Received: 31 July 2021 Revised: 20 September 2021 Accepted article published: 24 September 2021 Published online in Wiley Online Library: 21 October 2021

(wileyonlinelibrary.com) DOI 10.1002/jctb.6938

The role of hydrogen-based power systems in the energy transition of the residential sector

Víctor M Maestre, Alfredo Ortiz and Inmaculada Ortiz*

Abstract

The unsustainable and continuous growth of anthropogenic emissions of greenhouse gases (GHG) has pushed governments, private companies and stakeholders to adopt measures and policies to fight against climate change. Within this framework, increasing the contribution of renewable energy sources (RES) to final consumed energy plays a key role in the planned energy transition. Regarding the residential sector in Europe, 92% of GHG emissions comes from 75% of the building stock that is over 25 years old, and highly inefficient. Thus, this sector must raise RES penetration from the current 36% to 77% by 2050 to comply with emissions targets. In this regard, the hybridization of hydrogen-based technologies and RES represents a reliable and versatile solution to facilitate decarbonization of the residential sector. This study provides an overview and analysis of standalone renewable hydrogen-based systems (RHS) focusing on the residential and buildings sector, as well as critical infrastructures like telecom stations, data servers, etc. For detailed evaluation of RHS, several pilot plants and real demonstration plants implemented worldwide are reviewed. To this end, a techno-economic assessment of relevant parameters like self-sufficiency ratio, levelized cost of energy and hydrogen roundtrip efficiency is provided. Moreover, the performance of the different configurations is evaluated by comparing the installed power of each component and their energy contribution to cover the load over a defined period of time. Challenges ahead are identified for the wider deployment of RHS in the residential and buildings sector.

Keywords: renewable hydrogen; residential and buildings sector; fuel cell; self-sufficiency; technical feasibility; cost-competitiveness

NOMENCLATURE

AC	alternating current
Bat	battery
BoP	balance of plant
$C_{ann,tot}$	total annualized cost of a system, US$
CHP	combined heat and power
DC	direct current
DG	diesel generator
E_{BAT}	total energy stored or provided by battery, kWh
E_{COMP}	total energy consumed by compressor, kWh
E_{DG}	total energy generated by diesel generator, kWh
E_{EL}	total energy consumed by electrolyzer, kWh
E_{FC}	total energy generated by fuel cell, kWh
E_{GC}	total imported energy from the grid, kWh
EL	electrolyzer
E_{load}	total energy consumed by load, kWh
EMS	energy management strategy
E_{RES}	total energy generated by renewable energy sources, kWh
ESS	energy storage system
$E_{UNCOVERED}$	total uncovered energy load, kWh
FC	fuel cell
FCEV	fuel cell electric vehicle
GC	grid connection
GHG	greenhouse gases
HRE	hydrogen roundtrip efficiency, %
LCOE	levelized cost of energy, US$ kWh^{-1}
mCHP	micro-combined heat and power
nZEB	nearly zero emissions building
PEMFC	proton exchange membrane fuel cell
P_{EL}	total installed capacity of electrolyzer, kW
P_{FC}	total installed capacity of fuel cell, kW
P_{RES}	total installed capacity of renewable energy sources, kW
PV	photovoltaic
RCS	regulations, codes and standards
RES	renewable energy sources
RHS	renewable hydrogen-based systems
SMEs	small–medium enterprises
SMR	steam methane reforming
SOC	state of charge
SOFC	solid oxide fuel cell
SSR	self-sufficiency ratio, %
TCO	total cost of ownership
WT	wind turbine
η_{EL}	fuel cell efficiency, %

* *Correspondence to: I Ortiz, Chemical and Biomolecular Engineering Department, University of Cantabria, Av. Los Castros 46, 39005 Santander, Spain. E-mail: ortizi@unican.es*

Chemical and Biomolecular Engineering Department, University of Cantabria, Santander, Spain

η_{FC} electrolyzer efficiency, %

INTRODUCTION

Since the first Industrial Revolution at the end of the 18th century, the anthropogenic contribution to the increase in greenhouse gases (GHG) has triggered an unsustainable climate change situation. As a result, governments, private companies and stakeholders have been forced to define and implement a series of measures and policies to limit GHG emissions.[1-3] One of the major factors impacting the exponential growth of pollutants is the increase in energy requirements, and therefore other related problems such as energy poverty compromising the social wellbeing of the most vulnerable citizens.[4]

In this sense, the large-scale installation of renewable energy systems (RES) is essential to achieve the necessary energy transition. By 2020, more than 2500 GW of RES capacity were installed worldwide, with solar photovoltaic and wind energy, both onshore and offshore, predominating.[5] However, the contribution of RES to the energy mix barely reaches 10% of the final energy consumed globally, and a sixfold increase is required to comply with the Paris agreement by 2050.[6]

To ensure a higher RES penetration and address their intermittency and shifting nature, the deployment of energy storage systems (ESS) is key to boost systems reliability. Several traditional ESS have been implemented and developed so far like batteries, compressed air, flywheels or pumped water, but they have important drawbacks related to their environmental impact and waste management.[7] In this regard, hydrogen has emerged as a very promising and feasible energy carrier.[8]

Despite nowadays more than 95% of total hydrogen being produced by steam methane reforming (SMR),[9] the production of green hydrogen obtained through water electrolysis and renewable energy is being highly promoted.[10] Moreover, hydrogen can be obtained from industrial waste streams with high hydrogen content[11,12] requiring an intermediate purification stage.[13,14] This hydrogen is used for various purposes: to balance the grid when needed using a fuel cell (FC) system (power-to-power);[15] to be blended in the natural gas grid or used as feedstock in industrial processes in refineries, steelmaking or chemical plants (power-to-gas);[16] to be used as fuel in the transport sector (power-to-fuel);[17,18] or to be employed as a valuable commodity to produce chemical compounds or synthetic fuels (power-to-feedstock).[19] This versatility makes hydrogen a very interesting alternative, and for this reason, leading countries and regions like the USA,[20,21] Japan,[22,23] Canada,[24] Australia[25,26] and Europe[15] have defined a series of roadmaps and strategies for the development of hydrogen technologies.

One of the sectors where renewable hydrogen-based strategies (RHS) can represent a step towards atmosphere decarbonization is the residential and buildings sector, as well as other stationary applications such as telecom stations, data servers, etc. The current RES share in energy use in buildings is 36% for both heat and power. This value needs to be increased up to 77% by 2050 to comply with emission reduction targets.[27] The most employed RES in buildings are photovoltaic (PV) panels, solar thermal collectors, biomass, geothermal and heat pumps.[28] In Europe, the energy consumption in buildings is responsible for 40% of the total energy consumed and 36% of GHG emissions.[29] Besides, most of the buildings are inefficient as they are older than 25 years and contribute to over 90% of emissions associated with this sector. Residential buildings account for three-quarters of the total building stock. These are divided into single-family houses (64%) and apartment blocks (36%). The remaining 25% of buildings includes offices, hotels, educational buildings, sports facilities and hospitals among others.[30] Therefore, efforts are focused on the renovation of old buildings to improve their energy efficiency. These measures may potentially reduce the energy consumption of buildings by 6% and may result in CO_2 emissions savings up to 5%. Moreover, new buildings must have a minimum renewable energy contribution of 70%.[31] However, these measures are not enough to reach the planned decarbonization of the building sector.

In this context, hybrid renewables–hydrogen schemes represent reliable and adaptive alternatives, from microgrids and residential communities to small backup systems and detached households. The hybridization of RES with traditional energy storage systems has been broadly investigated so far.[32,33] Different ways of integrating hydrogen and RES across energy sectors such as power-to-gas for green hydrogen production, power-to-fuel within the transportation sector or power-to-feedstock with industrial purposes have aroused great interest in the last decade. Several publications address simulated hybrid renewables–hydrogen systems.[34] Furthermore, recent studies have analyzed novel configurations to be implemented in buildings such us trigeneration systems (those providing electricity and covering heating and cooling demands) or reversible solid oxide fuel cells operating as both fuel cell and electrolyzer.[35,36] In this context, this paper focuses on off-grid and self-sufficient configurations in the residential and buildings sector and evaluates current pilots and demonstratives worldwide.

This study thoroughly analyzes each type of configuration and load reported focusing on the most relevant techno-economic aspects such as the self-sufficiency ratio achieved with each installation, the levelized cost of energy obtained and the efficiency of the hydrogen chain. In addition, the performance of facilities is evaluated through a comparison of ratios between installed power of RES, fuel cell and electrolyzer to their final energy contribution over a period of time. Besides, a breakdown of energy contributions and the different possible control strategies is made. Finally, the future challenges that RHS will face to become a real alternative in the medium term for the decarbonization of the residential and buildings sector are identified.

METHODOLOGY

RHS are diverse and have different particularities depending on the type of load to be supplied, the meteorological conditions of the location, the type of technologies to be used and the budget available for the execution of the installation, among others. Therefore, this evaluation requires a deep understanding of RHS, energy balances within the system, implemented control strategies and key indicators defined to assess and compare the performance of different configurations in a uniform and harmonized manner. Figure 1 depicts a general schematic diagram of a renewable hydrogen-based scheme that is divided into three main parts: (i) power generation, (ii) energy storage and supply and (iii) load demand.

