



**HAL**  
open science

## Trends in design of distributed energy systems using hydrogen as energy vector: A systematic literature review

Juan Fonseca, Mauricio Camargo, Jean-Marc Commenge, Laurent Falk, Iván Gil

### ► To cite this version:

Juan Fonseca, Mauricio Camargo, Jean-Marc Commenge, Laurent Falk, Iván Gil. Trends in design of distributed energy systems using hydrogen as energy vector: A systematic literature review. International Journal of Hydrogen Energy, 2018, 10.1016/j.ijhydene.2018.09.177 . hal-01910588

**HAL Id: hal-01910588**

**<https://hal.science/hal-01910588>**

Submitted on 22 Oct 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

## Trends in Design of Distributed Energy Systems Using Hydrogen as Energy Vector: A Systematic Literature Review

Juan D. Fonseca<sup>a,c\*</sup>, Mauricio Camargo<sup>a</sup>, Jean-Marc Commenge<sup>b</sup>, Laurent Falk<sup>b</sup>, Iván D. Gil<sup>c</sup>

<sup>a</sup> Équipe de Recherche sur les Processus Innovatifs (ERPI), Université de Lorraine, 8 rue Bastien Lepage, 54000 Nancy Cedex, France

<sup>b</sup> Laboratoire Réactions et Génie des Procédés (LRGP), Université de Lorraine, 1 rue Grandville, BP 20451, 54001 Nancy Cedex, France

<sup>c</sup> Grupo de Procesos Químicos y Bioquímicos, Department of Chemical and Environmental Engineering, Universidad Nacional de Colombia – Sede Bogotá, Carrera 30 45-03, Bogotá, Colombia

\*Corresponding Author: Juan David Fonseca Gamboa

Address : Équipe de Recherche sur les Processus Innovatifs (ERPI), Université de Lorraine, 8 rue Bastien Lepage, 54000 Nancy Cedex, France

Phone: + 33 0767340854

Email: [jdfonseca@unal.edu.co](mailto:jdfonseca@unal.edu.co)

### Abstract

Currently, a significant transformation for energy systems has emerged as a result of the trend to develop an energy framework without fossil fuel reliance, the concerns about climate change and air quality, and the need to provide electricity to around of 17% of world population who lacks the service. Accordingly, the deployment of power plants located close to end-users and including multiple energy sources and carriers, along with the growing share of renewable energies, have suggested changes in the energy sector. Despite their potential capabilities, the design of distributed energy systems (DES) is a complex problem due to the simultaneous goals and constraints that need to be considered, as well as to the high context dependence of this kind of projects. For these reasons, in this work a systematic literature review of DES including hydrogen as energy vector, was made analyzing 106 research papers published between the years 2000-2018, and extracted from Scopus® and Web of Science databases. The aim was to identify how hydrogen is employed (technologies, uses) and the criteria that are evaluated (economic, technical, social and environmental) when these systems are designed, planned and/or operated. The results constitute a baseline information covering the type of technologies, equipment sizes and hydrogen applications, that could be valuable for the preliminary stages of research or project planning of DES involving hydrogen. Furthermore, other factors have also been identified, such as the focus on techno-economic issues, and the lack of considering socio/political aspects and the uncertainty about input data like weather conditions, energy prices and demands. Additionally, a more integrated approach is needed including all the hydrogen supply chain stages and project stakeholders, to tackle issues like safety of the energy systems that could produce consumer rejections.

### Keywords

Hydrogen, energy carrier, decentralized energy system, decarbonization, power-to-gas, renewable sources.

## **Introduction**

Global energy demand grew by 2,1% in 2017 and is expected to increase by 30% until 2040 with respect to the current world consumption. This increase is equivalent to add another China and India to the current energy demand [1]. Although this growth is slower than in the past, when a rise of 40% from 2000 to 2017 was registered, the constant expansion of world economy and population, as well as the concerns about climate change, represent new challenges for the energy sector [1,2]. One of the main issues to handle is the need to satisfy the energy requirements in a sustainable manner, considering that, among human activities, the use of energy is the largest source of greenhouse gas emissions [3]. Thus, the trend for the upcoming years is to increase electricity as an end-use energy due to its important role for the share of renewable and low-emission sources (25% in 2017) [2].

Besides mitigating the climate change effects, the use of renewable energies is boosted by concerns about air quality and energy security. Free-emission sources are a great opportunity to reduce health problems derived from air contamination, which is mainly produced by the dependence of fossil fuels in transport, power and industry sector [4]. On the other hand, energy security has to deal not only with the finite character of traditional energy sources, but also with the need to supply electricity to 1,2 billion people (mainly in developing countries and rural regions) who lack of it [5]. In this line, the emergence of distributed energy systems (DES) and the growing share of renewable energies are changing the way in which power systems are planned, designed and operated [6].

DES are based on the idea that they replace or complement the large-scale and conventional centralized generation plants, with smaller units located close to energy consumers [7]. This concept suggested a shift in the paradigm of energy framework, and appears as an alternative to face the aforementioned challenges of the energy sector, e.g. providing electricity to isolated communities. Besides offering more flexibility in generation, reducing inefficiencies in delivering and vulnerability of the system, DES can provide a reliable pathway for energy transition from the technological, economic, environmental and social point of view [8]. One of the key aspects about DES lies in the inclusion of multi-generation technologies and the use of renewable sources. Hence, by easing the integration of renewables through a flexible transformation system, DES allow to take advantage of the synergies among different sources and energy carriers while responding to electricity, heat, cooling, fuel and even water demands [9,10].

Among energy carriers, hydrogen has emerged as a friendly solution for climate change, air pollution and energy security [10]. Although hydrogen is the most abundant element on earth, it cannot be found by itself in nature. However, rather than a barrier, this represents a large range of possibilities, since hydrogen can be obtained from a great variety of sources covering fossil fuels, biomass, nuclear power and renewable energies [11,12]. Hydrogen as an energy carrier and raw material has a wide range of applications that includes fuel (e.g. transportation, power units), chemical industry (e.g. oil refining, fertilizers production) and energy storage [10]. When hydrogen is employed to store energy, it offers the possibility to be an interface among electricity, chemical and heat energy networks through the so-called power-to-gas process [13]. This can help to balance the intermittent renewable energy supply (wind and solar) with the demand, and therefore, facilitates and promotes its development [10,14]. This ability makes hydrogen a valuable element to

be incorporated in DES, in addition to the fact that only steam water and heat are emitted during its combustion.

Introducing hydrogen into a multi-generation system as DES is a complex problem, and as a consequence, an integrated approach including several aspects is required. Indeed, this complexity could be explained by the simultaneous objectives and constraints to be considered. From the technical point of view, a set of potential technological alternatives must be evaluated in order to establish their complementarities and build the most adequate configuration. Furthermore, this set of possible configurations also needs to be studied under economic, environmental and socio/political dimensions [15–17], and fitted to the conditions (e.g. climate, resources availability, scale) of the specific context where it would be implemented. In this way, modelling and optimization tools are crucial to study, design/select and operate a system to satisfy all these dimensions from a global perspective. Currently, literature includes a significant amount of scientific documents about DES with and without hydrogen as a vector. However, the research work has been focused on some specific aspects, most of them from a single-disciplinary point of view and mainly addressing economic and technical issues. Hence, there is a lack of multi-disciplinary approaches including all the above-mentioned aspects, and thus a need to improve the decision-making process to hydrogen-related DES deployment.

The cited publications include the general presentation of some fundamental concepts related to distributed energy systems, their structures, characteristics and applications at small scale [18]. The study in [19] presents a review addressed to identify the models proposed for energy. Research about the perspectives of hydrogen in energy systems for upcoming years are discussed in [20] considering regional and national scales, as well as its drivers and challenges. Some reviews have emphasized on production methods, storage and safety issues about hydrogen, and also some challenges and perspectives of hydrogen as energy carrier are discussed in [21,22]. Meanwhile, [23] presents a work around the concept of 100% renewable energy, and the importance of hydrogen and fuel cells in the energy transition of storage and transport sectors. In [24], a study for the assessment of hydrogen options in energy systems under the criterion of smartness is developed according to a sustainable-based portfolio, including exergization, greenization, renewabilization, integration, hydrogenization, multigeneration, storagization and intelligization concepts. Regarding technological and economic aspects, this issue has been considered from the energy management point of view [25], reviewing the most important technical and economical optimization criteria. Likewise, some studies have focused on techno-economic difficulties [26], and assessment of hydrogen use in relation with end-users of power-to-gas processes in Germany [27].

Additionally, an overview of software tools for hybrid renewable energy systems, their capabilities and limitations is carried out in [28], and specifically, the state of the art of research using HOMER software is presented in [29]. A general classification of agent-based modelling techniques applied to electricity grids, and their relevance for the integration of stakeholders is given in [30,31]. A review of energy management strategies for hybrid renewable energy systems (only electricity generation) can be found in [32]. Authors in [33] present a state of the art about application and optimization tools in microgrids integrating renewable energies, emphasizing on optimization objectives and methods. In [34], a review of power-to-gas pilot plants is presented, which includes both, the plants already operating and the ones that are being planned worldwide. This document

also gives information about components, capacities and obtained experience during the systems operation, and highlights the influence of the design, sizing and operation strategy on the efficiency and reliability of the projects.

Furthermore, for hydrogen production and storage several documents have been published. For instance, concerning the production stage, [35] shows the current energy landscape, and highlights the main characteristics, strengths and weaknesses of the hydrogen production process. Likewise, in [36], 19 hydrogen production routes are assessed and compared under sustainability concept, so that energy and exergy efficiencies, cost, global warming potential, acidification potential, and social cost of carbon are evaluated. Meanwhile, in [37] hydrogen production, processing and end-use are summarized from the innovation point of view under the 18s concept, which includes some items such as source, sector, safety, sustainability, stakeholder, and scale-up among others. With respect to hydrogen storage, an overview of technologies is given in [38], along with their recent improvements and industrial perspectives. In [39] an expert opinion survey is performed for analyzing both, the current state and the perspectives of renewable hydrogen storage systems in Europe, as well as their locations, capacities, economic factors, and regulatory and government frameworks. [40] presents a benchmarking and an Analytical Hierarchy Process to compare the power-to-gas with other energy storage technologies for different application scales. In [41], the analysis of storage needs and its performance from a process perspective is performed, with focus on power-to-gas and long-term storage.

The hydrogen supply chain issue has been analyzed in [42,43], where the objective is to understand the way for integrating the hydrogen supply pathways in bottom-up energy system models. Additionally, in [44] is presented a study on the economic and environmental assessment of three different hydrogen delivery scenarios, which include storage, transmission and distribution stages. From the social perspective, some publications have appeared about the assessment of the socio-technical evolution of DES in urban planning and policies, focusing on solar photovoltaics and thermal applications [6], and on the review of drivers and barriers for social acceptance of distributed energy systems [45].

