions for different load requirements.

On the contrary, renewable hydrogen-based configurations imply higher requirements than mCHP, being necessary to purchase renewable generators (usually PV panels) and hydrogen chain technologies separately, but they are facing a decreasing trend in CAPEX thanks to their development. Some companies are creating tailored hybrid-RES solutions. For instance, Home Power Solutions has created PICEA, a compact solution that integrates the hydrogen chain (FC, electrolyzer, and tank) to be coupled with an externally installed renewable source [261]. It also includes compression up to 300 bar, batteries, and heat storage in a water tank. Similarly, the Australian company LAVO has developed a hydrogen battery system with hydrogen storage in metal hydride tanks with an autonomy of 40 kWh and a peak power of 5 kW [262]. Besides, SOLENCO POWER BOX [263] consists of a reversible-SOFC for a compact mCHP running on hydrogen with solar energy.

Other manufacturers like BALLARD, TOSHIBA, or PLUG POWER have created FC systems like FCgen-H2PM [264], H_2ONE [265], or PLUG POWER GENSURE [266] for off-grid and backup applications. Additionally, recent reports analyze the possibility of combining low enthalpy heat pumps with numeric control and hybrid systems to provide both heat and power for buildings taking advantage of high efficiencies from heat pumps and reducing the investment needed [267].

From the hybridization point of view, the focus of large-scale commercial systems is on grid balancing services where PV and wind farms can harvest huge amounts of energy. These facilities involve other considerations like more advanced BoP, utilities and process automation, power supply, electronics, and bigger stacks [268]. Thus, the analyzed pilot projects aim at lowering CAPEX, OPEX, and contingencies costs for wide deployment. Both MW-scale fuel cell and electrolyzer capital expenditures are targeted at 1500 and 400–800 US$/kW respectively [65]. Alkaline electrolyzers are the most developed ones, followed by PEM-based ones that are being employed for capacities beyond 10 MW. Besides, solid oxide electrolyzers are still under development with promising efficiencies reported. Similarly, PEMFC has broader market uptake, with a higher lifetime than alkaline fuel cells. Additionally, reversible-SOFC is being researched to reduce the infrastructure and equipment needed as it can be run in both electrolyzer and fuel cell modes.

Several companies are creating large-scale FC systems with rated powers over 100 kW based on different FC technologies: PAFC, MCFC, SOFC, and PEMFC [49]. For instance, Bloom Energy agreed with Apple to provide a 4 MW biogas-fuelled FC and 16 MW of rated PV capacity along with battery storage for 100% self-sufficiency in a new campus in California [269,270]. The manufacturer Doosan FC received the order to build a 30.8 MW FC system to cover the heat and power demands of a residential complex in South Korea [271]. Likewise, FC Energy installed 5.6 MW FC capacity at Pfizer’s facility in Connecticut [272].

Therefore, large-scale hybrid-RES systems with improvements in efficiency, reliability, and cost-competitiveness are paving the way toward carbon neutrality by 2050.

3. Regulations and barriers

The implementation of RHS for stationary sector power supply needs to consider factors beyond techno-economic ones to ensure their feasibility. Despite the particularities of small, medium, and large-scale systems, cross-cutting boundaries are impacting different applications, being some of them also shared with the transport sector. Therefore, Table 8 collects and sorts these barriers in the legal framework, environmental impact, infrastructures, safety, and social factors.

Moreover, it gathers actions and milestones from general to particular and whose target is removing barriers for every analyzed impact factor. These proposed solutions arise from blocking factors evaluation and include specific information from different projects, international agencies, policymakers, and stakeholders related to stationary applications.

Table 8
Stationary RHS barriers and proposed actions.