Standalone RHS employ different RES for power generation, usually solar or wind energy harvested using photovoltaic (PV) panels and/or wind turbines (WT), or a combination of them. RES may be connected to AC, DC or AC/DC power lines depending on their nature. For instance, PV panels generate DC, while WT, hydro turbines and tidal turbines produce AC. To ensure an

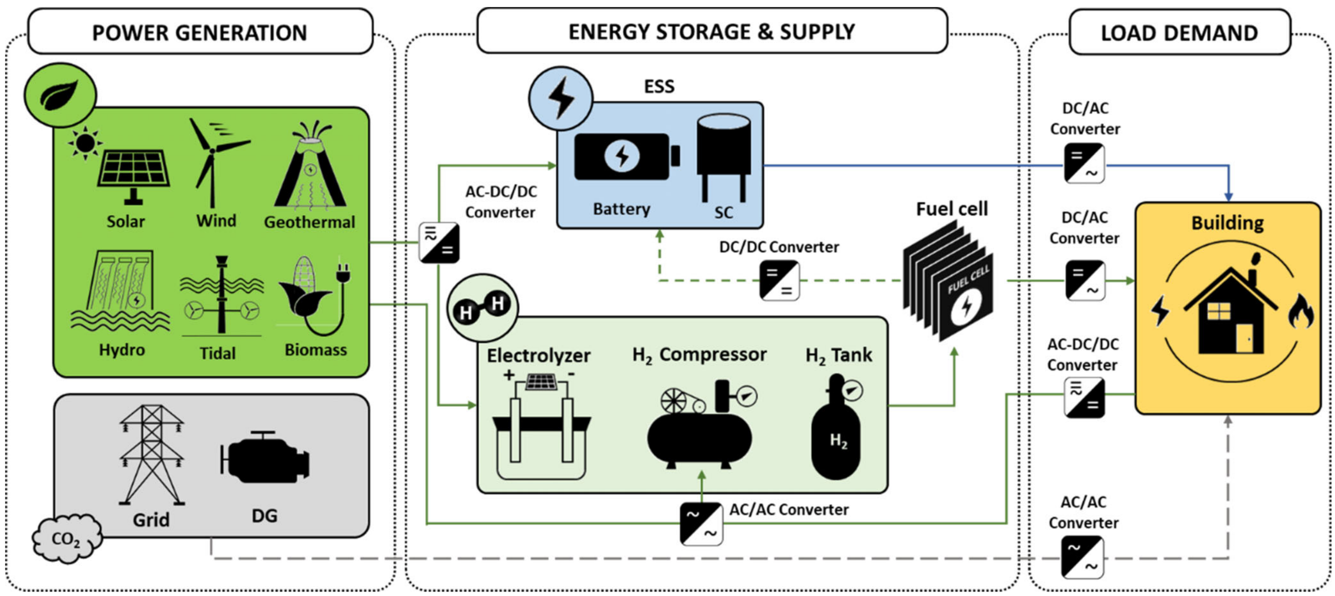

Figure 1. Schematic diagram of a RHS including RES and fossil fuel-based power generation (through grid and DG), energy storage and supply (through hydrogen-based technologies and other ESS) and load demand (considering required power converters).

appropriate integration and energy flow of RES within the system, power AC/AC and DC/AC converters are installed between RES, ESS and the load. Moreover, grid connection (GC) or dispatchable backup generators such as diesel generators (DG) may be considered to ensure supply continuity and reduce the size of ESS. Nevertheless, they generate CO_2 emissions as they employ fossil fuels to obtain power (the emissions associated with GC depend on the electricity mix of each location).

The buildings sector is dominated by residential applications, whose consumption periods can be differentiated into peak demand (times of high consumption) and off-peak demand (times of low consumption). Peak consumption occurs during the late afternoon and evening, while the off-peak occurs during the early morning and early evening. Average consumption varies according to the type of dwelling (single-family or apartment) and location, as the climate has a great influence (between 55% and 67% of final energy consumption in this sector corresponds to heating energy).[30] On the other hand, commercial and similar buildings have relatively stable consumption periods during the opening hours of the establishments, and practically zero during the rest of the day. Therefore, solutions are required that allow energy to be stored efficiently during off-peak periods of consumption and maximum RES generation, and that provide the necessary energy at times of maximum demand and low or zero RES production.

In this regard, the energy excess from RES can be reused employing different ESS such as conventional electrochemical devices (supercapacitors or batteries) or new energy carriers like hydrogen. Green hydrogen is obtained from water electrolysis avoiding GHG emissions. Thus, electrolyzers would be driven by RES surplus in the present case. The process byproducts are oxygen that can be directly released to the atmosphere and heat that can be recirculated and used for domestic heating purposes.

The generated hydrogen is then stored at low or high pressures (requiring an intermediate compressor) depending on the specific characteristics of the installation. The compression stage negatively affects the total cost of ownership (TCO) of an installation due to the high energy consumption, the need for auxiliary equipment to ensure its correct functioning and safety during operation and the low technology readiness level reached for this application. The economy of scale is also fundamental for this equipment, since even for low hydrogen flows the market availability is very limited due to the high price of the materials used in their manufacture. The most commonly used compressors are mechanical (reciprocating piston, linear piston, diaphragm, liquid), although there are several technologies under development (cryogenic, metal hydride, electrochemical, adsorption) that offer better performance in terms of energy efficiency, volumetric density or noise.[37]

Moreover, metal hydride tanks, steel tanks with different levels of fiber reinforcement and composite tanks are under development allowing higher pressures, and, therefore, higher autonomies in reduced spaces. Hydrogen is re-electrified in a fuel cell that generates DC. The electricity generated can be used to meet a building's demand directly or to charge the ESS and then supply power to the load. In both cases an intermediate DC/AC converter is required.

The energy contribution of each component within the renewable hydrogen-based scheme is detailed in Fig. 2. Depending on the configuration, the interaction between energy storage devices (battery and hydrogen value chain) may vary. On the one hand, whenever RES energy (E_{RES}) is higher than the load consumption (E_{LOAD}), the demand is directly covered and the surplus energy is stored in the form of hydrogen produced in the electrolyzer (E_{EL}), which can be compressed if a compressor (E_{COMP}) is installed. If there is also a battery pack aimed solely at covering the load (not connected to the electrolyzer), the surplus energy will be additionally used for battery recharge (E_{BAT}). In other configurations with direct connection between the battery and the electrolyzer, it is the battery that first stores energy (E_{BAT}) until a defined threshold state of charge is reached. After this, the electrolyzer starts generating hydrogen (E_{EL}) from the remaining excess renewable energy, but with the electrolyzer being powered directly by the battery. Finally, in specific cases where the

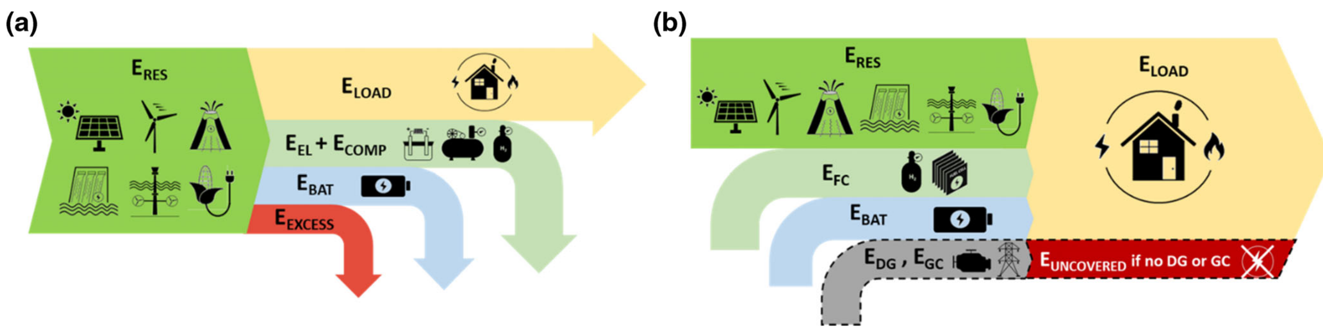

Figure 2. Energy balance of a typical RES/EL/FC/Bat configuration for (a) $E_{RES} > E_{LOAD}$ and (b) $E_{LOAD} > E_{RES}$ with possible ancillary DG or GC. Abbreviations: E_{RES}, energy generated by RES; E_{LOAD}, load consumption; E_{EL}, energy consumed by the electrolyzer; E_{COMP}, energy consumed by the compressor; E_{BAT}, energy stored/provided by the battery; E_{FC}, energy generated by the fuel cell; E_{DG}, energy produced by diesel generator; E_{GC}, energy imported from the grid; E_{EXCESS}, energy excess; $E_{UNCOVERED}$, uncovered energy load.

system is not able to assimilate all the stored energy, the excess will be curtailed or injected back into the grid to obtain benefits according to the self-consumption policy of each location.

Otherwise, if RES production (E_{RES}) is lower than the load (E_{LOAD}), ancillary energy is needed to fulfill the consumption requirements. Therefore, the fuel cell (E_{FC}) and the battery (E_{BAT}), if any, provide the remaining energy. In the case of a direct connection between the fuel cell and the battery, it is the fuel cell that starts charging the battery when its charge decreases to a defined value. The fuel cell stops working once the battery has been charged up to the defined maximum value. Moreover, if load demand is still higher than the sum of E_{RES}, E_{FC} and E_{BAT}, an additional DG (E_{DG}) or GC (E_{GC}) may be employed to meet all the requirements, but this implies the acceptance of pollutant emissions. If these backup systems are not employed, there will be an energy shortfall ($E_{UNCOVERED}$).

To properly manage the energy flows of the renewable hydrogen-based configuration, an optimal control strategy plays a fundamental role. These strategies ensure the correct supply of electricity demand, as well as efficient energy storage. This avoids the oversizing of certain components and the installation of redundant equipment. Depending on whether a battery bank is used in the system, Fig. 3 displays different energy management strategies:

(1) Battery state of charge (SOC)-based strategy: the control system reads the difference between E_{RES} and E_{LOAD}. Depending on whether such difference is positive or negative and based on the thresholds set for the maximum and minimum SOC of the batteries, the control system acts as follows: if the difference is negative, the energy is stored in the form of hydrogen or in the batteries (if there is sufficient storage capacity); if it is negative, the system activates the FC, batteries or auxiliary equipment to cover the load.
(2) Hydrogen tank SOC-based strategy: in this case, the control strategy employs hydrogen tank SOC thresholds to either store or consume energy.
(3) Hybrid battery–hydrogen tank SOC-based strategy: this energy management system (EMS) considers both battery and hydrogen tank SOC to manage the energy flows within the configuration.

More recent and developed systems include predictive control, forecasting and parametric operation of the components (for instance, electrolyzer or fuel cell operating at different capacities depending on the available energy and load requirements respectively). In all cases, a DG or GC may be included to avoid energy shortfalls.

Finally, different techno-economic parameters are defined to evaluate the size requirements and performance of every analyzed pilot plant. These parameters are:

$$\text{Self-sufficiency ratio: SSR} = 1 - \frac{E_{GC}}{E_{load}} \quad (1)$$

$$\text{Levelized cost of energy: LCOE} = C_{ann,tot}/E_{load} \quad (2)$$

$$\text{Hydrogen roundtrip efficiency: HRE} = \eta_{EL} \cdot \eta_{FC} \quad (3)$$

$$\text{Installed capacity ratio FC/RES}: \frac{P_{FC}}{P_{RES}} \quad (4)$$

$$\text{Total generated energy ratio FC/RES}: \frac{E_{FC}}{E_{RES}} \quad (5)$$

$$\text{Installed capacity ratio EL/RES}: \frac{P_{EL}}{P_{RES}} \quad (6)$$

Here E_{GC} is the total energy imported from the grid, E_{load} is the total load consumption, $C_{ann,tot}$ is the total annualized cost of the system and η_{EL} and η_{FC} are the electrolyzer and FC efficiencies, respectively. Moreover, P_{FC}/P_{RES} is the ratio between the installed capacity of the FC and the installed capacity of RES, P_{EL}/P_{RES} is the ratio between EL and RES installed capacities and E_{FC}/E_{RES} is the ratio between total generated energy by both FC and RES. These ratios have been defined to evaluate the relationship between the size of the facilities and their energy contribution to meet demand. Thus, a high ratio of installed power of fuel cell and renewables together with a low ratio of generated energy indicates that the fuel cell is underutilized and that it has been necessary to oversize it to cover peak demand. If the opposite case occurs (low installed power and high energy ratio), the fuel cell has a high utilization rate, which results in a higher return on the investment.