According to the previous overview, this work presents a systematic study regarding DES with hydrogen as energy vector. It integrates a technological overview, analyzing multi-generation technologies (sources, energy converters), and the specific hydrogen-related infrastructure in the system. A review is also included about the hydrogen end-use in the energy system (storage, fuel, raw material), and the scale of application (e.g. building, neighborhood). In addition, the performance goal (e.g. economic, technical, environmental) and uncertainty management (inherent to renewables and energy demand) are studied too.

The originality of this work lies in the global perspective to address the analysis of DES, specifically when hydrogen is incorporated. In contrast to previous works, that were focused on approaches, software tools or optimization algorithms, this study is oriented to summarize the main results that have been obtained by the scientific community. This means that this work can constitute a baseline to identify trends and gaps that could be object of future research.

## 2. Overview on DES and Hydrogen as Energy Carrier

The crucial role of renewable sources to face the challenges like energy systems decarbonization, energy security, and the trend to move towards electricity as end-use energy have boosted the transition of energy sector. As a result, the goals are focused in the deployment of flexible and efficient energy systems that enable to increase the electricity coverage and the sharing of zero or low-emission resources. To reach these objectives, the decentralization of power plants and the integration of different energy networks by means of the combination of multiple energy sources, converters and carriers are needed. In this line, the DES and the introduction of energy vectors as hydrogen have emerged like possible solutions, and have been studied by researchers. For this reason, and taking into account the scope of this work, a brief overview regarding DES and hydrogen as energy carrier is presented in the following subsections.

### 2.1. Distributed Energy Systems

The growing concerns about climate change, energy independence, and the need to supply electricity to isolated communities have fostered a great transformation for energy systems. Therefore, the focus is oriented to develop power plants located close to end-users and designed according to local resources and demands, in addition to renewable sources deployment [46]. These issues have been addressed under the DES concept, which involves both the placement of generation plants (decentralized generation), and the integration of different energy sources [47]. In DES, the distributed generation can offer technical (e.g. system flexibility), economic (e.g. local resources development) and social (e.g. self-sufficient communities) advantages, while the employment of a variety of energy forms can ease the renewables penetration.

According to the increasing interest in DES, a diversity of aggregation concepts and approaches has emerged in the scientific community. In the following, some of these concepts are defined with the aim to clarify the framework of this work. However, it is important to highlight that there is no complete consensus about this terminology, and in some cases it is used indistinctly.

*Energy hub:* This approach represents an interface between energy sources (fossil fuels, biomass, solar, wind) and demands (electricity, cooling, heating, fuels). Energy hub is based on considering the energy system as a unit where multiple energy carriers can be converted, stored and distributed [48]. It is characterized by a black-box approach oriented to obtain an optimal arrangement among energy vectors, where the components relationships are modelled through coupling matrices composed of efficiencies and conversion factors [18,49].

*Microgrid:* It is defined as a local power system composed of distributed generation and storage units, in addition to clearly delimited energy loads [6,50]. Microgrids have the capability to operate in isolated (self-sufficient) and grid-connected modes, and are generally operated by means of a control center that is in charge of managing energy supply and demands in real-time [51]. One of the key advantages of microgrids lies on their distributed generation based on local resources, because besides improving the resilience of the system, it enables the integration of renewable energies [52].

*Multi-energy systems:* These are based on the idea of changing the paradigm where sector-oriented (electricity, heating, fueling) energy systems just have few interactions, or are even planned and

operated in a completely independent way [19]. Thus, this approach intends to expand the system boundary beyond a specific energy sector in order to take advantage of the synergies provided by the integration (also called integrated energy systems) of different energy networks [51]. Regarding scale, it is important to point out that in contrast with microgrids, multi-energy systems (MES) can be addressed for both centralized and decentralized generation.

*Polygeneration:* From the most general point of view, it consists in the generation of more than one energy vector from a single process [53]. However, the concept can be used for referring to a unit as well as to the whole system. On the one hand, the most common examples of polygeneration units are the combined heat and power plants (CHP) and fuel cells, where heat and electricity can be obtained from a unique fuel and process. On the other hand, when all the energy system is considered, polygeneration represents one case of MES [51].

*Hybrid energy systems:* These systems represent the kind of applications where more than one energy conversion device or source are involved to supply an energy requirement [54,55]. Unlike polygeneration definition, which is based on the produced energy, the concept of hybrid energy systems (HES) is addressed to energy sources and transformation units. For instance, a power plant fed by wind and sun, or employing batteries and hydrogen simultaneously for energy storage, can be considered as a hybrid system. Nevertheless, it has to be indicated that HES are not constrained by system products (more than one could be considered), whereby these can be seen as a sub-case of MES as well.

As described-above, one of the main issues for energy systems transition relies on incorporating different energy carriers and establishing relationships among energy networks. In this line, hydrogen has appeared as a promising alternative thanks to its capabilities to be obtained from a wide range of renewable and non-renewable resources, and to connect different energy networks.

## 2.2. Hydrogen as Energy Vector

Hydrogen is an energy carrier with a wide range of properties to be used as fuel, as raw material or as interface between electricity and chemical energy forms through the power-to-gas process. There, it can be used as storage medium to absorb the renewables fluctuations and/or as feedstock for synthetic natural gas production through methanation reaction, with the key feature of offering a completely emission-free pathway [10,56]. Its high content of energy per mass (higher heating value 142 MJ/kg), is around three times larger than common fossil-derived fuels, namely natural gas (53,6 MJ/kg), diesel (45,4MJ/kg) and gasoline (46,4MJ/kg). Additionally, its capability to enable the decarbonization of some chemical processes and the transport sector, makes hydrogen a key energy carrier to face the current energy and environmental challenges [22,57].

Although hydrogen is the most common element, it is not present by itself in nature but combined mainly with carbon and oxygen, thus it needs to be extracted and/or separated. In this regard, there are several sources, such as biomass, fossil fuels, sun and wind energies, and different pathways, including reforming, electrochemical and biochemical processes to produce hydrogen. All these possibilities about sources and processes represent a great opportunity for its integration into DES, because as mentioned previously, one of the main issues of this kind of systems lies on incorporating a variety of sources and technologies for energy transformation. The following

overview presents the main characteristics, strengths, weaknesses and perspectives of the hydrogen production processes (Table 1), as well as some hydrogen storage alternatives.

*Reforming:* The steam reforming of natural gas is the most mature technology and common process to produce hydrogen around the world [58]. It consists in the catalytic reaction of methane with steam to produce syngas (Eq. 1), which is a mixture composed of H<sub>2</sub> and CO. In general, this reaction is carried out using a nickel-based catalyst, and under temperature and pressure ranging between 700-900°C and 3-25 bar respectively. Then, in order to increase the amount of hydrogen, the syngas is submitted to water-gas shift reaction (Eq. 2), where H<sub>2</sub> and CO<sub>2</sub> are the products. Finally, the resulting gas stream (rich in H<sub>2</sub>) is subjected to separation/purification by means of pressure swing adsorption (PSA) process, to obtain the desired hydrogen purity according to its end-use [58].



Usually, reformer units are conceived to operate at large-scale (150-300 MW), mainly to supply refining and chemical industry requirements, with mature technologies that reach efficiencies around 70-85% [10]. However, in order to respond to the current energy trends towards decentralized systems, and the expected deployment of hydrogen as fuel in transport applications, the reforming technology is being adapted to small scales (0,15-15 MW) for on-site hydrogen production [10,58].

Furthermore, from the process perspective, it is well known that the packed-bed reactors used in large-scale plants, have to deal with problems like the diffusional limitations produced by the size of catalyst particles (needed to avoid excessive pressure drop), the low heat-transfer rates, and the thermodynamic constraints intrinsic to equilibrium reactions [59]. Meanwhile, small-scale hydrogen production systems are operated using process intensification principles, in micro-reactor reformers, which allow the deployment of on-site and portable hydrogen infrastructure. These units are composed of a set of plates with parallel channels (diameter between 10 and 500 μm), where the catalyst is charged or coated, and where the reaction occurs. As a result, this configuration provides the process with a higher surface area to volume ratio than large reactors, overcoming their heat and mass transfer limitations [59,60]. Taking into account the decreasing influence of transport phenomena, in micro-reformers the process becomes kinetically controlled, and thus, it achieves additional improvement by acting over the catalyst. In this way, it has been identified that noble metals (mainly Pt, Pd and Rh) are more active, more resistant to sulfur, and less prone to coke deposition than nickel-based ones [58,60,61]. Currently, the main challenges of these miniaturized systems concern to the sensitivity to fouling, pressure drop and difficulties in sealing, which are expected to be solved in the near future through research in the materials selection and equipment design [60].

*Electrolysis:* This electro-chemical process consists in the water splitting into oxygen and hydrogen by using electrical energy (Eq.3). The electrolyzer is composed of a cathode, an anode, and an electrolyte that acts as the medium for ions transport. The process is based on the transfer of electron through an electrical circuit and ionic species across the electrolyte, from the anode

(oxidation) to the cathode (reduction), i.e. a redox reaction occurs [62]. Currently, there are three main electrolysis technologies: alkaline, polymer electrolyte membrane (PEM) and solid oxide electrolyzer cell (SOEC), which differ in the material of the electrolyte, efficiency and operational conditions.



Alkaline electrolyzers are the most mature technology. They use a solution of sodium or potassium hydroxide (20-40% wt.) as electrolyte, and operate at temperatures between 60-90°C with a resulting efficiency of 70-80% [58]. Unlike alkaline ones, PEM devices have an acidic and solid electrolyte, and a platinum-based catalyst is needed to make that reaction proceeds. These electrolyzers have efficiencies of 65-80%, and their working temperatures are 25-80°C [10]. Some advantages of PEM technology are its higher power density and hydrogen purity, the short response time, and its capability to operate in a wider load range and at more elevated pressures with respect to alkaline ones [58]. However, they are limited by the lifetime of the membrane and the cost of the catalyst [10]. Otherwise, SOEC with a solid ceramic electrolyte are considered as high-temperature electrolysis units, because the reaction is carried out at 700-900°C, which allows to achieve efficiencies up to 90% [10]. Nowadays, despite the promising potential of this electrolysis alternative, SOEC is the least mature technology and its current development is still restricted at lab-scale processes [13,39,58], whereas alkaline and PEM electrolyzers systems are already available at megawatt scale [39,63]. From the economic point of view, challenges for the electrochemical process still remain. For instance, considering a price of 27 €/MWh for the natural gas, in Europe the cost for producing hydrogen from methane reforming is about 1,6 €/kg, which can be between two and five times lower than the cost of electrolysis, due to the current prices of equipment and electricity [39]. Nevertheless, thanks to the continuous research and technological developments on electrolyzers and the installation of larger plants, a significant decrease in their investment and operating costs is expected in the upcoming years [39].