Category	Barriers and needs	Actions and milestones
Legal and policy framework [273–275]	- No specific regulatory and legal framework applicable to hydrogen as an energy carrier. - Lack of supporting policies for RHS.	- Identification of current legislation and gaps to be covered. - Promote large green hydrogen generation and blending through tax exemptions. - Integrate green hydrogen into refineries carbon intensity calculations. - Create a guarantee of origin certifications for green hydrogen and electricity from RHS. - Subsidies for RHS in the residential and buildings sector.
Environmental impact [276–278]	- 95% of total hydrogen production comes from fossil fuels (SMR and by-product from chlorine production). - RES broad deployment is associated with land restrictions and impacts on the biosphere. - Location with great RES potential may have water availability restrictions.	- Large-scale implementation of RHS to cut GHG emissions and avoid acidification associated with fossil fuels-based hydrogen and energy generation. - Hydrogen-RES hybridization to reduce RES land employment. - Promote hydrogen storage as it represents a lower footprint than pumped hydro, batteries, or compressed air facilities. - Recover water produced during FC operation in evaporation columns. Use regenerated water from wastewater treatment plants. Create specific standards for proper water management.
Infrastructures [279–281]	- Lack of transport, distribution, and storage infrastructure. - Limited access and availability to hydrogen in residential and buildings. - Low hydrogen blending percentages allowed.	- Invest in R&D to enhance infrastructure efficiency. - New hydrogen storage methods like metal hydrides for small-medium scale systems. - Salt caverns, depleted oil and gas reservoirs, liquid hydrogen, or ammonia for large-scale systems. - Create a dedicated hydrogen network and allow higher blending in the natural gas grid. - Subsidize natural gas-fuelled mCHP units for residential and buildings, and their upgrade to allow higher hydrogen blending or pure hydrogen network.
Safety [282,283]	- Hydrogen causes material embrittlement. - Fire and explosion risks. - Hydrogen is odorless and colorless, with corresponding detection concerns.	- Creation and harmonization of regulations, codes, and standards (RCS). - Development of reliable sensors and uniform metering procedures for rooms and confined areas in residential and buildings. - Safety protocols for high-pressure hydrogen handling. - Detaching of large RHS plants from storage facilities to avoid deflagration/detonation propagation. - Definition of safety distances and protocols for specific stationary applications.
Societal factors [14,284]	- End-users safety concerns and knowledge gaps.	- Promote hydrogen and hybridization potential benefits with similar strategies as ones used for RES. - Creation of specific, accessible legal framework and RCS. - Education, information, dialogue, and experience to boost end-users awareness and knowledge. - Involve end-users in RHS development. - Benefit RHS with domestic purposes. - Train end-users to apply RCS safely.

4. Concluding remarks and prospects

Reducing GHG emissions forces human beings to find feasible and reliable RES. Despite growing trends on renewables deployment, their intermittency leads to uncertainties, requiring energy storage systems to smooth the power variability. Thereby, hydrogen has been recognized as a versatile alternative to traditional ESS for large-scale decarbonization of different economic sectors. In particular, the stationary sector (power generation, industry, residential and buildings, and backup systems) represents a major source of CO_2 emissions in the world.

This extensive framework has raised the current status and different challenges that lie ahead for the broader implementation of RHS in the stationary sector through the examination of published studies, relevant pilot projects and commercial devices available in the market. Besides, additional constraints are identified to enable a low-carbon scenario in the mid to long term.

Theoretical publications show the prevalence of mature RES (PV and WT) in combination with hydrogen chain technologies as a reliable and cost-competitive alternative to fossil fuel-based generation schemes. Levelized cost of energy, loss of power supply probability, self-sufficiency ratio, hydrogen roundtrip efficiency, and renewable fraction are the most relevant techno-economic parameters analyzed within theoretical studies, having a major impact on the renewable hydrogen-based configuration.

Lab-scale prototypes offer interesting information on the development of energy management systems and integration methods focusing on RHS performance and dynamic response to fluctuations through on-field and lab trials. Nevertheless, these schemes still reflect economic drawbacks, so larger-scale projects are required to minimize LCOE.

Accordingly, countries like Japan or Germany are deploying small-scale mCHP units through pilot projects running on natural gas or LPG to decarbonize urban areas. These units are cost-effective, without needing additional room for components, but they achieve limited reductions of CO_2 emissions. Conversely, RHS are suitable for medium-scale applications and single-family households where the economy of scale dumps the investment and reduces the payback time. Besides, large power generation designs and industrial pilots reduce curtailed energy levels and leverage waste streams with high hydrogen content to generate synthetic fuels or to obtain heat and power for their plants respectively.

The current market trend reveals the utilization of mCHP devices by end-users and future prospects aimed at equipment upgrading and upstream decarbonization of power systems and industrial facilities with hydrogen re-electrification and blending in natural gas networks. Additional progress on the efficiency of the alternative configurations, the BoP, and capital expenditures constitute a turning point for the economic feasibility. Thus, the improvement of energy management systems will increase the direct use of RES and its integration within the hydrogen chain. Moreover, the mass production and the modularity of fuel cells, electrolyzers, and compressors will contribute to decreasing the total cost of ownership and the investment required as already proved with other technologies such as PV panels. This mass production will require the substitution of expensive noble metal-based catalysts by new non-PGM materials that achieve a good trade-off between durability, stability, and mass transport [285].

Nevertheless, hybrid systems require focused, consistent and specific policies to establish a solid legal framework to create a robust hydrogen infrastructure, which considers aspects like storage needs or refurbishment of old facilities and to reduce the environmental footprint associated with water management and land requirements. Furthermore, defining proper regulation, codes and standards for safe hydrogen management combined with dialogue, education and experience has been highlighted as crucial to encourage end-users awareness and thus, their acceptance.

Declaration of competing interest

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

Acknowledgment

This research is being supported by the Project ENERGY PUSH SOE3/P3/E0865, which is co-financed by the European Regional Development Fund (ERPF) in the framework of the INTERREG SUDOE Programme and the Spanish Ministry of Science, Innovation, and Universities (Project: RTI2018-093310-B-I00).

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