RESULTS

Several pilot projects have been implemented worldwide during the last few years to address the required energy transition in residential, buildings and other critical infrastructures such as telecom stations or data servers. These demonstratives aim at providing a reliable system with the highest self-sufficiency ratio feasible. This implies a trade-off between the required investment, the system size and the space available to place the equipment. Therefore, Table 1 gathers data for renewable hydrogen-based configurations to

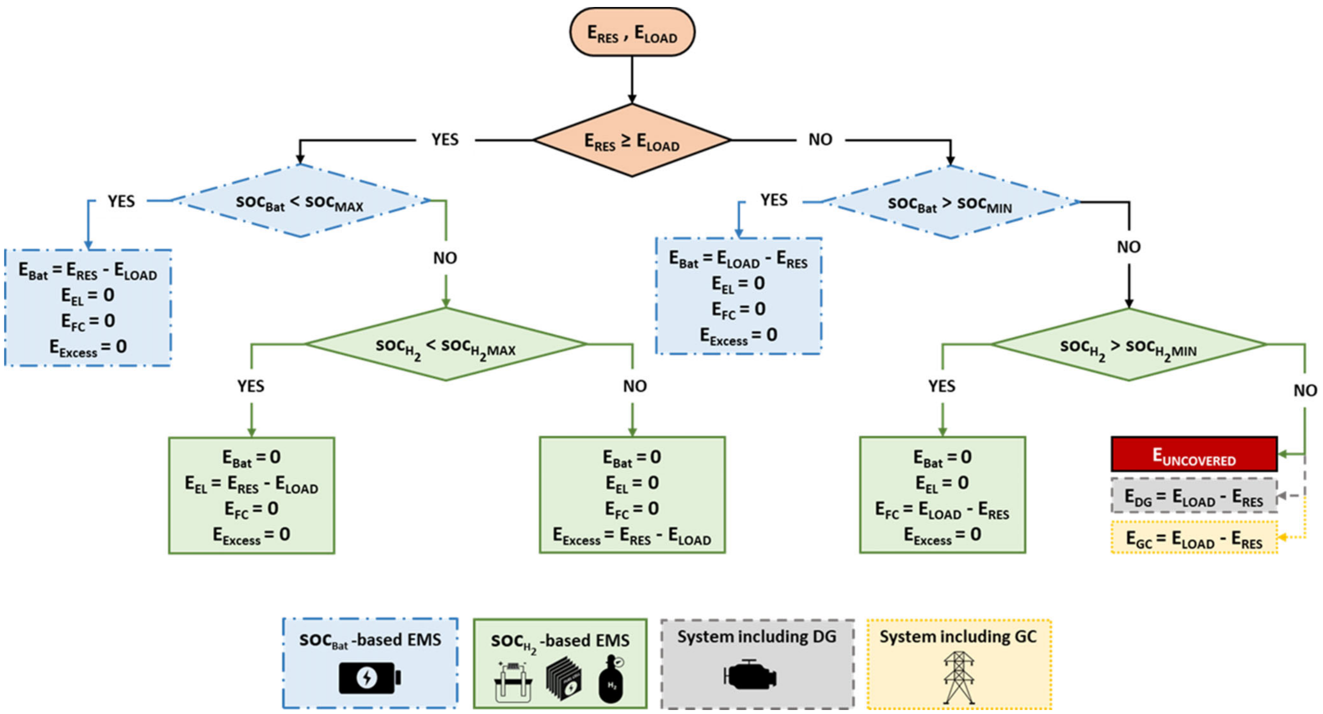

Figure 3. Flowchart of different energy control strategies based on SOC: battery SOC-based (blue, strategy 1), hydrogen tank SOC-based (green, strategy 2), combined battery–hydrogen tank SOC-based (blue and green, strategy 3). Abbreviations: E_{RES}, energy generated by RES; E_{LOAD}, load consumption; E_{EL}, energy consumed by the electrolyzer; E_{COMP}, energy consumed by the compressor; E_{BAT}, energy stored/provided by the battery; E_{FC}, energy generated by the fuel cell; E_{DG}, energy produced by diesel generator; E_{GC}, energy imported from the grid; E_{EXCESS}, energy excess; $E_{UNCOVERED}$, uncovered energy load.

supply different loads and applications from small mobile houses with a daily consumption of 2 kWh to large microgrids consuming 350 kWh per day. Relevant techno-economic parameters are analyzed in depth, such as the SSR, which evaluates the performance of each configuration, and the LCOE, which is reflected to assess cost competitiveness with other power generation solutions. Besides, the major achievements are summarized. The entries are sorted in descending order according to the load supplied.

Most of the reported pilot projects employ PV energy to power a wide range of applications such as single-family houses,[42,44,69] mobile houses,[45,46] telecom stations,[48,49] communities[58-61] and others. PV panels are much deployed as main RES because of their easier installation at roofs, facades, gardens or surrounding plots close to the target building. However, there are other alternatives employed for larger applications. For instance, the REMOTE project uses a combined PV and WT plant to power a microgrid in Norway and a hydro turbine for another microgrid in Greece.[38-41] Moreover, in the frame of the BIG HIT project, both wind and tidal energies are integrated into an off-grid microgrid at Orkney Islands, Scotland.[50-54]

Regarding the employed fuel cells, there is a clear prevalence of proton exchange membrane FC (PEMFC) over other technologies. Only Serra *et al.*[62] employed a combination of PEMFC and solid oxide FC (SOFC) to re-electrify the stored hydrogen. However, there is a bigger mix of electrolyzer technologies employed: alkaline-based,[43,47-49] PEM-based[38-41,57,61,63] and AEM-based technologies.[58,59,70,71] Besides, the INNOVATHUIS project[69] comprises a novel reversible SOFC operating in both fuel cell and electrolyzer modes when required.

Focusing on integration, pilot plants are designed following two criteria: the accomplishment of 100% off-grid systems or multi-criteria optimization to find the best trade-off between SSR, LCOE and system size. In this last case, RHS require ancillary generators to avoid energy shortfalls that can be either fossil fuels-based generators like DG or GC whose GHG emissions vary depending on the electricity mix at the location.

Most of the listed examples provide uninterrupted energy to different loads using off-grid configurations with remarkable success. Yuñez-Cano *et al.*[46] and Eroglu *et al.*[45] achieved 100% self-sufficiency in a mobile house with a PV/FC system for 2 days, and during a year through the combination of PV panels and a small WT, and an electrolyzer/fuel cell/battery system to store and provide energy when required, respectively.

Conversely, Cordiner *et al.*[48] and Bartolucci *et al.*[49] deployed different RHS combining hydrogen storage and batteries in nine telecom stations across Italy. These configurations achieved 100% self-sufficiency via two different hydrogen supply pathways. On the one hand, whenever PV energy excess is available, hydrogen is generated through water electrolysis and stored at 30 bar. Nevertheless, only four out of nine locations have an electrolyzer integrated into their RHS. On the other hand, all the locations comprise a bundle of hydrogen bottles refilled externally at 200 bar. In the case of the locations with an equipped electrolyzer, these bundles act as a backup when green hydrogen is not sufficient to meet demand. This external hydrogen is assumed to be produced by SMR, so it implies the acceptance of certain GHG emissions. In this framework, both publications analyzed the influence of the system size on the production and direct consumption of RES, the use of green hydrogen from water electrolysis and grey hydrogen refilled externally, as well as the global efficiency (η_{SYS}) achieved (energy coming from PV panels to energy provided by FC and batteries).

Concerning larger residential applications, communities and microgrids, RHS usually aim at supplying electricity to the main building. However, they can also supply energy for other applications. For instance, the BIGHIT project[50-54] supplies heat and

Table 1. Small–medium and large-scale pilot projects for residential, buildings and other applications

Ref.	Application (country)	Load ($kWh\ d^{-1}$)	SSR (%)	LCOE ($ kWh^{-1})	HRE (%)	$\frac{P_{FC}}{P_{RES}}$	$\frac{E_{FC}}{E_{RES}}$	$\frac{P_{EL}}{P_{RES}}$	Other results
38-41	Microgrid (Norway)	347.3	>95	—	31.5	0.15	0.02	0.08	Almost complete substitution of DG for a microgrid including residential loads and fish industry
38-41	Microgrid (Greece)	239	100	—	31.5	0.06	—	0.03	Complete substitution of DG for a microgrid including residential loads and local SMEs
42	Residential (Brazil)	23.8	100	1.351	—	0.11	—	0.23	—
43	Lighting (Italy)	15.6	100	0.8	24	0.18	0.30	1.03	Conventional lighting supply, storage tanks 4.5 m^3
44	Residential (USA)	15.4	69 (1 week)	1.166	16.6	1.20	0.08	2.00	FC-based system 202% more expensive than Bat-based, 1 week simulated
43	Lighting (Italy)	13.2	100	0.8	24	0.18	0.33	1.03	LED lighting supply, storage tanks 3.4 m^3
45	Mobile house (Turkey)	4.22	100	—	—	1.11	0.18	0.22	960 kWh energy excesses stored in stored H_2/Bat, which enables 2.6 days of autonomy
46	Mobile house (Mexico)	2–6	100 (2 days)	—	65	0.43	—	0.55	Two days of autonomy using hydrogen
47	Lighting (Italy)	1.5 kW	80	—	—	0.20	0.34	0.12	Night load setup with PV/EL direct coupling
47	Lighting (Italy)	1.5 kW	93	—	—	0.20	0.11	0.12	Daylight load setup with PV/EL direct coupling
48	Telecom (Italy)	1.31 kW	100[a]	—	—	0.34	0.64	—	Nine different
49	Telecom (Italy)	1.28 kW	100[a]	0.48	—	0.34	0.81	1.00	locations achieving
48	Telecom (Italy)	1.28 kW	100[a]	—	—	0.34	0.75	1.00	100% SSR with
49	Telecom (Italy)	0.87 kW	100[a]	0.54	—	0.68	0.51	—	different size and
48	Telecom (Italy)	0.87 kW	100[a]	—	—	0.57	0.51	—	energetic ratios. Global
48	Telecom (Italy)	0.72 kW	100[a]	—	—	0.34	0.16	—	efficiencies between
49	Telecom (Italy)	0.65 kW	100[a]	0.66	—	0.45	0.47	0.91	7% and 18.6% depending
48	Telecom (Italy)	0.65 kW	100[a]	—	—	0.68	0.55	2.00	on the location.
48	Telecom (Italy)	0.35 kW	100[a]	—	—	0.45	0.38	—	These systems include external hydrogen refilling[a]
50-54	Microgrid (Scotland)	—	100	—	—	0.01	—	0.26	FC supplies heat and power for several harbor buildings, a marina, and 3 ferries (when docked) apart from FCEVs on the island
55,56	Winery (USA)	—	100	—	—	0.22	—	—	Includes hydrogen-refueling station.
57	Community (UK)	—	—	—	52	0.28	—	0.34	PV introduction increases EL operational hours by 116%
58,59	Community (Thailand)	—	100	—	—	0.04	—	0.09	97 T of CO_2 saved annually, supplies 8 buildings and a swimming pool
60	Community (Japan)	—	—	—	34.5	0.18	—	1.30	Power consumption of MH tanks reduced by 99% with an overall system efficiency of 60% (CHP)
61	Community (Japan)	—	—	—	34.5	0.18	—	1.30	Nearly zero grid consumption.
62	Research building (Italy)	—	77	0.41	30	0.29	—	—	Better trade-off between LCOE and SSR for output ratios PV/load = 1.2, EL/PV = 0.6
63-65	Research building (Spain)	—	100	—	—	0.08	—	0.81	