*Gasification:* It is a thermo-chemical conversion of solid or liquid carbon-formed materials (fossil fuels or biomass) mainly into hydrogen and carbon monoxide (syngas). However, depending on the feedstock and operating conditions, CH<sub>4</sub>, H<sub>2</sub>S, CO<sub>2</sub> and NH<sub>3</sub> can be produced as well [64]. Gasification is a process involving different steps. The first one consists in moisture removal (drying); then, a chemical decomposition by heating in absence of oxygen (pyrolysis) is done in order to release volatile compounds (mainly CH<sub>4</sub>, CO, H<sub>2</sub>). In the next step, an oxygen-controlled environment is supplied to the system for the combustion of the volatile matter, which helps to increase the process temperature and provides the medium for the subsequent operation. Finally, the gasification ends with the reactions (e.g. Eq.4-7) between the char coal and a gas phase mainly composed of CO<sub>2</sub>, H<sub>2</sub>O and O<sub>2</sub> under temperatures of 800-1300°C [64].

Subsequently, depending on the end-use of the syngas produced, it is further subjected to water-gas shift reaction and/or purification processes to employ it as fuel, or raw material for methanol or synthetic natural gas production (methanation) [64].





In general, gasifiers can be classified according to a wide variety of characteristics such as bed temperature and type, pressure, oxidant flow through the equipment and ash formations [64,65]. The most conventional grouping considers entrained-flow, fixed-bed and fluidized-bed gasification technologies. Currently entrained-flow gasifiers are the most efficient alternative and, have the smallest environmental impact and the largest production capacity, thus they represent the major part of the commercial market for centralized syngas plants [65]. This technology is characterized by operating at high temperatures (1100-1500°C), which allows good conversions in short reaction times, and avoids technical limitations in the feedstock type. Fluidized-bed equipment offers a homogeneous temperature environment promoting the heat and mass transfer between the reactants. The main advantages of these gasifiers are their easy scale-up and adaptation to changes in the feedstock, as well as the better temperature control, whereas their drawbacks are related to the need of specific particle size and lower conversion with respect to other gasification options [64,65]. Otherwise, fixed-bed reactors are commonly used for biomass gasification, and are divided into co-current (downdraft) and counter-current (updraft) gasifiers. From these, downdraft gasifiers are the preferred option for small scale and on-site applications due to their relatively easy design, fabrication and operation, as well as their low tar content in the product [65,66]. However, there are some drawbacks such as the channeling, and the limitations to obtain good performances with feedstock moisture over 20% that still need to be overcome [66].

*Biochemical Processes:* There are several different pathways to produce hydrogen from microorganisms and/or biomass (waste, wood, agricultural crops, and human or animal residues) including dark fermentation, direct and indirect biophotolysis, photofermentation, and even the biogas synthesis through anaerobic digestion and its subsequent reforming process [67]. Among these, dark fermentation and digestion exhibit the major developments and offer the most promising options for biochemical production of hydrogen [58,67]. In dark fermentation, the process is performed by an anaerobic bacterium that acts over the organic matter to produce a gas stream composed of H<sub>2</sub> and CO<sub>2</sub>. The main advantages of this process are the possibility to use a wide variety of waste as feedstock and its simple reactor technology, making even nonsterile conditions and impurities acceptable without negative effect on the performance of the process [24]. However, the process constraint due to the accumulation of by-products in the reactor and the difficulties of hydrogen purification are some drawbacks that need to be further studied. On the other hand, anaerobic digestion is a biochemical process where different types of microorganisms metabolize the organic compounds of biomass to produce biogas (mixture of CH<sub>4</sub> and CO<sub>2</sub>), which is then subjected to a reforming process for hydrogen synthesis [67].

**Table 1.** Summary of characteristics and challenges of hydrogen production technologies. Adapted from [35–37,68].

<b>Technology</b>	<b>Strengths</b>	<b>Weaknesses</b>	<b>Perspectives/ Challenges</b>
<b>Steam Reforming</b>	Established and mature technology	High energy consumption and operating costs	Improve product purification
	High thermal efficiency	CO <sub>2</sub> emissions	Renewable feedstocks (biofuels, biogas, bio-ethanol)
	Cheapest production method (currently)	Catalyst deactivation	Process intensification (membranes, on-site units)
<b>Electrolysis</b>	No pollution - decarbonized pathway	High electricity consumption	Improve efficiency
	Hydrogen purity	Low system efficiency	Renewable sources integration
	Link between electrical and chemical energy	High capital cost	Durable and cheap materials
<b>Gasification</b>	Abundant and cheap feedstock (biomass)	High reactor costs	Product purification
	Environment-friendly	System efficiency	Handle with feedstock variability
	Favorable for large-scale production	Greenhouse gas emissions	Process cost and efficiency
<b>Dark Fermentation</b>	Simple reactor technology	Low hydrogen yield	Research in metabolic engineering
	No light and oxygen dependence	Large quantity of side products is formed	Materials science breakthrough
	Wide variety of carbon sources can be used	Reactor-to-reactor variation	Improve hydrogen selectivity

Besides synthesis alternatives, the reliable deployment of hydrogen as energy carrier is strongly connected to the performance of its storage [38]. In this regard, hydrogen has the capability to be stored as compressed gas or in liquefied cryogenic form (physical), and through metal hydrides (chemical) in solid state. Among these alternatives, high pressure system for gaseous hydrogen storage is the most common method, and offers capacities up to 10 MWh [10]. However, due to the low density of hydrogen as gas (0,08 kg/m<sup>3</sup>) pressures up to 700 bar are employed to avoid excessive volume of the tanks, which implies challenges for vessel materials and safety concerns [38,69]. Otherwise, liquid hydrogen storage is carried out by cryogenic process to condense the hydrogen from gas to liquid state using temperatures around -253°C. This method allows higher energy densities (capacity up to 100 GWh), and is the preferred option for transport, short-term storage and in space applications. Nevertheless, its main limitations lie in the energy consumption and isolation conditions that the process demands, along with the product losses by boil-off (0,3% per day) [10,38,62].

Considering the aforementioned hydrogen storage technologies, the cryo-compressed alternative has been developed in order to trade-off their properties. In this option, the hydrogen is stored under cryogenic temperature (-253°C) and elevated pressure (> 300 bar) to avoid evaporation losses keeping high energy density, and with the key advantage of being compatible with hydrogen in gas and liquid state [38]. Furthermore, hydrogen can be stored as solid by means of metal hydrides formation in a physicochemical process. In this alternative, the hydrogen atoms are chemically

bonded to the host material (e.g. sodium, lithium, aluminum or magnesium) during the adsorption phase (charging), and subsequently released by heating through the desorption process (discharging). This is a promising technology because it provides high volumetric densities with operating conditions that do not entail the safety concerns of pressurized and cryogenic processes [38,69]. However, it is the least mature technology, and some issues still need to be solved, such as the material volume expansion due to the stress produced by the adsorption/desorption cycles [70].

Besides reducing the environmental impacts, increasing the efficiency, and promoting the deployment of renewable sources, it is also expected that energy systems be safe along the whole system supply chain, which includes production, storage, transport, delivery and end-use [37,38]. In this regard, hydrogen energy systems, particularly in distributed applications, have to deal with the limited operative experience of this kind of plants, and with the public reputation of hydrogen for some unfortunate accidents that implied significant societal and economic costs in the history [71,72]. However, from the safety point of view, hydrogen is not more or less dangerous than other fuels, e.g. gasoline or natural gas, but like all the fuels, it must be manipulated responsibly and according to specific standards and procedures [37,73]. Leaking is one of the main challenges that hydrogen has to tackle due to its difficult detection, since it is a colorless, odorless and tasteless gas. Other safety concerns are its low ignition energy, and its capability to have a wide range of combustible concentrations with air [58,73]. Nevertheless, these issues can be addressed with a well-defined framework including standards, community education, and technology improvement and certification, in order to ease the consumer acceptability and the integration of hydrogen solutions in the energy network [37,73].

Despite of the potential benefits of using hydrogen as energy vector, there are several economic, technical, environmental and social issues that have to be considered in order to take advantage of the complementarities between DES features and hydrogen capabilities. This problem could be addressed from the point of view of an optimization case, where multiple constraints must be satisfied to support the feasibility of the solution for a problem with defined objectives. For instance, in this case the constraints could be technical (capacity, technological maturity, efficiency), geographical (resources availability) and/or socio/political (legislation, safety), whereas the objectives can be economical (profit), environmental (gas emissions, residues), social (employability) or technical (share of renewables, optimal operation). For this reason, a systematic literature review is proposed in this work with the aim to identify the current state of research about DES using hydrogen as energy vector, and thereby find trends, gaps and opportunities that could be explored for further research work.

### **3. Methodology**

Considering the above-mentioned challenges, trends and perspectives of DES, the goal of this study is to understand how hydrogen is employed in DES (production technologies, applications), and to identify the criteria that are evaluated when this kind of system is designed, planned and/or operated. The results of this mapping include a general framework about technologies (e.g. electrolyzers, reforming, gasification), end-uses (e.g. storage, fuel, raw material) and objectives (e.g. technical, economic, environmental) addressed by researchers. Thus, a systematic literature review based on a search strategy, and the documents classification and analysis was performed.

### 3.1. Search Strategy Definition

This step consists in defining the search equation, which is composed of keywords, period of time, database and type of documents to be analyzed (Table 2). The key word field was divided into two complementary parts. The first one regarding DES, and the second one focused on specific studied technologies, namely hydrogen and power to gas. Taking into account the great variety of terminology related with DES, this aspect is composed of a set of terms (e.g. energy hub, microgrid, hybrid energy system). These keywords were defined according to a preliminary literature review, whereas the period of time was selected from 2000 because the first documents found in databases date back of this year.

**Table 2.** Search strategy

Field	Option Introduced
<b>Keywords</b>	("energy hub" OR microgrid OR "integrated energy systems" OR "distributed energy system" OR "decentralized energy system" OR "multi energy system" OR "hybrid energy system" OR "polygeneration") AND (hydrogen OR "power to gas")
<b>Search in</b>	Title, abstract, keywords
<b>Period explored</b>	2000 - 2018
<b>Type of documents</b>	Articles and conference papers
<b>Database</b>	Scopus® and Web of Science

### 3.2. Documents Analysis

After applying this search strategy, the corresponding classification, selection and analysis of the documents was realized. In order to choose the most relevant papers according to objectives of the work, two main filters were established. The first one lies on the inclusion of hydrogen or power-to-gas technologies within an energy system with defined sources and demands. It implies that documents focused on hydrogen production, isolated technology applications, methane synthesis or related, were not selected for the subsequent analysis. The second filter deals with one of the key aspects of DES that is synergy among different sources. For that reason, only documents including more than one energy source (i.e. solar, wind, biomass, natural gas) were chosen. In the same way, research work dedicated to control of energy systems was not covered in this study.

## 4. Results and Discussion

According to the defined search strategy, 501 and 352 scientific publications (many are repeated) were found in Scopus® and Web of Science databases respectively. Then, the two proposed filters were used to classify the documents, and 106 research papers were selected to be analyzed in detail. Among them, a wide range of scales is covered in the cases studied by researchers. These scales range from national energy networks and the replacement of current coal-based power plants, to laboratory pilot-scale systems, neighborhoods, schools, buildings, or even households. In Table 3, a general summary of the results related with the hydrogen infrastructure and use, size of the energy system (peak electricity demand) and the evaluated objective is presented.

**Table 3.** Publications summary. Elc, electrolyzer (Alk-alkaline, PEM-polymer electrolyte membrane, SOEC-solid oxide electrolyzer cell); FC, fuel cell (SOFC-solid oxide fuel cell); Met, methanation; Rfo, reforming; Gas, gasification; St Op, storage option (G-compressed gas, MH-metal hydrid, U-underground).St, storage; F, fuel; F-NG, blend with natural gas; RM, raw material.Ec, economical; Tec, technical, Env, environmental; \* health impact cost

Ref.	Hydrogen related infrastructure						Hydrogen Use				Peak Demand	Perf. Goal	
	Elc	FC	Met	Rfo.	Gas	St. Op.	St	F	F-NG	RM			
[74]	PEM					G		x					Ec - Tec - Env
[75]	PEM		x			G			x	x			Tec
[76]		SOFC						x					Tec - Env
[77]					x			x					Ec - Tec - Env
[78]				x	x			x					Ec - Tec - Env
[79]	x		x			G					x		Tec
[80]	Alk.							x			x	3250 MW	Ec - Env
[81]	PEM	PEM					x					7,5 kW	Tec
[82]	PEM	PEM				MH	x					500 W	Tec - Ec
[83]	x	x					x					600 kW	Tec
[84]	x					U		x	x	x			Ec - Env
[85]	PEM			x							x		Env
[86]	x							x				220 kW	Tec
[87]	PEM					G		x	x	x		4 MW	Tec
[88]	SOEC	SOFC	x		x						x		Ec - Tec
[89]	PEM	PEM				MH	x						Tec
[90]	Alk.					G		x				1500 kW	Ec - Tec
[91]	PEM	PEM				MH	x					1,3 kW	Tec
[92]	x	PEM				G	x	x				550 kW	Ec
[93]	x	x				MH	x						Tec
[94]	PEM	PEM				MH	x	x				1,6 kW	Ec
[95]	x	x				G	x					40 kW	Ec - Tec - Env
[96]	PEM	PEM				MH	x	x				1,6 kW	Ec-Tec
[97]	x	PEM				G	x	x				7,7 kW	Ec
[98]	x	PEM		x		G	x					480 kW	Ec

[99]	PEM	PEM			G	x				5 kW	Ec - Tec
[100]		PEM	x		G		x	x	x		Ec
[101]	Alk.	PEM			G	x					Tec
[102]	x	PEM			G	x				50 kW	Ec-Tec
[103]	x	x				x				1600 kW	Ec
[104]	PEM	PEM			G	x				3,2 kW	Ec
[105]	x	x				x	x			100 kW	Ec
[106]	Alk.	PEM			G	x				222,7 kW	Ec
[107]	x	x	x		G	x	x			310 kW	Ec-Tec
[108]	x	x			MH	x	x	x	x	800 kW	Ec
[109]	PEM	x			G	x	x			5410 kW	Ec - Env
[110]	Alk.					x	x	x			Ec -Tec- Env*
[111]	x	PEM			G	x				175 kW	Ec
[112]	x	PEM		x	G	x				500 kW	Ec-Tec
[113]	x	x			G	x				9 kW	Ec-Tec
[114]	x	x			G	x				0,66 kW	Ec-Tec
[115]		x	x				x				Env
[116]	x	x			G	x				750 kW	Ec - Env
[117]		PEM	x		G		x	x	x	160 kW	Ec - Env
[118]	Alk.			x					x		Tec
[119]		PEM	x	x	x	G		x		1,1 MW	Ec - Env
[120]		x					x			2,3 MW	Ec - Env
[121]	x	x				x				400 kW	Ec-Tec
[122]	x				G	x	x			130 kW	Ec
[123]			x	x			x			500 kW	Ec-Tec - Env
[124]	PEM	PEM			G	x		x		430 kW	Ec - Env
[125]	x	x				x			x		Ec
[126]			x	x			x	x	x	340 MW	Ec-Tec
[127]	x	x	x			x	x			500 kW	Ec-Tec
[128]	x	x			MH		x	x	x		Ec
[129]				x			x	x		1300 kW	Ec

[130]	x	x		G	x				Tec
[131]	x	x		G	x			100 kW	Ec
[132]	x	x	x	G	x	x		500 kW	Ec
[133]	PEM	PEM		G	x			4 kW	Ec-Tec
[134]	x		x				x		Ec
[135]	x	x		G	x			2,8 kW	Ec
[136]	x	x		G	x			4,73 kW	Ec
[137]	x	x		G	x			239 kW	Ec-Tec
[138]	x	x		G	x			30 kW	Ec - Tec - Env
[139]		PEM	x			x		2,5 kW	Ec
[140]	x	x		G	x			50 kW	Ec
[141]		x				x		25 kW	Tec
[142]	x			G		x		1,5 kW	Ec
[143]		PEM	x			x		2 kW	Ec-Tec
[144]	x	x		G	x			2,5 kW	Ec
[145]	x	PEM		G	x			2 kW	Ec-Tec
[146]	x	PEM		G	x				Ec-Tec - Env
[147]	x	x		G	x			48 kW	Ec
[148]	x	x		G	x			160 kW	Ec-Tec
[149]	x	x		G	x			45 kW	Ec
[150]	x			G		x		1,5 kW	Ec
[151]	x	x			x				Ec-Tec
[152]	x	PEM		G	x			2 kW	Ec
[153]	x	x		G	x				Ec-Tec
[154]	x	x			x			1,7 kW	Ec
[155]	Alk.	PEM		U		x	x	3750 MW	Ec - Env
[156]	Alk.						x	4800 MW	Ec - Env
[157]	x	x		G	x			3,8 kW	Ec
[158]	Alk.	PEM		G	x			3,8 kW	Tec
[159]	x	PEM		G	x			14,6 kW	Tec
[160]	x	x		G	x			4,25 kW	Ec - Tec - Env

[161]	x	x		G	x			0,64 kW	Ec - Tec
[162]	x	x		G	x			1,2 kW	Tec
[163]	x	PEM		G	x			110 kW	Tec
[164]	Alk.	PEM		G	x				Ec - Tec
[165]		PEM	x			x		90,3 kW	Ec - Env
[166]	x	PEM		MH		x		7,72 kW	Ec
[167]	x	PEM		G	x			6 kW	Ec - Tec
[168]	x						x		Tec
[169]	x	x		G	x				Ec
[170]	PEM	PEM		G	x			17 kW	Ec - Tec
[171]	PEM	PEM		G	x	x		14 kW	Ec - Tec
[172]	x	x		G	x			135 kW	Ec - Tec
[173]	PEM	PEM		MH	x				Tec
[174]	PEM	PEM		G	x			4,2 kW	Tec
[175]	x	x		G	x			1,3 kW	Ec
[176]	x	x			x		x		Ec
[177]	PEM	PEM		G	x			4 kW	Ec - Tec
[178]	x	x		G	x			3,3 kW	Ec
[179]	Alk.	PEM		G	x			23,3 kW	Ec - Tec

Among these results, two studies evaluate energy systems coupling renewable sources with nuclear reactors to supply power requirements [151,155]. In [85], the life cycle assessment for the application of microgrids to cover hydrogen and energy demands of an industrial ammonia plant is reported. On the other hand, the synergies of a combined biorefinery - microgrid system in terms of optimal design and costs, and their comparison with each structure separately is presented in [125]. The sustainability assessment, using thermodynamic, economic and environmental factors, and the safety evaluation in terms of failure mode and effect analysis for a hybrid energy system are made in [146] and [109] respectively. Concerning modelling strategies, most of the publications developed scenario-based studies (combination of technologies, prices, demands), whereas only a few documents employ fuzzy logic and multi-agent approaches to deal with optimal equipment sizing and energy management strategies [93,95–97,107]. The consideration of some input data like weather conditions and energy demands was done through deterministic approaches in the major part of the reviewed papers. However, 17 research works include probabilistic functions and Monte-Carlo simulations (stochastic approach) to consider the uncertainty of this information.

Regarding conversion technologies, the most commonly used are photovoltaic panels, wind turbines, engine generators and gas turbines. From the obtained results, it can be noticed that only one research does not include any renewable source, namely solar, wind or biomass within its configuration, whereas around 70% of the documents employ at least two of them, which reflects the high integration of renewable energy sources in DES. Additionally, it is important to highlight that biomass can be burned to supply heat demands, but also, can be employed as feedstock for biogas and syngas synthesis, through anaerobic fermentation (digestion) and gasification processes respectively.

#### 4.1. Hydrogen Technologies

The set of technological alternatives analyzed in this work includes electrolyzers (EL), fuel cells (FC), methanation and reforming reactors, gasification units and hydrogen storage options (gas, liquid, metal hydride adsorption). Figure 1 shows that (EL) and (FC) are the preferred technologies to involve hydrogen in energy systems. In this regard, alkaline electrolyzers are selected because of their higher capacity and technological maturity, whereas PEM and SOEC options are chosen when response to operational conditions (frequent start-ups and shut-downs) or energy efficiency are privileged.

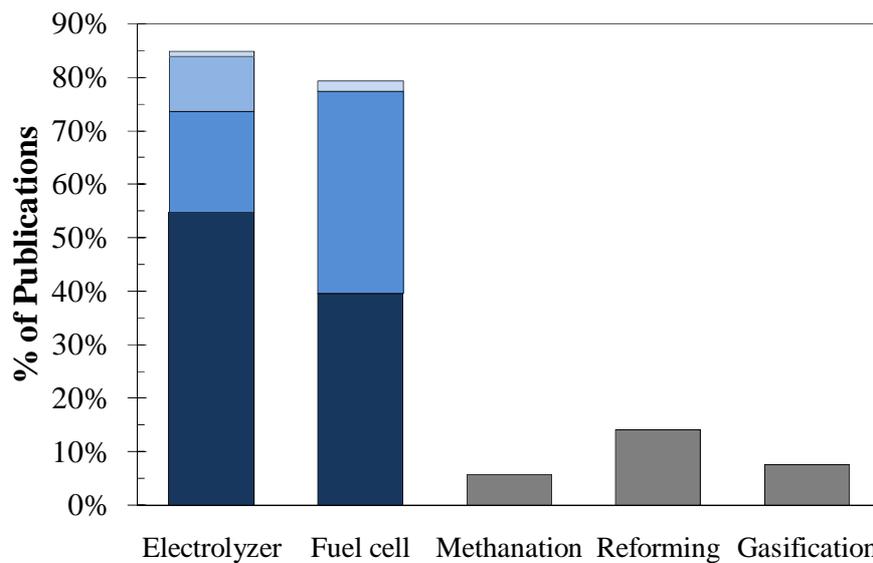


Figure 1. Publication distribution as a function of hydrogen technologies. (■) solid oxide technology; (■) alkaline electrolyzers; (■) PEM technology; (■) not specified.