Table 1. Continued

Ref.	Application (country)	Load (kWh d^{-1})	SSR (%)	LCOE (\$ kWh^{-1})	HRE (%)	$\frac{P_{FC}}{P_{RES}}$	$\frac{E_{FC}}{E_{RES}}$	$\frac{P_{EL}}{P_{RES}}$	Other results
									Aragonese hydrogen foundation building and a small microgrid, including both electric and heating needs
66	Residential (Sweden)	—	100	—	—	0.05	—	0.33	Surplus 800–1000 Nm^3 of hydrogen a year, enough to drive a Toyota Mirai an estimated 10 000 km annually. Electricity to charge 2 electric vehicles apart from house electricity and home demand
67	Residential (Italy)	—	100	0.6	—	0.45	—	1.00	Active control strategy allows 100% SSR.
68	Residential (USA)	—	100	—	—	—	—	—	Colonial house. Planned hydrogen refueling station
69	Residential (Netherlands)	—	100	—	95 CHP	0.30	—	0.30	nZEB with charging station for electric vehicles
70,71	Mountain hut (France)	—	100	—	—	—	—	—	100% SSR in a mountain hut in the French Alps
72,73	Gensets (Europe)	—	—	—	52	—	—	—	Containerized FC/tank 'plug and play' solution for shows, construction sites and other events

[a] SSR, self-sufficiency ratio; LCOE, levelized cost of energy; HRE, hydrogen roundtrip efficiency; P_{FC}/P_{RES}, output ratio FC/renewables; E_{FC}/E_{RES}, energy ratio FC/renewables; P_{EL}/P_{RES}, output ratio EL/renewables; CHP, combined heat and power. More information about the topologies and configurations can be found in Appendix A.

power not only for harbor buildings but also for a marina of three ferries when docked. Additionally, hydrogen surpluses are employed for fuel cell electric vehicles (FCEVs) refilling in the harbor. Phi Suea House[58,59] provides both heat and power to five different buildings and a swimming pool without needing either GC or DG during the whole year. Likewise, the Hydrogen House Project in the USA[68] is grid-independent owing to a renewable hydrogen-based scheme in combination with batteries as ESS. Besides, an expansion is planned of the hydrogen production and the tank's capacity to power a FCEV.

Conversely, other pilot plants are designed and optimized attending to different objectives apart from achieving 100% self-sufficiency. To ensure supply continuity, these configurations include either GC or DG. Carbone *et al.*[47] studied the impact of the load pattern in the SSR achieved, resulting in 80% SSR for night load and 93% for daylight load. The grid provides the remaining electricity. Moreover, Stewart *et al.*[67] compared two different EMS to assess their influence on the energy share, avoiding the need for ancillary generation systems employing an active control strategy and reaching an LCOE of \$0.60 kWh^{-1}.

On the other hand, Endo *et al.*[60,61] evaluated the performance of a containerized solution with metal hydride (MH) storage tanks. They reported up to 99% of energy savings in MH tank ancillary power requirements and global performance of the system of 60% with limited grid contribution. Finally, Parra *et al.*[57] emphasized the techno-economic benefits of a grid-connected community of seven houses combined with an RHS that comprises MH tanks. According to their results, the community achieved HRE up to 52%. An increase in electrolyzer operational hours and hydrogen production of 116% is also reported. This value is calculated in comparison with the base scenario when PV panels are combined with a demand load shifting management strategy (taking advantage of periods with low grid prices to run the electrolyzer).

One of the major and most interesting outcomes for understanding the operating of renewable hydrogen-based pilot plants is the energy contribution per component within the configuration. Thus, Fig. 4 represents the energy balance of two different pilot plants, corresponding to a microgrid in Norway in the frame of the REMOTE project[38-41] and an off-grid private villa of 500 m^2 in Sweden.[66]

In the first case, RES generate 282.2 MWh yr^{-1}. From this amount, only a 31% is directly consumed by the load, while RES surplus makes up the remaining 69% of total RES generation (194.9 MWh yr^{-1} from 282.2 MWh yr^{-1}). From the total RES excess, one-third is employed for energy storage in batteries (15%) and to produce green hydrogen (18.8%). The rest of the RES energy that the system is not able to assimilate is wasted (66.2%). Concerning the load, around 69% of the energy consumed is directly supplied by RES (87.3 MWh yr^{-1} from 126.75 MWh yr^{-1} of load consumption). The battery bank contributes to cover a quarter of the energy demand and the FC only provides 4.6% of the demand. Despite all the energy surpluses from renewable energies, a small contribution from a DG is still needed to cover periods of energy shortage. This issue could be solved by increasing the storage capacity and/or increasing the EL installed output, the main drawback being the additional expenses to overcome the operation of the DG.

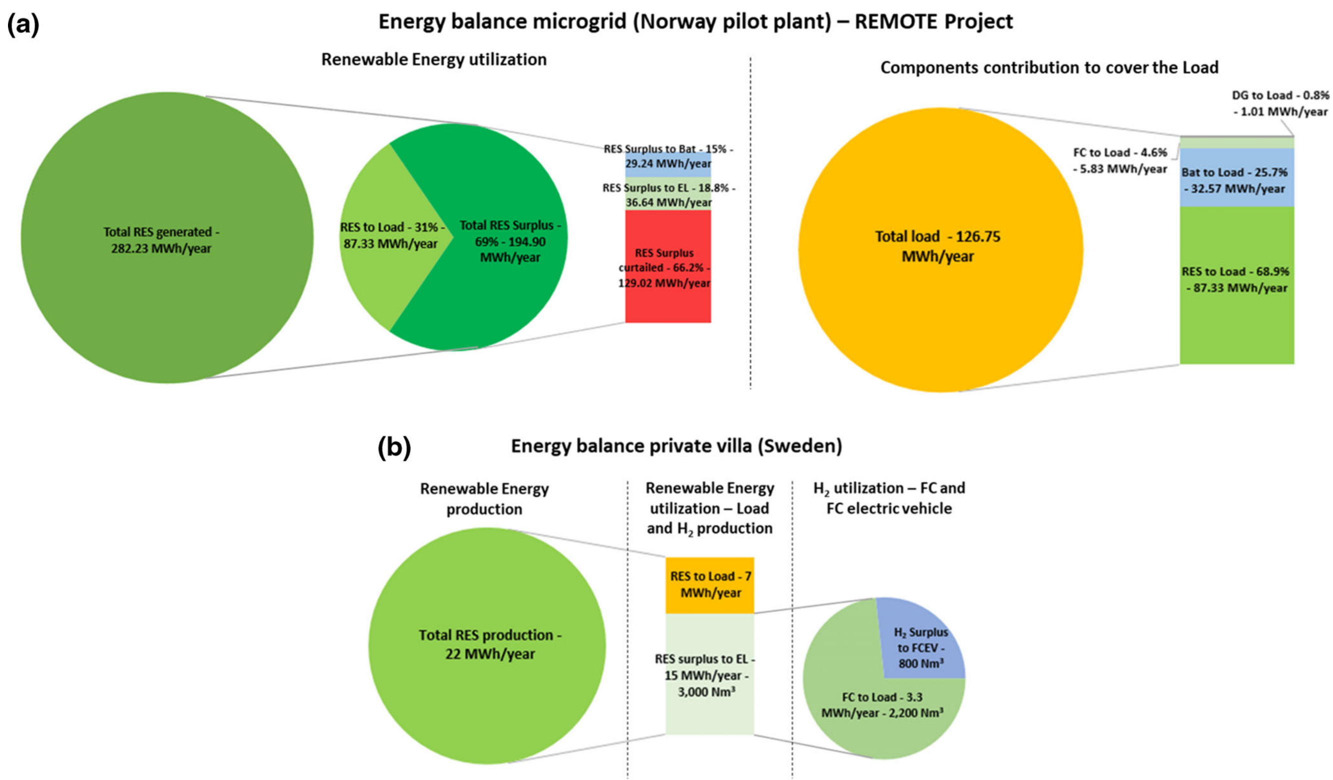

Figure 4. Energy balance of (a) microgrid in Norway in the frame of the REMOTE project[38-41] and (b) off-grid private villa in Sweden.[66]

Concerning the Swedish case, the RHS operates more efficiently. The facility harvests solar energy from PV panels and produces heating via a combined system comprising solar thermal collectors and a geothermal heat pump. Moreover, the waste heat produced during electrolyzer and fuel cell operation is recirculated into the heating circuit to ensure thermal comfort inside the villa and to defrost the snow in the surroundings of the house. From the total RES production, around one-third is directly consumed, while the remaining electricity is completely employed for hydrogen production. Thus, the FC provides electricity to charge the battery bank, and then the electricity is supplied to the villa, covering around 30% of the total energy consumption. This consumption includes the charge of two battery electric vehicles. Finally, the hydrogen excess that is not needed for electricity purposes is used to power a FC-powered Toyota Mirai for around 10 000 km yr^{-1}.