In Figure 1, the distribution of EL and FC technologies is also presented, where PEM type represents the most widely used technology for both EL and FC. Regarding the methanation process, it is significant to foreground that the hydrogen employed comes from the gasification product, or from an electrolyzer powered by wind turbines or photovoltaic panels. This means that the whole methane produced in the evaluated system proceeds from renewable sources. In the case of reforming process, natural gas (NG), biogas or bioethanol are used as raw materials.

In order to identify some trends for the sizing of EL and FC in DES, Figure 2 is presented. From the data reported on the studied papers, the total installed capacity of EL and FC are correlated with the peak electricity demand of the system. It is important to clarify that despite the couple EL – FC is present in most of cases, there are few studies where only one of them is included depending on the configuration of the whole system and/or hydrogen use. For instance, just EL could appear when hydrogen is going to be used as raw material or directly as fuel (boiler, transport). On the other hand, systems with FC but without EL represent the studies where hydrogen is obtained from reforming, gasification or biomass digestion processes.

From these results, three groups of data that represent different application scales can be identified in accordance with the information reported by researchers (Table 2). The first one corresponds to energy systems with peak demands lower than 20 kW, the second one has energy requirements between 25 and 80 kW approximately, and the third one for electricity consumptions upper 90 kW. Besides, there is one additional set of works that is addressed to replace current coal-based power plants, and correspond to energy peak demands between 3200 – 4800 MW. It is important to note that the proposed classification aims to show some trends relative to application cases, however it is not the standard one, because the case study information (peak demand, scale) is not reported in all the documents.

Table 2. Classification of peak electricity demand with respect to application scale.

Group	Peak Demand	Scale	Characteristics
1	< 20 kW	Household	Domestic demands, studies from 1 to 5 five homes are included
2	20 - 80 kW	Small village	Mainly focused in rural sector, farms and remote areas far from the grid.
3	90 - 1500 kW	Neighborhood	Urban areas, including faculties of universities, schools, residential complexes, buildings, refueling stations

Figure 2 illustrates that a considerable range of capacity factors exist for sizing of units, mainly for electrolyzers. However, it appears that the size of FC is generally smaller than of EL, because the electrolyzer is the equipment in charge of responding to fluctuations of renewable sources (solar and wind). Additionally, it seems that this intermittence has greater influence in smaller systems (< 20 kW), and as a consequence, a higher installed capacity of EL is needed for the energy management in this type of systems. In general, it is well known that several factors need to be evaluated for equipment sizing in DES. However, the results of this work can be useful for preliminary design stages and constraints definition (in optimization problems) for DES with hydrogen as energy vector.

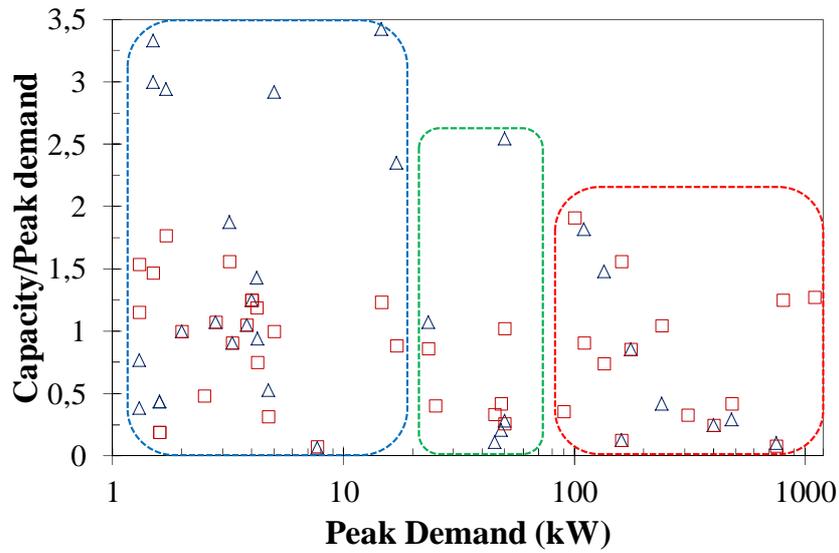


Figure 2. Correlation between installed capacity of electrolyzers ( $\Delta$ ) and fuel cells ( $\square$ ) with respect to peak electricity demand.

The box plot of Figure 3 illustrates the size distribution of EL, FC, and peak demand for the analyzed energy systems. Most research works (75%) represent applications with electricity requirements below 200 kW. This means, according to above mentioned results (Table 2), that the major part of case studies employed for evaluating DES with hydrogen as energy vector correspond to households or small villages. This result could constitute an opportunity for further research, supported with the technological development, towards the deployment of this kind of systems in larger applications.

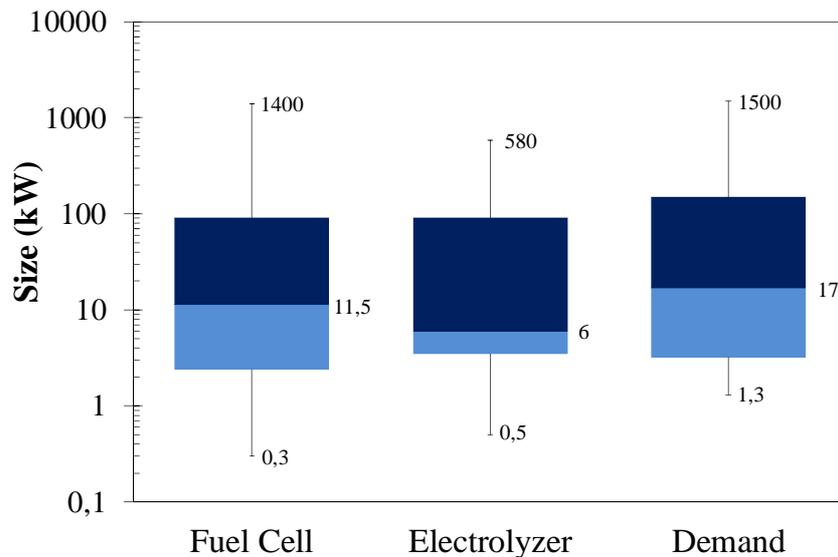


Figure 3. Size distribution of hydrogen-related units (electrolyzer – fuel cell) and peak electricity demands.

With respect to hydrogen storage alternatives, it is important to point out that no studies with hydrogen stored as a liquid were found. It is mainly due to the high economic and energetic costs to liquefy it and keep it in liquid state (high pressure and low temperature). Among the publications that report a specific form of hydrogen storage, gas in pressurized tanks (58%) is the preferred one. Metal hydride adsorption, natural gas pipelines and underground (salt caverns) alternatives are also used. In [122], the so-called vehicle-to-grid system is proposed, with the aim to use the hydrogen stored in the fuel cell vehicles for providing energy to the microgrid, when cars are parked and renewable generation is scarce.

#### 4.2. Hydrogen end-uses

Regarding end-uses, the following hydrogen applications were found: as storage medium, as fuel, fuel blended with natural gas, and as raw material for industry. The storage option refers to the cases where the only objective is to manage the surplus renewable production through the electrolyzer – storage - fuel cell system. The applications in transport (vehicles, buses), gas turbines and combined heating and power units like fuel uses are included. The syngas utilization for methanation process, and the case where hydrogen is sold for chemical industry are covered by raw material group.

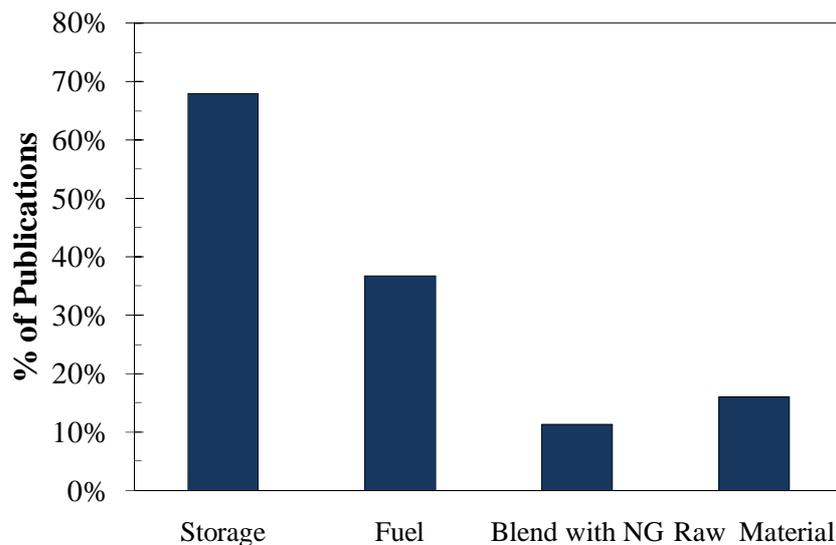


Figure 4. Publication distribution of hydrogen end-uses in distributed energy systems.

It is important to clarify that hydrogen applications are not excluding each other, therefore, studies with more than one or even the whole set of considered possibilities were found. The prevalence of hydrogen to store energy shown by results (Figure 4), appears as a response to the high penetration of intermittent renewable sources in DES. From these results, it is also interesting to note that DES have the capacity to provide a clean fuel for transport, and to supply chemical industry with renewable-based feedstock. This fact represents a valuable opportunity for the economic and social development of communities, because in addition to satisfying their energy needs, they could participate as hydrogen suppliers, based on their local resources.

### 4.3. Performance Objectives

Economic, technical and environmental issues are the focus of research to evaluate the energy systems involving hydrogen as energy vector. Among economic objectives, net present value, levelized (\$/kWh) and operational costs, are the most commonly used. In a few cases, environmental and human health impacts (produced by emissions) were also addressed in economic terms [74,110,116,123,156]. Exergy analysis, energy efficiency, technological feasibility and experimental validations like technical targets were considered, while, the life cycle assessment and greenhouse gas emissions represent the main goals with respect to environmental aspects.

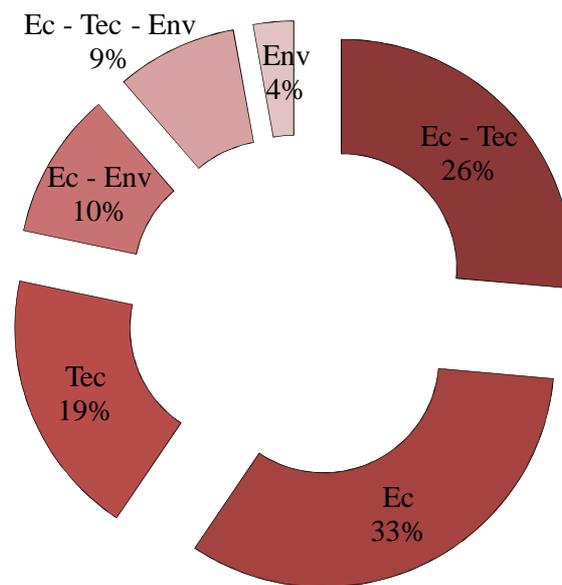


Figure 5. Publication distribution of performance objectives evaluated in distributed energy systems. (Ec-economic, Tec-technical, Env-environmental)

Figure 5 shows the distribution of publications according to their evaluated objective. It highlights the prevalence of economic issues, which are involved in almost 80% of studies. It is also important to notice that around 45% of documents include multi-objective analysis, 9 works address economic, technical and environmental goals simultaneously and one of them includes the health impact cost produced by pollution (social factor) [110].