The electricity share within a renewable hydrogen-based scheme and, therefore, the achievable self-sufficiency highly depends on the system configuration itself, the efficiency of the different equipment and the direct use of RES energy. In this regard, Fig. 5 addresses the relation between the installed capacity ratio FC/RES (P_{FC}/P_{RES}), total generated energy ratio FC/RES (E_{FC}/E_{RES}), and installed capacity ratio EL/RES (P_{EL}/P_{RES}) with the final SSR reported: 100% in Fig. 5(a) and less than 100% in Fig. 5 (b). Figure 5(c) reflects these values together with the global efficiency for the case of telecom stations in Cordiner *et al.*[48] and Bartolucci *et al.*[49] that include external hydrogen refiling to reach 100% self-sufficiency. Finally, the dotted line represents the turning point where the dimensions of the fuel cell and electrolyzer are greater than the installed capacity of RES, as well as the energy contribution of the fuel cell greater than that of renewables.

For 100% self-sufficient systems, Marino *et al.*[43] studied the influence of changing from conventional lighting to more efficient LED-based lighting, and reported that this replacement reduces the hydrogen storage capacity requirements by 1.1 m^3. Therefore, the LED lighting presents a higher FC/RES energy ratio (E_{FC}/E_{RES}) owing to the decrease on RES needs. However, in Eroglu *et al.*,[45] E_{FC}/E_{RES} is equal to 18% while P_{FC}/P_{RES} is 111%. In this case, the combination of PV panels and WT ensured a better fitting between the profiles of RES production and consumption, requiring FC operation to cover small periods with high peak demands.

Concerning configurations reporting self-sufficiency ratios below 100%, Carbone *et al.*[47] report a lower E_{FC}/E_{RES} ratio for daylight load as RES utilization increases with daylight setup. Maclay *et al.*[44] achieved only a 69% SSR during 1 week of operation despite having the highest P_{FC}/P_{RES} and P_{EL}/P_{RES} ratios (120% and 200%, respectively), due to the very low HRE of the system (16.6%). Therefore, a grid connection was needed to ensure supply continuity. Conversely, Serra *et al.*[62] analyzed the best trade-off between LCOE and SSR, reporting values of \$0.41 kWh^{-1} and 77% respectively in a grid-connected system with a high energetic contribution of the FC as it operates around 1900 h per year. These values are obtained for a PV/load output ratio of 1.2 and an EL/PV installed capacity ratio of 0.6. Furthermore, the aforementioned Norwegian demonstrative of the REMOTE project[38-41] reflects very low output and energy ratios due to the large RES capacity deployed.

Finally, the RHS in telecom stations evaluated by Cordiner *et al.*[48] and Bartolucci *et al.*[49] reflect higher E_{FC}/E_{RES} ratios. The increased amount of hydrogen available from the combination of external tank filling at 200 bar and green hydrogen generated by electrolysis allows such an increase in the fuel cell's contribution. Regarding the achieved global efficiency (η_{SYS}), the systems with high E_{FC}/E_{RES} (above 50%) gave better results (between 16% and 18.6%, respectively) for this parameter as they avoided electricity losses during hydrogen generation in the electrolyzers.

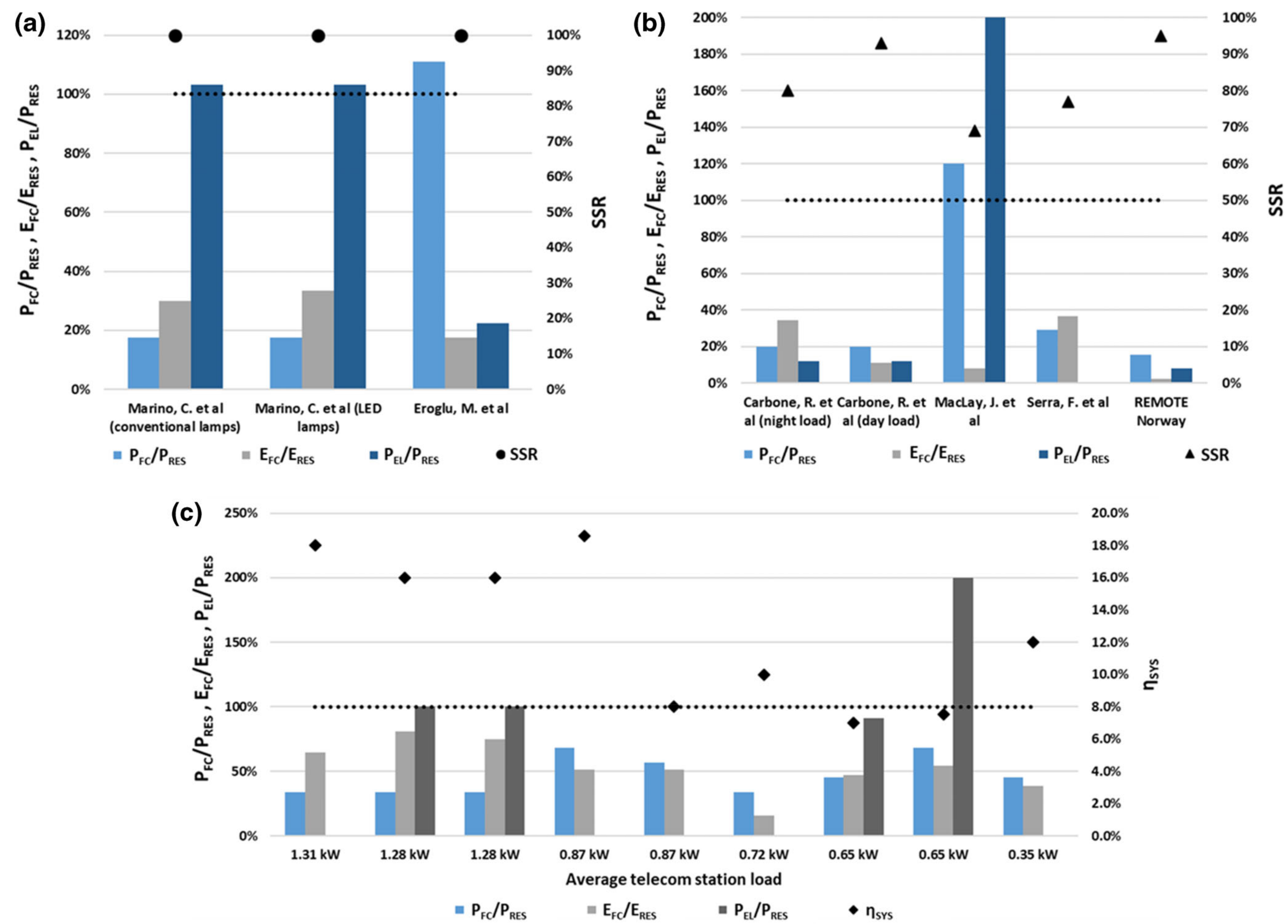

Figure 5. FC/RES installed capacity ratio, FC/RES total energy generation ratio and EL/RES installed capacity ratio for (a) systems with 100% SSR (black circles), (b) systems with SSR < 100% (black triangles) and (c) systems with 100% SSR (black diamonds) and external hydrogen refiling, including η_{SYS}.[48,49]

Moreover, in the case of the locations with an installed water electrolyzer, η_{SYS} is lower in those reporting higher P_{FC}/P_{RES} and P_{EL}/P_{RES} values. This fact can be explained via the larger installed capacities of the electrolyzers that operated during longer periods and the use of fuel cells employing greener hydrogen to supply the sites.

Despite the great relevance of renewable hydrogen-based schemes to boost the required decarbonization in the residential and buildings sector, these alternatives have not reached maturity yet. Thus, their wide deployment is not foreseen in the near term, as more efforts are required to techno-economically further develop these alternatives. However, urgent measures are needed to avoid jeopardizing the energy transition of this sector. In this sense, the implementation of cogeneration (CHP) and micro-cogeneration (mCHP) FC systems (also known as combined heat and power FC systems or stationary FC systems) helps to step forward in the reduction of GHG emissions, providing both heat and power.

These devices are compact solutions that can operate using pure hydrogen, but most common units employ different methane-rich hydrocarbons (natural gas, liquid petroleum gas, etc.) as easy and low-cost sources of hydrogen, integrating three main components: a fuel processor, a fuel cell stack and a burner. The fuel processor is designed to transform methane into hydrogen with low contaminants by SMR, the contaminants mainly being carbon monoxides and sulfur compounds. Sulfur compounds are eliminated by reacting with zinc oxides while shift reactors are employed to transform carbon monoxide into CO_2 (PEMFC-based systems are particularly sensitive to these contaminants). The fuel cell stack, typically PEMFC or SOFC, generates electricity and heat using the hydrogen stream obtained after fuel processing. Finally, the burner obtains extra heat energy via the burning of the unreacted hydrogen coming out the fuel cell stack.[74] The versatility of this equipment means that it can be integrated into the existing natural gas network without the need for major modifications to existing homes.[75] However, they have limited CO_2 savings and they will need a future upgrading to operate with higher hydrogen blending in the gas grid or with 100% hydrogen networks. Table 2 lists different CHP and mCHP devices worldwide with relevant obtained data.

There are several countries committed to the deployment of large-scale cogeneration systems for stationary applications. South Korea has installed two FC parks with an installed capacity of over 100 MW powered by a biogas obtained as a byproduct of petrochemical complexes to cover electricity demands of over 300 000 homes and recovering thermal power for district heating.[76,77] The USA has already installed more than 500 MW of cogeneration units in various stationary applications such as hospitals and office buildings.[78,79] Moreover, companies like Apple and Pfizer are also deploying FC systems in their facilities to

Table 2. Cogeneration and micro-cogeneration FC systems for residential, buildings and other applications

Ref.	Application (country)	FC type	SSR (%)	Eff (%)	Achievements
76	Town (South Korea)	PAFC	100	—	Energy and district heating for 160 000 homes
77	Town (South Korea)	MCFC	100	—	Energy and district heating for 140 000 homes
78	Hospital (USA)	DMFC	100	—	Uninterrupted power supply at Hartford hospital
79	Office building (USA)	SOFC	100	—	Cogeneration unit at Morgan Stanley offices, New York
22,80,81	Residential (Japan)	PEMFC/SOFC	100	95 (CHP)	Over 300 000 mCHP and CHP units deployed in Japan
82	Telecom (Italy)	SOFC	100	85 (CHP)	Integrated compact solution with SOFC and sodium nickel chloride batteries
83	Residential (Germany)	PEMFC/SOFC	100	95 (CHP)	Design and development of mCHP solutions in Germany
84-86	Residential (Europe)	PEMFC/SOFC	100	95 (CHP)	Deployment of 1000 mCHP units
87,88	Residential (Europe)	PEMFC/SOFC	100	95 (CHP)	Deployment of 2800 mCHP units in Europe
89	Residential (UK)	SOFC	100	60	Deployment of 100 mCHP units in the UK
90-97	Residential (UK)	SOFC	100	—	Development of trigeneration SOFC system (heating, cooling and power)
98	Telecom (Namibia)	PEMFC	100	—	Design and development of ammonia-fueled FC systems
99	Telecom (sub-Saharan Africa)	PEMFC	100	—	On-field demonstration of 40 ammonia-fueled FC systems

SSR, self-sufficiency ratio; Eff, efficiency; CHP, combined heat and power; PAFC, phosphoric acid fuel cell; MCFC, molten carbonate fuel cell; PEMFC, proton exchange membrane fuel cell; SOFC, solid oxide fuel cell; DMFC, direct methanol fuel cell.

ensure uninterrupted energy supply in data infrastructures and pharmaceutical laboratories.[100] Japan has deployed over 300 000 mCHP and CHP appliances across the country based on PEMFC and SOFC technologies, with combined heat and power efficiencies of up to 95%. There are 5 million more units planned by 2050.[22,80,81] Likewise, several countries and manufacturers jointly work to implement these mCHP units in Europe through the ENE.FIELD[84-86] and PACE[87,88] projects. There are also ammonia-fueled FC pilot systems in various countries of Africa to ensure uninterrupted power supply in telecom stations.[98,99]

CHALLENGES AND CONCLUSIONS

The combination of RES and emerging hydrogen technologies is continuously evolving as a solution to cover the energy requirements of various buildings and contribute to decarbonization of this sector. Both RES and hydrogen-based equipment are well-known technologies. Nevertheless, their integration into more complex systems in the residential and building sector is at an early stage of development. Thus, several RHS have been deployed for a variety of applications from a few kilowatts required guaranteeing uninterrupted supply in a mobile house to multi-megawatt systems for large microgrids. Despite the successfully implemented pilots in various locations worldwide, there are still pending challenges to overcome for a broader deployment of RHS in the residential and buildings sector. These challenges may vary depending on particular factors of each facility such as the system size or the load covered (in terms of variability or peak load). However, most of the barriers are shared among the different applications.

Regarding technical development, hydrogen-based technologies require a significant efficiency improvement to be competitive with fossil fuels, and thus to promote green hydrogen utilization. For instance, PEM electrolyzers report an average system efficiency of 60%,[8,101] while PEMFCs reflect values in the range 40–60%,[102] which results in HRE of between 24% and 36%. Moreover, if hydrogen compression is included the achieved HRE is even lower. Nevertheless, the complete hydrogen chain already reflects efficiencies comparable to those of conventional internal combustion engines and DG. Besides, hydrogen technologies do not emit GHGs during operation. In addition, important improvements are envisioned for both electrolyzers and fuel cells (with values up to 80%), as well as for CHP units that already achieve performances up to 95%.

The analyzed pilot plants reflect the possibility of achieving 100% self-sufficiency and decentralized generation for residential and building applications, without requiring ancillary dispatchable backup energy sources like diesel generators or grid extensions. However, the LCOE obtained by RHS has not reached yet cost competitiveness with current electricity grid prices. Furthermore, it is also necessary to reduce RES curtailments to increase the overall system efficiency. For instance, the Norwegian pilot plant within the

REMOTE project wastes around 45% of the total RES production annually. To solve this problem, there are several possibilities such as increasing storage capacity or using RES surplus in the transportation sector generating hydrogen for FCEVs. In the short term, coupling RHS with diesel generators or grid connection may reduce significantly pollutant emissions associated with buildings with a more competitive LCOE.

Space availability is a major constraint in the building sector. Therefore, compression is key to reducing storage capacity requirements. Nonetheless, it implies safety issues due to the high pressures involved and potentially explosive atmospheres that may be created and increases the total investment needed. Another alternative is the use of MH tanks that increase the volumetric density of stored hydrogen. However, these tanks are more expensive than conventional steel or plastic-reinforced ones and require an ancillary energy input to extract the hydrogen again from the MH. To avoid these drawbacks, mCHP units are easier to integrate that provide both heat and power. Currently, they have limited CO_2 emissions savings, as they are fueled by natural gas or liquid petroleum gas. In a long-term scenario, these units will need to be upgraded to adapt them to 100% hydrogen networks.

The low maturity of integrated RHS (currently at prototyping and demonstration stage) in terms of efficiency or lifetime implies an increase in LCOE, investment and maintenance costs. Electrolyzers and fuel cells with an advanced balance of plant (BoP) improve the overall performance of a system. Nevertheless, the increased demand for semiconductor materials required for the development of electronic components used in various applications, including for the BoP of hydrogen-based technologies, may negatively affect their cost. Moreover, the cost breakdown of a membrane electrode assembly reflects that the catalyst is the main cost driver. These catalysts need expensive noble metals, usually platinum group metals, for their manufacture, which are key to enhancing membrane electrode assembly durability and stability. The absence of these materials in the catalytic layer reduces the lifetime of the stack. Therefore, many research and development activities are focused on the design of new non-platinum group metal alloys to be used as catalysts that achieve a good trade-off between durability, stability and mass transport.[103]

The definition of an appropriate energy management strategy enables a better fitting between the generation and consumption profiles, lowering hydrogen chain and ESS sizes and degradation rates, with a consequent increase in lifetime. Furthermore, hydrogen-based technologies are experiencing the same downward trend in manufacturing costs and LCOE as renewable energies like PV and WT. This evolution will foster the energy transition and the decarbonization of every economic sector. In this regard, reaching 100% self-sufficiency with low FC/RES and EL/RES installed power ratios lowers the TCO of systems through the enhancement of RES direct utilization and the reduction of the hydrogen chain size.

Other relevant factors affect RHS implementation. It is necessary to define dedicated hydrogen regulations, codes and standards (RCS) to ensure the safe use of hydrogen-based technologies as well as establishing supporting mechanisms and subsidies to boost renewable hydrogen-based schemes among end-users. Besides, the creation of hydrogen networks, the acceptance of higher blending ratios in natural gas grids and the wide deployment of RES may help to decarbonize the buildings sector upstream, resulting in potential economic savings for building inhabitants. Finally, involving end-users in RHS development and informing them about potential benefits through education, training, dialogue and experience will foster awareness and knowledge about RHS, apart from contributing positively to a safe application of RCS.

ACKNOWLEDGEMENT

This research is 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).

REFERENCES

1 Foley A and Olabi AG, Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change. *Renew Sustain Energy Rev* **68**:1112–1114 (2017).
2 United Nations Treaty Collection – Paris Agreement. Available: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en (2015).
3 United Nations. Adoption of the Paris Agreement. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (2015).
4 Seabra B, Pereira PF, Corvacho H, Pires C and Ramos NMM, Low energy renovation of social housing: recommendations on monitoring and renewable energies use. *Sustainability* **13**:2718 (2021).
5 IRENA. Renewable capacity statistics 2020. International Renewable Energy Agency. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf (2020).
6 Salvia M, Reckien D, Pietrapertosa F, Eckersley P, Spyridaki NA, Krook-Riekkola A *et al*., Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU. *Renew Sustain Energy Rev* **135**:110253 (2021).
7 Ministerio para la Transición Ecológica el Reto Demográfico. Estrategia de almacenamiento energético. Available: https://www.miteco.gob.es/es/prensa/estrategiaalmacenamiento_tcm30-522655.pdf (2021).
8 Staffell I, Scamman D, Velazquez Abad A, Balcombe P, Dodds PE, Ekins P *et al*., The role of hydrogen and fuel cells in the global energy system. *Energy Environ Sci* **12**:463–491 (2019).
9 Council, H. Hydrogen decarbonization pathways potential supply scenarios. Available: www.hydrogencouncil.com (2021).
10 Taibi, E., Miranda R, Vanhoudt W, Winkel T, Lanoix JC & Barth F Hydrogen from renewable power: Technology outlook for the energy transition. Available: https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf (2018)
11 Abejón R, Fernández-Ríos A, Domínguez-Ramos A, Laso J, Ruiz-Salmón I, Yáñez M *et al*., Hydrogen recovery from waste gas streams to feed (high-temperature PEM) fuel cells: environmental performance under a life-cycle thinking approach. *Appl Sci* **10**:7461 (2020).
12 Yáñez M, Ortiz A, Brunaud B, Grossmann IE and Ortiz I, Contribution of upcycling surplus hydrogen to design a sustainable supply chain: the case study of northern Spain. *Appl Energy* **231**:777–787 (2018).
13 Yáñez M, Ortiz A, Gorri D and Ortiz I, Comparative performance of commercial polymeric membranes in the recovery of industrial hydrogen waste gas streams. *Int J Hydrogen Energy* **46**:17507–17521 (2021).
14 Yáñez M, Relvas F, Ortiz A, Gorri D, Mendes A and Ortiz I, PSA purification of waste hydrogen from ammonia plants to fuel cell grade. *Sep Purif Technol* **240**:116334 (2020).
15 FCH JU . Hydrogen Roadmap Europe: a sustainable pathway for the European energy transition. Available: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf (2019)
16 Mazza A, Bompard E and Chicco G, Applications of power to gas technologies in emerging electrical systems. *Renew Sustain Energy Rev* **92**:794–806 (2018).
17 Ortiz-Imedio R, Caglayan DG, Ortiz A, Heinrichs H, Robinius M, Stolten D *et al*., Power-to-ships: future electricity and hydrogen