In summary, the results of this mapping study can be presented in two main topic groups, one of them corresponds to technical issues, and the other one to approaches and research objectives. From the first one, which is related to conversion and hydrogen technologies, the results constitute baseline information (type of technologies, equipment sizes) that could be valuable for the preliminary stages of research or project planning of DES involving hydrogen. Additionally, the lack of approaches considering the unpredictable behavior of input data (weather conditions, prices, demands), or including social and/or political issues for DES evaluation, appears as a possibility to future research work.

Furthermore, regarding hydrogen production processes, it is noted that the technological challenges for the upcoming years are mainly focused on the improvement of the system efficiency (conversion, purification), the reduction of capital and operation costs, the emission decrease and the employment of renewable resources in processes like reforming and gasification. Besides, all these technological developments need to be supported by a framework that includes policies and the integration of the whole project stakeholders, along with the implementation of safety codes, standards, certifications, and education programs that enhance the community acceptability and comfort with hydrogen technologies.

Moreover, integrative and holistic point of view must be further explored. For instance, one promising area can be the implication (at the conceptual design stage of DES) of the changes in consumer patterns as a consequence of disaggregated consumption feedback and collaborative behavior. In this way, empirical studies in [180,181] have reported an average reduction of 7,8% and 4,5% in households energy demand, with a maximum of 14,5% for the named “energy enthusiast”. Evidences from these studies could represent the opportunity to explore new design spaces with implication in the entire system configuration, because changes in energy consumption could entail in smaller equipment and/or the economic viability of emerging solutions.

#### 4.4. Bibliometric Summary

This sub-section presents some results relative to the distribution of documents along the years, the main publication journals, and a summary of origin (countries and institutions) of the 106 analyzed papers. The results of the evolution of publications over the years (Figure 6) show an increase of published documents about DES including hydrogen mainly in the last 8 years. It emerges as a response of the research community to the concerns about climate change and the new trends in the energy sector.

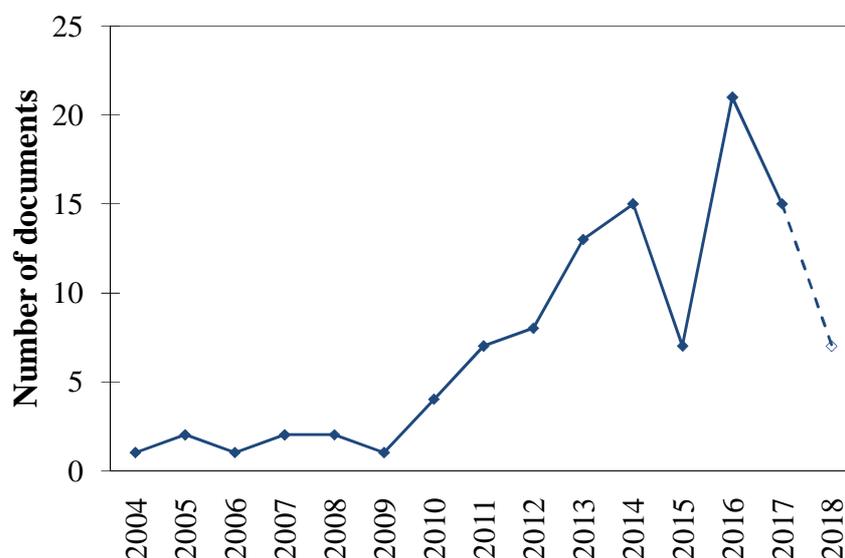


Figure 6. Distribution of publications over the years. (--) Partial result for the year 2018.

In Figure 7, the chart depicts the main publication journals for documents related to DES including hydrogen as energy carrier. From these results, it appears that *International Journal of Hydrogen Energy*, *Applied Energy*, *Renewable Energy* and *Energy* journals have been preferred by the researchers for publishing their works, and thus represent an important source of information for the studied subject.

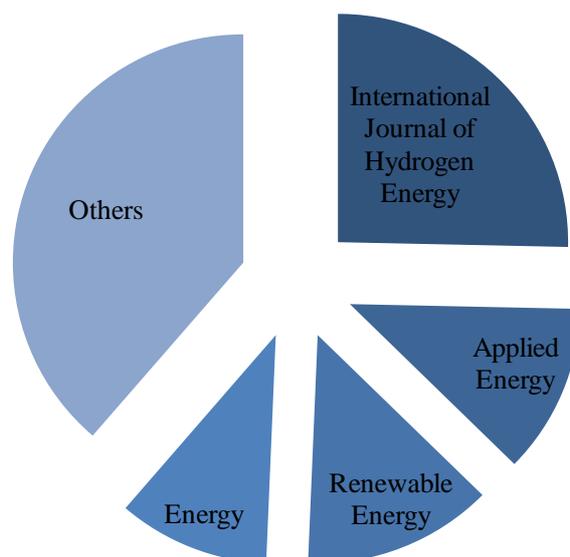


Figure 7. Chart with the main publication journals.

Concerning the origin of the analyzed papers, the results indicate that in Europe most documents come from Germany (Karlsruhe Institute of Technology), Spain (University of Seville), Italy (Politecnico di Milano and University of Cagliari), Netherlands (Delft University of Technology and Utrecht University), Greece (Agricultural University of Athens), Switzerland (Swiss Federal Institute of Technology and École Polytechnique Fédérale de Lausanne), France (Université de Bourgogne and European Institute for Energy Research) and United Kingdom (Imperial College London). In North America, the publications come from Canada (University of Waterloo and University of Ontario Institute of Technology) and United States (University of Minnesota). In the rest of the world, papers are mainly from China, Japan and Iran (Sharif University of Technology and Islamic Azad University).

## 5. Conclusions

In this paper, a systematic literature review of distributed energy systems involving hydrogen as energy carrier was done through the analysis of 106 research documents. It includes a general mapping of energy sources and a detailed revision of hydrogen-related technologies (type, size), the identification of hydrogen end-uses, and the evaluated objectives when this kind of systems are planned, designed or operated. From these results, it appears that a wide variety of scales (household, neighborhood, buildings, universities, current power plants) are considered as application cases, as well as the high penetration of renewable sources (mainly sun and wind). Regarding hydrogen technologies, the prevalence is for electrolyzers and fuel cells, although

reforming, gasification and methanation process have also been included by researchers. In general, it is noted that the installed capacity of EL is larger than FC, and that small systems (< 20 kW) receives greater influence of the intermittence of renewables on the size of the EL, thus a higher capacity respect to peak demand could be required. With respect to end-use, most publications have considered the application of hydrogen as storage medium for mitigating renewable production fluctuations. However, the hydrogen use as fuel in cars, scooters, boilers or CHP units (alone and blended with natural gas), and as raw material for the industry have also been addressed, which constitute an opportunity for communities to participate in hydrogen economy.

Results concerning about evaluated objectives show that the design and analysis of DES including hydrogen have been predominantly focused on techno-economic issues. Nevertheless, there is lack of approaches including data uncertainties in weather conditions, prices and demands that can affect the performance of the system. Hence, there is an opportunity for future work to include social aspects, and consider specific context conditions (e. g. sources availability, weather) and uncertainty to improve the decision-making process for planning this type of energy systems.

### **Acknowledgments**

This work was supported partly by the french PIA project « Lorraine Université d'Excellence », reference ANR-15-IDEX-04-LUE »

### **References**

- [1] International Energy Agency (IEA). World Energy Outlook 2017 2017. <http://www.iea.org/weo2017/> (accessed April 8, 2018).
- [2] International Energy Agency (IEA). Global Energy & CO2 Status Report: The latest trends in energy and emissions in 2017 2018. <https://www.iea.org/geco/> (accessed April 8, 2018).
- [3] International Energy Agency (IEA). CO2 Emissions from Fuel Combustion 2017 - Highlights. vol. 1. 2017. doi:10.1787/co2\_fuel-2017-en.
- [4] International Energy Agency (IEA). Key World Energy Statistics. 2017.
- [5] Renewable Energy Policy Network for the 21st Century (REN21). Avanzando en la Transición Mundial hacia la Energía Renovable. 2017.
- [6] Adil AM, Ko Y. Socio-technical evolution of Decentralized Energy Systems: A critical review and implications for urban planning and policy. *Renew Sustain Energy Rev* 2016;57:1025–37. doi:10.1016/j.rser.2015.12.079.
- [7] Alanne K, Saari A. Distributed energy generation and sustainable development. *Renew Sustain Energy Rev* 2006;10:539–58. doi:10.1016/j.rser.2004.11.004.
- [8] Bouffard F, Kirschen DS. Centralised and distributed electricity systems. *Energy Policy* 2008;36:4504–8. doi:10.1016/j.enpol.2008.09.060.
- [9] Müller S, International Energy Agency (IEA). The power of transformation: Wind, Sun and the Economics of Flexible Power Systems. Paris: IEA Publications; 2014. doi:10.1007/BF01532548.
- [10] International Energy Agency (IEA). Technology Roadmap: Hydrogen and Fuel Cells. 2015. doi:10.1007/SpringerReference\_7300.
- [11] Air Liquide. Hydrogen Energy 2018. <https://www.airliquide.com/science-new-energies/hydrogen-energy> (accessed March 28, 2018).

- [12] The Linde Group. H2 Production 2018. [https://www.the-linde-group.com/en/clean\\_technology/clean\\_technology\\_portfolio/hydrogen\\_energy\\_h2/h2\\_one\\_stop\\_shop/h2\\_production/index.html](https://www.the-linde-group.com/en/clean_technology/clean_technology_portfolio/hydrogen_energy_h2/h2_one_stop_shop/h2_production/index.html) (accessed March 28, 2018).
- [13] Nastasi B, Lo Basso G. Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. *Energy* 2016;110:5–22. doi:10.1016/j.energy.2016.03.097.
- [14] Altmann M, Brenninkmeijer A, Lanoix J-C, D. E, Crisan A, Hugyecz A, et al. *Decentralised Energy Systems*. Brussels: 2010.
- [15] Eriksson ELV, Gray EMA. Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems – A critical review. *Appl Energy* 2017;202:348–64. doi:10.1016/j.apenergy.2017.03.132.
- [16] International Renewable Energy Agency (IRENA). *Global Energy transformation: A roadmap to 2050*. Abu Dhabi: 2018.
- [17] Wolfe P. The implications of an increasingly decentralised energy system. *Energy Policy* 2008;36:4509–13. doi:10.1016/j.enpol.2008.09.021.
- [18] Chicco G, Mancarella P. Distributed multi-generation: A comprehensive view. *Renew Sustain Energy Rev* 2009;13:535–51. doi:10.1016/j.rser.2007.11.014.
- [19] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Yousefi H. Energy hub: From a model to a concept – A review. *Renew Sustain Energy Rev* 2017;80:1512–27. doi:10.1016/j.rser.2017.07.030.
- [20] Hanley ES, Deane JP, Gallachóir BPÓ. The role of hydrogen in low carbon energy futures—A review of existing perspectives. *Renew Sustain Energy Rev* 2018;82:3027–45. doi:10.1016/j.rser.2017.10.034.
- [21] Dutta S. A review on production, storage of hydrogen and its utilization as an energy resource. *J Ind Eng Chem* 2013;20:1148–56. doi:10.1016/j.jiec.2013.07.037.
- [22] Mazloomi K, Gomes C. Hydrogen as an energy carrier: Prospects and challenges. *Renew Sustain Energy Rev* 2012;16:3024–33. doi:10.1016/j.rser.2012.02.028.
- [23] Uyar TS, Besikci D. Integration of hydrogen energy systems into renewable energy systems for better design of 100% renewable energy communities. *Int J Hydrogen Energy* 2017;42:2453–6. doi:10.1016/j.ijhydene.2016.09.086.
- [24] Dincer I, Acar C. Smart energy solutions with hydrogen options. *Int J Hydrogen Energy* 2018;43:8579–99. doi:10.1016/j.ijhydene.2018.03.120.
- [25] Vivas FJ, De las Heras A, Segura F, Andújar JM. A review of energy management strategies for renewable hybrid energy systems with hydrogen backup. *Renew Sustain Energy Rev* 2018;82:126–55. doi:10.1016/j.rser.2017.09.014.
- [26] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, et al. Renewable Power-to-Gas: A technological and economic review. *Renew Energy* 2016;85:1371–90. doi:10.1016/j.renene.2015.07.066.
- [27] Schiebahn S, Grube T, Robinius M, Tietze V, Kumar B, Stolten D. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. *Int J Hydrogen Energy* 2015;40:4285–94. doi:10.1016/j.ijhydene.2015.01.123.
- [28] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. *Renew Sustain Energy Rev* 2014;32:192–205. doi:10.1016/j.rser.2014.01.035.
- [29] Bahramara S, Moghaddam MP, Haghifam MR. Optimal planning of hybrid renewable energy systems using HOMER: A review. *Renew Sustain Energy Rev* 2016;62:609–20. doi:10.1016/j.rser.2016.05.039.

- [30] Ringler P, Keles D, Fichtner W. Agent-based modelling and simulation of smart electricity grids and markets - A literature review. *Renew Sustain Energy Rev* 2016;57:205–15. doi:10.1016/j.rser.2015.12.169.
- [31] Malik FH, Matti L. Agents in Smart Grids. *Electr Power Syst Res* 2016;131:71–9.
- [32] Olatomiwa L, Mekhilef S, Ismail MS, Moghavvemi M. Energy management strategies in hybrid renewable energy systems: A review. *Renew Sustain Energy Rev* 2016;62:821–35. doi:10.1016/j.rser.2016.05.040.
- [33] Fathima AH, Palanisamy K. Optimization in microgrids with hybrid energy systems - A review. *Renew Sustain Energy Rev* 2015;45:431–46. doi:10.1016/j.rser.2015.01.059.
- [34] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *Int J Hydrogen Energy* 2013;38:2039–61. doi:10.1016/j.ijhydene.2012.12.010.
- [35] da Silva Veras T, Mozer TS, da Costa Rubim Messeder dos Santos D, da Silva César A. Hydrogen: Trends, production and characterization of the main process worldwide. *Int J Hydrogen Energy* 2017;42:2018–33. doi:10.1016/j.ijhydene.2016.08.219.
- [36] Dincer I, Acar C. Review and evaluation of hydrogen production methods for better sustainability. *Int J Hydrogen Energy* 2014;40:11094–111. doi:10.1016/j.ijhydene.2014.12.035.
- [37] Dincer I, Acar C. Innovation in hydrogen production. *Int J Hydrogen Energy* 2017;42:14843–64. doi:10.1016/j.ijhydene.2017.04.107.
- [38] Barthelemy H, Weber M, Barbier F. Hydrogen storage: Recent improvements and industrial perspectives. vol. 42. Elsevier Ltd; 2017. doi:10.1016/j.ijhydene.2016.03.178.
- [39] Garcia DA, Barbanera F, Cumo F, Di Matteo U, Nastasi B. Expert opinion analysis on renewable hydrogen storage systems potential in Europe. *Energies* 2016;9. doi:10.3390/en9110963.
- [40] Walker SB, Mukherjee U, Fowler M, Elkamel A. Benchmarking and selection of Power-to-Gas utilizing electrolytic hydrogen as an energy storage alternative. *Int J Hydrogen Energy* 2016;41:7717–31. doi:10.1016/j.ijhydene.2015.09.008.
- [41] Blanco H, Faaij A. A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage. *Renew Sustain Energy Rev* 2018;81:1049–86. doi:10.1016/j.rser.2017.07.062.
- [42] Bolat P, Thiel C. Hydrogen supply chain architecture for bottom-up energy systems models. Part 1: Developing pathways. *Int J Hydrogen Energy* 2014;39:8881–97. doi:10.1016/j.ijhydene.2014.03.176.
- [43] Bolat P, Thiel C. Hydrogen supply chain architecture for bottom-up energy systems models. Part 2: Techno-economic inputs for hydrogen production pathways. *Int J Hydrogen Energy* 2014;39:8898–925. doi:10.1016/j.ijhydene.2014.03.170.
- [44] Demir ME, Dincer I. Cost assessment and evaluation of various hydrogen delivery scenarios. *Int J Hydrogen Energy* 2018;43:10420–30. doi:10.1016/j.ijhydene.2017.08.002.
- [45] von Wirth T, Gislason L, Seidl R. Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance. *Renew Sustain Energy Rev* 2017;82:2618–28. doi:10.1016/j.rser.2017.09.086.
- [46] International Energy Agency (IEA). Status of Power System Transformation. 2017.

doi:10.1787/9789264278820-en.

- [47] Shivarama Krishna K, Sathish Kumar K. A review on hybrid renewable energy systems. *Renew Sustain Energy Rev* 2015;52:907–16. doi:10.1016/j.rser.2015.07.187.
- [48] Geidl M, Koeppl G, Favre-Perrod P. The Energy Hub—A powerful concept for future energy systems. *Third Annu. Carnegie Mellon Conf. Electr. Ind.*, 2007. doi:http://dx.doi.org/10.1016/j.solener.2010.12.027.
- [49] Geidl M. *Integrated Modeling and Optimization of Multi-Carrier Energy Systems*. ETH Zurich, 2007. doi:10.3929/ethz-a-005377890.
- [50] Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: Methods and models. *Appl Energy* 2011;88:1032–48. doi:10.1016/j.apenergy.2010.10.018.
- [51] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy* 2014;65:1–17. doi:10.1016/j.energy.2013.10.041.
- [52] Koirala BP, Koliou E, Friege J, Hakvoort RA, Herder PM. Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renew Sustain Energy Rev* 2016;56:722–44. doi:10.1016/j.rser.2015.11.080.
- [53] Rong A, Lahdelma R. Role of polygeneration in sustainable energy system development challenges and opportunities from optimization viewpoints. *Renew Sustain Energy Rev* 2016;53:363–72. doi:10.1016/j.rser.2015.08.060.
- [54] Shivarama Krishna K, Sathish Kumar K. A review on hybrid renewable energy systems. *Renew Sustain Energy Rev* 2015;52:907–16. doi:10.1016/j.rser.2015.07.187.
- [55] Manwell JF. *Hybrid Energy Systems*. *Encycl Energy* 2004:215.
- [56] Nastasi B, Lo Basso G. Power-to-Gas integration in the Transition towards Future Urban Energy Systems. *Int J Hydrogen Energy* 2017;42:23933–51. doi:10.1016/j.ijhydene.2017.07.149.
- [57] Dincer I, Acar C. Smart energy solutions with hydrogen options. *Int J Hydrogen Energy* 2018:1–21. doi:10.1016/j.ijhydene.2018.03.120.
- [58] Stolten D, Emonts B. *Hydrogen Science and Engineering*. vol. 1. Weinheim: Wiley VCH; 2016. doi:10.1017/CBO9781107415324.004.
- [59] Subramani V, Basile A. *Compendium of Hydrogen Energy*. vol. 1 Hydrogen. Elsevier; 2015.
- [60] Squadrito G, Andaloro L, Ferraro M, Antonucci V. *Advances in Hydrogen Production, Storage and Distribution*. 2014. doi:10.1533/9780857097736.3.451.
- [61] Chen J, Yan L, Song W, Xu D. Methane steam reforming thermally coupled with catalytic combustion in catalytic microreactors for hydrogen production. *Int J Hydrogen Energy* 2017;42:664–80. doi:10.1016/j.ijhydene.2016.12.114.
- [62] Dincer I, Zamfirescu C. *Sustainable hydrogen production*. vol. 305. Weinheim: Elsevier Inc.; 2004. doi:10.1126/science.1103197.
- [63] Valladares M-R de. *Global Trends and Outlook for Hydrogen*. 2017.
- [64] Liu K, Song C, Subramani V. *Hydrogen and Syngas Production and Purification Technologies*. New Jersey: Wiley - AICHE; 2010. doi:10.1002/9780470561256.
- [65] Luz Silveira J. *Sustainable Hydrogen Production Processes*. Switzerland: Springer; 2017. doi:10.1007/978-3-319-41616-8.
- [66] Susastriawan AAP, Saptoadi H, Purnomo. Small-scale downdraft gasifiers for