demands for shipping on the Atlantic coast of Europe in 2050. *Energy* **228**:120660 (2021).
18 Ortiz-Imedio R, Ortiz A, Urroz JC, Diéguez PM, Gorri D, Gandía LM *et al*., Comparative performance of coke oven gas, hydrogen and methane in a spark ignition engine. *Int J Hydrogen Energy* **46**:17572–17586 (2021).
19 IEA. Technology roadmap: hydrogen and fuel cells. Available: www.iea.org/t&c/ (2015).
20 Satyapal, S. DOE hydrogen and fuel cell perspectives and overview of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE): part of a comprehensive energy strategy. Available: https://www.energy.gov/sites/default/files/2020/07/f77/hfto-satyapal-gabi-workshop-jul20.pdf (2020).
21 US DoE & Fuel Cell & Hydrogen Energy Association Roadmap to US hydrogen economy. Available: https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf (2020).
22 Arias, J. Hydrogen and fuel cells in Japan. Available: https://lnkd.in/ff8Fc3S. (2019).
23 Iida S and Sakata K, Hydrogen technologies and developments in Japan. *Clean Energy* **3**:105–113 (2019).
24 Government of Canada. *Hydrogen strategy for Canada: seizing the opportunities for hydrogen*. (2020).
25 COAG Energy Council. Australia's National Hydrogen Strategy. Available: https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf (2019).
26 Commonwealth of Australia A briefing paper for the COAG Energy Council: Hydrogen for Australia's future. Available: https://www.chiefscientist.gov.au/sites/default/files/HydrogenCOAGWhitePaper_WEB.pdf (2018).
27 IRENA Global energy transformation: a roadmap to 2050. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf (2018).
28 Gerhardt, N., Bard, J., Schmitz, R., Beil, M., Pfennig, M. & Kneiske, T . Hydrogen in the energy system of the future: focus on heat in buildings. Available: https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FraunhoferIEE_Study_H2_Heat_in_Buildings_final_EN_20200619.pdf (2020).
29 Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Available: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF (2010).
30 Europe's buildings under the microscope: a country-by-country review of the energy performance of buildings. Available: https://bpie.eu/wp-content/uploads/2015/10/HR_EU_B_under_microscope_study.pdf (2011).
31 Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (text with EEA relevance). Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN (2018).
32 Lian J, Zhang Y, Ma C, Yang Y and Chaima E, A review on recent sizing methodologies of hybrid renewable energy systems. *Energy Convers Manag* **199** (2019).
33 Khan FA, Pal N and Saeed SH, Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies. *Renew Sustain Energy Rev* **92**:937–947 (2018).
34 Maestre VM, Ortiz A and Ortiz I, Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications. *Renew Sustain Energy Rev.*:**152**:111628 (2021). https://doi.org/10.1016/j.rser.2021.111628.
35 Calise F, Cappiello FL, Dentice d'Accadia M and Vicidomini M, Thermo-economic optimization of a novel hybrid renewable trigeneration plant. *Renew Energy* **175**:532–549 (2021).
36 Knosala K, Kotzur L, Röben FTC, Stenzel P, Blum L, Robinius M *et al*., Hybrid hydrogen home storage for decentralized energy autonomy. *Int J Hydrogen Energy* **46**:21748–21763 (2021).
37 Sdanghi G, Maranzana G, Celzard A and Fierro V, Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renew Sustain Energy Rev*: **102**:150–170 (2019). https://doi.org/10.1016/j.rser.2018.11.028.
38 Remote area energy supply with multiple options for integrated hydrogen-based technologies: REMOTE Project – H2020, European Commission. Available: https://cordis.europa.eu/project/id/779541 (2018).
39 REMOTE project. Available: https://www.remote-euproject.eu/ (2018).
40 Kafetzis A, Ziogou C, Panopoulos KD, Papadopoulou S, Seferlis P and Voutetakis S, Energy management strategies based on hybrid automata for islanded microgrids with renewable sources, batteries and hydrogen. *Renew Sustain Energy Rev* **134**:110118 (2020).
41 Marocco P, Ferrero D, Lanzini A and Santarelli M, Optimal design of stand-alone solutions based on RES + hydrogen storage feeding off-grid communities. *Energ Conver Manage* **238**:114147 (2021).
42 Silva SB, Severino MM and De Oliveira MAG, A stand-alone hybrid photovoltaic, fuel cell and battery system: a case study of Tocantins, Brazil. *Renew Energy* **57**:384–389 (2013).
43 Marino C, Nucara A, Panzera MF, Pietrafesa M and Varano V, Energetic and economic analysis of a stand alone photovoltaic system with hydrogen storage. *Renew Energy* **142**:316–329 (2019).
44 MacLay JD, Brouwer J and Samuelsen GS, Experimental results for hybrid energy storage systems coupled to photovoltaic generation in residential applications. *Int J Hydrogen Energy* **36**:12130–12140 (2011).
45 Eroglu M, Dursun E, Sevencan S, Song J, Yazici S and Kilic O, A mobile renewable house using PV/wind/fuel cell hybrid power system. *Int J Hydrogen Energy* **36**:7985–7992 (2011).
46 Yunez-Cano A, González-Huerta RD, Tufiño-Velázquez M, Barbosa R and Escobar B, Solar-hydrogen hybrid system integrated to a sustainable house in Mexico. *Int J Hydrog Energy* **41**:19539–19545 (2016).
47 Carbone R, Marino C, Nucara A, Panzera MF and Pietrafesa M, Electric load influence on performances of a composite plant for hydrogen production from RES and its conversion in electricity. *Sustainability* **11**:6362 (2019).
48 Cordiner S, Mulone V, Giordani A, Savino M, Tomarchio G, Malkow T *et al*., Fuel cell based hybrid renewable energy systems for off-grid telecom stations: data analysis from on field demonstration tests. *Appl Energy* **192**:508–518 (2017).
49 Bartolucci L, Cordiner S, Mulone V and Pasquale S, Fuel cell based hybrid renewable energy systems for off-grid telecom stations: data analysis and system optimization. *Appl Energy* **252**:113386 (2019).
50 BIG HIT Project. Available: https://www.bighit.eu/ (2016).
51 Building innovative green hydrogen systems in an isolated territory: a pilot for Europe – H2020, European Commission. Available: https://cordis.europa.eu/project/id/700092 (2016).
52 Zhao G, Nielsen ER, Troncoso E, Hyde K, Romeo JS and Diderich M, Life cycle cost analysis: a case study of hydrogen energy application on the Orkney Islands. *Int J Hydrogen Energy* **44**:9517–9528 (2019).
53 Widera B, Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. *Therm Sci Eng Prog* **16**:100460 (2020).
54 Hydrogen & Fuel Cells in the Nordic countries. Hydrogen and FC activities in Scotland & the Orkney Islands. (2016).
55 Stone Edge Farm MicroGrid. Available: https://sefmicrogrid.com/overview/components/ (2016).
56 Plug power GenSure provides power hive for stone edge farm micro-grid. Available: https://www.plugpower.com/plug-power-gensure-provides-power-hive-for-stone-edge-farm-micro-grid/ (2016).
57 Parra D, Gillott M and Walker GS, Design, testing and evaluation of a community hydrogen storage system for end user applications. *Int J Hydrogen Energy* **41**:5215–5229 (2016).
58 Phi Suea House. Available: https://www.phisueahouse.com/index.php.
59 Phi Suea House Project micro-grid. Available: https://www.enapter.com/use-cases/residential-multi-home-phi-suea-house (2016).
60 Endo N, Goshome K, Tetsuhiko M, Segawa Y, Shimoda E and Nozu T, Thermal management and power saving operations for improved energy efficiency within a renewable hydrogen energy system utilizing metal hydride hydrogen storage. *Int J Hydrogen Energy* **46**:262–271 (2021).
61 Endo N, Shimoda E, Goshome K, Yamane T, Nozu T and Maeda T, Construction and operation of hydrogen energy utilization system for a zero emission building. *Int J Hydrogen Energy* **44**:14596–14604 (2019).
62 Serra F, Lucariello M, Petrollese M and Cau G, Optimal integration of hydrogen-based energy storage systems in photovoltaic microgrids: a techno-economic assessment. *Energies* **13**:4149 (2020).
63 Gracia L, Casero P, Bourasseau C and Chabert A, Use of hydrogen in off-grid locations, a techno-economic assessment. *Energies* **11**:3141 (2018).

64 PEM electrolysers for operation with offgrid renewable installations – H2020, European Commission. Available: https://cordis.europa.eu/project/id/700359 (2016).
65 ELY4OFF – PEM electrolysers for operation with offgrid renewable installations. Available: http://ely4off.eu/ (2016).
66 Off-grid private villa in Gothenburg. Available: http://www.hystorsys.no/download/ATruePioneerGoesOff-Grid.html (2017).
67 Stewart EM, Lutz AE, Schoenung S, Chiesa M, Keller JO, Fletcher J *et al*., Modeling, analysis and control system development for the Italian hydrogen house. *Int J Hydrogen Energy* **34**:1638–1646 (2009).
68 Hydrogen House Project. Available: https://www.hydrogenhouseproject.org/index.html (2019).
69 Innovathuis project. Available: https://www.innovathuis.nl/ (2020).
70 Hydrogen power for French alpine refuge. *Fuel Cells Bulletin* **2015**:6 (2015). https://doi.org/10.1016/S1464-2859(15)30184-X
71 Refuge du Col du Palet – Vig'Hy. Available: https://www.vighy-afhypac.org/projets/refuge-du-col-du-palet/.
72 Everywh2ere project. Available: https://www.everywh2ere.eu/ (2018).
73 Making hydrogen affordable to sustainably operate everywhere in European cities: EVERYWH2ERE Project – H2020, European Commission. Available: https://cordis.europa.eu/project/id/779606 (2018).
74 Olabi AG, Wilberforce T, Sayed ET, Elsaid K and Abdelkareem MA, Prospects of fuel cell combined heat and power systems. *Energies* **13**:4104 (2020).
75 FCH JU. Advancing Europe's energy systems: stationary fuel cells in distributed generation. FCH JU publications. Available: http://www.rolandberger.com/media/pdf/Roland_Berger_Fuel_Cells_Study_20150330.pdf (2015) doi:https://doi.org/10.2843/088142.
76 Doosan starts installation of hydrogen-fueled 50 MW fuel cell power plant in South Korea. *Fuel Cells Bulletin* **2018**:1 (2018). https://doi.org/10.1016/S1464-2859(18)30270-0
77 Ghezel-Ayagh, H. Power advances in SOFC development at fuelcell energy: SOFC systems with improved reliability and endurance. Available: https://netl.doe.gov/sites/default/files/2018-01/FE0011691-Hossein-Ghezel-Ayagh.pdf (2014).
78 Clean Energy Group. Fuel cells in hospitals – fuel cells help provide life-supporting services. Available: www.resilient-power.org. (2015).
79 Bloom Energy completes fuel cell project at Morgan Stanley Global Headquarters in New York City. Available: https://www.prnewswire.com/news-releases/bloom-energy-completes-fuel-cell-project-at-morgan-stanley-global-headquarters-in-new-york-city-300377447.html (2016).
80 Maruta, A. & Manager, P. Japan's ENE-FARM programme. Available: www.technova.co.jp (2016).
81 ENE FARM programme. Available: https://www.j-lpgas.gr.jp/en/appliances/.
82 Operation of a novel SOFC-battery integrated hybrid for telecommunication energy systems: ONSITE Project – FP7, European Commission. Available: https://cordis.europa.eu/project/id/325325 (2013).
83 Callux project. Available: http://enefield.eu/related-projects/callux-project/ (2008).
84 Ene.field project. Available: http://enefield.eu/ (2012).
85 European-wide field trials for residential fuel cell micro-CHP: ENE.FIELD Project – FP7, European Commission. Available: https://cordis.europa.eu/project/id/303462 (2012).
86 Nielsen ER, Prag CB, Bachmann TM, Carnicelli F, Boyd E, Walker I *et al*., Status on demonstration of fuel cell based micro-CHP units in Europe. *Fuel Cells*, **19**: 340–345 (2019). https://doi.org/10.1002/fuce.201800189.
87 Pathway to a competitive European FC mCHP market: PACE Project – H2020, European Commission. Available: https://cordis.europa.eu/project/id/700339 (2016).
88 Pathway to a competitive European fuel cell micro-cogeneration market. Available: https://www.pace-energy.eu/ (2016).
89 Solid oxide fuel cell micro-CHP field trials: SOFT-PACT Project – FP7, European Commission. Available: https://cordis.europa.eu/project/id/278804 (2011).
90 Durable solid oxide fuel cell tri-generation system for low carbon buildings: TriSOFC Project – FP7, European Commission. Available: https://cordis.europa.eu/project/id/303454 (2012).
91 Fan L, Wang C, Chen M and Zhu B, Recent development of ceria-based (nano)composite materials for low temperature ceramic fuel cells and electrolyte-free fuel cells. *J Power Sources* **234**:154–174 (2013).
92 Fan L, Zhang H, Chen M, Wang C, Wang H, Singh M *et al*., Electrochemical study of lithiated transition metal oxide composite as symmetrical electrode for low temperature ceramic fuel cells. *Int J Hydrogen Energy* **38**:11398–11405 (2013).
93 Zhu B, Fan L, He Y, Zhao Y and Wang H, A commercial lithium battery LiMn-oxide for fuel cell applications. *Mater Lett* **126**:85–88 (2014).
94 Lu Y, Zhu B, Cai Y, Kim JS, Wang B, Wang J *et al*., Progress in electrolyte-free fuel cells. *Front Energy Res* **4**:1 (2016).
95 Xia C, Wang B, Ma Y, Cai Y, Afzal M, Liu Y *et al*., Industrial-grade rare-earth and perovskite oxide for high-performance electrolyte layer-free fuel cell. *J Power Sources* **307**:270–279 (2016).
96 Worall M, Elmer T, Riffat S, Wu S and Du S, An experimental investigation of a micro-tubular SOFC membrane-separated liquid desiccant dehumidification and cooling tri-generation system. *Appl Therm Eng* **120**:64–73 (2017).
97 Elmer T, Worall M, Wu S and Riffat S, Assessment of a novel solid oxide fuel cell tri-generation system for building applications. *Energ Conver Manage* **124**:29–41 (2016).
98 Ammonia based, fuel cell power for off-grid cell phone towers: NH34PWR Project – FP7, European Commission. Available: https://cordis.europa.eu/project/id/256856 (2010).
99 Demonstration of FC-based integrated generator systems to power off-grid cell phone towers, using ammonia fuel: TOWERPOWER Project – FP7, European Commission. Available: https://cordis.europa.eu/project/id/279190 (2011).
100 Curtin, S. & Gangi, J. Fuel Cell Technologies Market Report 2016 – US DoE. Available: https://www.energy.gov/sites/prod/files/2017/10/f37/fcto_2016_market_report.pdf (2017).
101 IEA. The future of hydrogen. Seizing today's opportunities. (2019).
102 Felseghi RA, Carcadea E, Raboaca MS, Trufin CN and Filote C, Hydrogen fuel cell technology for the sustainable future of stationary applications. *Energies* **12**: 4593 (2019).
103 Wang Y, Ruiz Diaz DF, Chen KS, Wang Z and Adroher XC, Materials, technological status, and fundamentals of PEM fuel cells – a review. *Mater Today* **32**:178–203 (2020).

APPENDIX

Configuration and topology information for pilot plants with RHS considered in Table 1

				RES		FC			EL			StH_2	Bat
Ref.	Off-G/DG/GC	Application (country)	Load (kWh d^{-1})	Type (kW)	Energy RES (kWh yr^{-1})	Type	(kW)	Energy FC (kWh yr^{-1})	Type	(kW)	Energy EL (kWh yr^{-1})	(kg)	(kWh)
38-41	DG	Microgrid (Norway)	347,3	PV (82) – WT (225)	284 680	PEMFC	50	5830.5	PEMEL	25	—	13.9	550
38-41	DG	Microgrid (Greece)	239	HD (900)	3 711 300	PEMFC	50	—	PEMEL	25	—	27.8	30
42	Off-G	Residential (Brazil)	23.8	PV (8.8)	—	PEMFC	1	—	PEMEL	2	—	0.41	10.6
43	Off-G	Lighting (Italy)	15.6	PV (9.7)	21 046	PEMFC	1.7	6282	ALKEL	10	18 437	100	12
44	GC	Residential (USA)	15.4	PV (5)	224.8	PEMFC	6	17.8	PEMEL	10	33.4	1.7	—
43	Off-G	Lighting (Italy)	13.2	PV (9.7)	15 947	PEMFC	1.7	5319	ALKEL	10	14 723	80	12
45	Off-G	Mobile house (Turkey)	4.22	PV (0.8) – WT (1)	1598.7	PEMFC	2	280.3	PEMEL	0.4	960	0.25	19.2
46	Off-G	Mobile house (Mexico)	2–6	PV (3)	—	PEMFC	1.3	—	PEMEL	1.66	—	0.35 (MH)	
47	GC	Lighting (Italy)	1.5 kW	PV (5)	10 800	PEMFC	1	3700	ALKEL	0.6	—	—	—
47	GC	Lighting (Italy)	1.5 kW	PV (5)	10 800	PEMFC	1	1200	ALKEL	0.6	—	—	—
48	Off-G	Telecom (Italy)	1.31 kW	PV (5)	7000	PEMFC	1.7	4500	ALKEL	—	—	—	30.7
49	Off-G	Telecom (Italy)	1.28 kW	PV (5)	5898	PEMFC	1.7	4780	ALKEL	5	—	—	30.7
48	Off-G	Telecom (Italy)	1.28 kW	PV (5)	6000	PEMFC	1.7	4500	ALKEL	5	—	—	30.7
49	Off-G	Telecom (Italy)	0.87 kW	PV (2.5)	3894	PEMFC	1.7	1987	ALKEL	—	—	—	15.4
48	Off-G	Telecom (Italy)	0.87 kW	PV (3)	3900	PEMFC	1.7	2000	ALKEL	—	—	—	18.2
48	Off-G	Telecom (Italy)	0.72 kW	PV (5)	3200	PEMFC	1.7	500	ALKEL	—	—	—	30.7
49	Off-G	Telecom (Italy)	0.65 kW	PV (5.5)	3510	PEMFC	2.5	1650	ALKEL	5	—	—	30.7
48	Off-G	Telecom (Italy)	0.65 kW	PV (2.5)	3300	PEMFC	1.7	1800	ALKEL	5	—	—	15.4
48	Off-G	Telecom (Italy)	0.35 kW	PV (5.5)	5200	PEMFC	2.5	2000	ALKEL	—	—	—	30.7
50-54	Off-G	Microgrid (Scotland)	Harbor building/ transport	WT (1800) – TD (4000)	—	PEMFC	75	—	PEMEL	1500	—	200 bar	—
55,56	Off-G	Winery (USA)	—	PV (126)	—	PEMFC	28	—	PEMEL	—	—	—	500
57	GC	Community (UK)	—	PV (3.2)	—	PEMFC	0.9	—	PEMEL	1.1	—	4 (MH)	
58,59	Off-G	Community (Thailand)	—	PV (101.1)	140 233	PEMFC	4.5	—	AEMEL	9.6	—	7.5/30 bar	192
60	GC	Community (Japan)	—	PV (20)	—	PEMFC	3.5	—	PEMEL	26	—	MH	20
61	GC	Community (Japan)	—	PV (20)	—	PEMFC	3.5	—	PEMEL	26	—	MH	20
62	GC	Research building (Italy)	—	PV (50.2)	—	PEMFC/SOFC	14.5	—	PEMEL	2.1 Nm^3/h	—	1.34	100
63-65	Off-G	Research building (Spain)	—	PV (62)	—	PEMFC	5	—	PEMEL	50	—	23/20 bar7/350 bar	36
66	Off-G	Residential (Sweden)		PV (20) – STC (13) – Geo (13)	22 000	PEMFC	1.5	3300	ALKEL	11	16 500	324/300 bar	144
67	GC	Residential (Italy)	—	PV (11)	—	PEMFC	5	—	ALKEL	11	—	MH	144
68	Off-G	Residential (USA)	—	PV (40)	—	—	20 (FC/Bat)	—	—	—	—	—	—
69	Off-G	Residential (Netherlands)	—	PV (10)	—	rSOFC	3	—	rSOFC	3	—	—	—
70,71	Off-G	Mountain hut (France)	—	PV (–)	—	PEMFC	2.5	—	AEMEL	2.5	—	5	—
72,73	Off-G	Gensets (Europe)	—	—	—	PEMFC	25–100	—	—	—	—	350 bar	

*Abbreviations: Off-G, off-grid; GC, grid-connected; DG, diesel generator; RES, renewable energy sources; PV, photovoltaic; WT, wind turbine; HD, hydraulic; TD, tidal; STC, solar thermal collector; Geo, geothermal; FC, fuel cell; PEMFC, proton exchange membrane fuel cell; SOFC, solid oxide fuel cell; rSOFC, reversible solid oxide fuel cell; EL, electrolyzer; PEMEL, proton exchange membrane electrolyzer; ALKEL, alkaline electrolyzer; AEMEL, anion exchange membrane electrolyzer; StH_2, stored hydrogen; MH, metal hydride; Bat, battery.