- biomass gasification: A review. *Renew Sustain Energy Rev* 2017;76:989–1003. doi:10.1016/j.rser.2017.03.112.
- [67] Luque R, Lin CSK, Clark J, Wilson K. *Handbook of Biofuels Production*. Elsevier Ltd; 2016. doi:10.1016/B978-0-08-100455-5.00010-2.
- [68] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. *Renew Sustain Energy Rev* 2017;67:597–611. doi:10.1016/j.rser.2016.09.044.
- [69] Viswanathan B. *Energy Sources: Fundamentals of Chemical Conversion Processes and Applications*. 2016. doi:10.1080/00908310490450836.
- [70] Zhang YH, Jia ZC, Yuan ZM, Yang T, Qi Y, Zhao DL. Development and Application of Hydrogen Storage. *J Iron Steel Res Int* 2015;22:757–70. doi:10.1016/S1006-706X(15)30069-8.
- [71] Najjar YSH. Hydrogen safety: The road toward green technology. *Int J Hydrogen Energy* 2013;38:10716–28. doi:10.1016/j.ijhydene.2013.05.126.
- [72] Royle M, Willoughby D. The safety of the future hydrogen economy. *Process Saf Environ Prot* 2011;89:452–62. doi:10.1016/j.psep.2011.09.003.
- [73] Saffers JB, Molkov V V. Hydrogen safety engineering framework and elementary design safety tools. *Int J Hydrogen Energy* 2014;39:6268–85. doi:10.1016/j.ijhydene.2013.06.060.
- [74] Ahmadi P, Dincer I, Rosen M a. Thermo-economic multi-objective optimization of a novel biomass-based integrated energy system. *Energy* 2014;68:958–70. doi:10.1016/j.energy.2014.01.085.
- [75] Clegg S, Mancarella P. Integrated modelling and assessment of the operational impact of power - to - gas ( P2G ) on electrical and gas transmission networks. *IEEE Trans. Sustain. Energy*, vol. 6, 2015, p. 1234–44.
- [76] Kazempoor P, Dorer V, Weber A. Modelling and evaluation of building integrated SOFC systems. *Int J Hydrogen Energy* 2011;36:13241–9. doi:10.1016/j.ijhydene.2010.11.003.
- [77] Tock L, Maréchal F. Co-production of hydrogen and electricity from lignocellulosic biomass: Process design and thermo-economic optimization. *Energy* 2012;45:339–49. doi:10.1016/j.energy.2012.01.056.
- [78] Tock L, Maréchal F. H<sub>2</sub> processes with CO<sub>2</sub> mitigation: Thermo-economic modeling and process integration. *Int J Hydrogen Energy* 2012;37:11785–95. doi:10.1016/j.ijhydene.2012.05.046.
- [79] Zoss T, Dace E, Blumberga D. Modeling a power-to-renewable methane system for an assessment of power grid balancing options in the Baltic States' region. *Appl Energy* 2016;170:278–85. doi:10.1016/j.apenergy.2016.02.137.
- [80] Dawoud B, Amer E, Gross D. Design of an energy hub based on natural gas and renewable energy sources. *Int J Energy Res* 2007;31:135–47. doi:10.1002/er.
- [81] San Martín I, Ursúa A, Sanchis P. Integration of fuel cells and supercapacitors in electrical microgrids: Analysis, modelling and experimental validation. *Int J Hydrogen Energy* 2013;38:11655–71. doi:10.1016/j.ijhydene.2013.06.098.
- [82] Mendes PRC, Isorna LV, Bordons C, Normey-Rico JE. Energy management of an experimental microgrid coupled to a V2G system. *J Power Sources* 2016;327:702–13. doi:10.1016/j.jpowsour.2016.07.076.
- [83] Keshtkar H, Mohammadi FD, Ghorbani J, Solanki J, Feliachi A. Proposing an improved optimal LQR controller for frequency regulation of a smart microgrid in

- case of cyber intrusions. *Can. Conf. Electr. Comput. Eng.*, 2014, p. 1–6.  
doi:10.1109/CCECE.2014.6901017.
- [84] Peng DD, Fowler M, Elkamel A, Almansoori A, Walker SB. Enabling utility-scale electrical energy storage by a power-to-gas energy hub and underground storage of hydrogen and natural gas. *J Nat Gas Sci Eng* 2016;35:1180–99.  
doi:10.1016/j.jngse.2016.09.045.
- [85] Li M, Zhang X, Li G, Jiang C. A feasibility study of microgrids for reducing energy use and GHG emissions in an industrial application. *Appl Energy* 2016;176:138–48.  
doi:10.1016/j.apenergy.2016.05.070.
- [86] Shinoda K, Park Lee E, Nakano M, Lukszo Z. Optimization Model for a Microgrid with Fuel Cell Vehicles. 2016 IEEE Int. Conf. Networking, Sens. Control, Mexico City: 2016. doi:10.1109/ICNSC.2016.7479027.
- [87] El-Emam RS, Dincer I. Development and assessment of a novel solar heliostat-based multigeneration system. *Int J Hydrogen Energy* 2018;43:2610–20.  
doi:10.1016/j.ijhydene.2017.12.026.
- [88] Sigurjonsson HÆ, Clausen LR. Solution for the future smart energy system: A polygeneration plant based on reversible solid oxide cells and biomass gasification producing either electrofuel or power. *Appl Energy* 2018;216:323–37.  
doi:10.1016/j.apenergy.2018.02.124.
- [89] Mendes PRC, Maestre M, Bordons C, Normey-rico JE. Binary Search Algorithm for Mixed Integer Optimization : Application to energy management in a microgrid. *Eur. Control Conf.*, 2016, p. 2620–5.
- [90] Maroufmashat A, Fowler M, Sattari Khavas S, Elkamel A, Roshandel R, Hajimiragha A. Mixed integer linear programming based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy. *Int J Hydrogen Energy* 2016;41:7700–16.  
doi:10.1016/j.ijhydene.2015.08.038.
- [91] Valverde L, Rosa F, Del Real AJ, Arce A, Bordons C. Modeling, simulation and experimental set-up of a renewable hydrogen-based domestic microgrid. *Int J Hydrogen Energy* 2013;38:11672–84. doi:10.1016/j.ijhydene.2013.06.113.
- [92] Maroufmashat A, Mukherjee U, Ranisau J, Barbouti M, Trainor A, El-Shayeb H, et al. Optimization of renewable powered hydrogen micro-grid; Taking in to account economic criteria. 4th IEEE Int. Conf. Smart Energy Grid Eng. SEGE 2016, 2016, p. 252–6. doi:10.1109/SEGE.2016.7589534.
- [93] Kyriakarakos G, Piromalis DD, Dounis AI, Arvanitis KG, Papadakis G. Intelligent demand side energy management system for autonomous polygeneration microgrids. *Appl Energy* 2013;103:39–51. doi:10.1016/j.apenergy.2012.10.011.
- [94] Kyriakarakos G, Dounis AI, Rozakis S, Arvanitis KG, Papadakis G. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. *Appl Energy* 2011;88:4517–26.  
doi:10.1016/j.apenergy.2011.05.038.
- [95] Zhang L, Gari N, Hmurcik L V. Energy management in a microgrid with distributed energy resources. *Energy Convers Manag* 2014;78:297–305.  
doi:10.1016/j.enconman.2013.10.065.
- [96] Kyriakarakos G, Dounis AI, Arvanitis KG, Papadakis G. A fuzzy logic energy management system for polygeneration microgrids. *Renew Energy* 2012;41:315–27.  
doi:10.1016/j.renene.2011.11.019.

- [97] Karavas CS, Kyriakarakos G, Arvanitis KG, Papadakis G. A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids. *Energy Convers Manag* 2015;103:166–79. doi:10.1016/j.enconman.2015.06.021.
- [98] Bagherian A, Moghaddas Tafreshi SM. A developed energy management system for a microgrid in the competitive electricity market. *IEEE Bucharest PowerTech Innov. Ideas Toward Electr. Grid Futur.*, 2009, p. 1–6. doi:10.1109/PTC.2009.5281784.
- [99] Garcia-Torres F, Bordons C. Optimal Economical Schedule of Hydrogen-Based Microgrids With Hybrid Storage Using Model Predictive Control. *IEEE Trans. Ind. Electron.*, vol. 62, 2015, p. 5195–207. doi:10.1109/TIE.2015.2412524.
- [100] Niknam T, Golestaneh F, Shafiei M. Probabilistic energy management of a renewable microgrid with hydrogen storage using self-adaptive charge search algorithm. *Energy* 2013;49:252–67. doi:10.1016/j.energy.2012.09.055.
- [101] Agbossou K, Kolhe ML, Hamelin J, Bernier É, Bose TK. Electrolytic hydrogen based renewable energy system with oxygen recovery and re-utilization. *Renew Energy* 2004;29:1305–18. doi:10.1016/j.renene.2003.12.006.
- [102] Baghaee HR, Mirsalim M, Gharehpetian GB, Talebi H a. Reliability/cost-based multi-objective Pareto optimal design of stand-alone wind/PV/FC generation microgrid system. *Energy* 2016;115:1022–41. doi:10.1016/j.energy.2016.09.007.
- [103] Narahariseti PK, Karimi I a., Anand A, Lee DY. A linear diversity constraint - Application to scheduling in microgrids. *Energy* 2011;36:4235–43. doi:10.1016/j.energy.2011.04.020.
- [104] Cau G, Cocco D, Petrollese M, Knudsen Kær S, Milan C. Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system. *Energy Convers Manag* 2014;87:820–31. doi:10.1016/j.enconman.2014.07.078.
- [105] Li B, Roche R, Paire D, Miraoui A. Sizing of a stand-alone microgrid considering electric power, cooling/heating, hydrogen loads and hydrogen storage degradation. *Appl Energy* 2017;205:1244–59. doi:10.1016/j.apenergy.2017.08.142.
- [106] Konstantinopoulos SA, Anastasiadis AG, Vokas GA, Kondylis GP, Polyzakis A. Optimal management of hydrogen storage in stochastic smart microgrid operation. *Int J Hydrogen Energy* 2018;43:490–9. doi:10.1016/j.ijhydene.2017.06.116.
- [107] Mohseni S, Moghaddas-Tafreshi SM. A multi-agent system for optimal sizing of a cooperative self-sustainable multi-carrier microgrid. *Sustain Cities Soc* 2018;38:452–65. doi:10.1016/j.scs.2018.01.016.
- [108] Proietto R, Arnone D, Bertoncini M, Rossi A, La Cascia D, Miceli R, et al. Mixed heuristic-non linear optimization of energy management for hydrogen storage-based multi carrier hubs. *ENERGYCON 2014 - IEEE Int. Energy Conf.*, 2014, p. 1019–26. doi:10.1109/ENERGYCON.2014.6850550.
- [109] Mukherjee U, Maroufmashat A, Ranisau J, Barbouti M, Trainor A, Juthani N, et al. Techno-economic, environmental, and safety assessment of hydrogen powered community microgrids; case study in Canada. *Int J Hydrogen Energy* 2017;42:14333–49. doi:10.1016/j.ijhydene.2017.03.083.
- [110] Al Rafea K, Elsholkami M, Elkamel A, Fowler M. Integration of Decentralized Energy Systems with Utility-Scale Energy Storage through Underground Hydrogen-Natural Gas Co-Storage Using the Energy Hub Approach. *Ind Eng Chem Res* 2017;56:2310–30. doi:10.1021/acs.iecr.6b02861.

- [111] Chade D, Miklis T, Dvorak D. Feasibility study of wind-to-hydrogen system for Arctic remote locations - Grimsey island case study. *Renew Energy* 2015;76:204–11. doi:10.1016/j.renene.2014.11.023.
- [112] Navaeefard A, Tafreshi SMM, Barzegari M, Shahrood AJ. Optimal sizing of distributed energy resources in microgrid considering wind energy uncertainty with respect to reliability. *IEEE Int. Energy Conf. Exhib. EnergyCon 2010*, 2010, p. 820–5. doi:10.1109/ENERGYCON.2010.5771795.
- [113] Nguyen T a, Crow ML, Fellow I. Optimization in Energy and Power Management for Renewable-Diesel Microgrids Using Dynamic Programming Algorithm. *IEEE Int. Conf. Cyber Technol. Autom. Control Intell. Syst.*, 2012, p. 11–6. doi:10.1109/CYBER.2012.6392518.
- [114] García P, Torreglosa JP, Fernández LM, Jurado F, Langella R, Testa A. Energy management system based on techno-economic optimization for microgrids. *Electr Power Syst Res* 2016;131:49–59. doi:10.1016/j.epsr.2015.09.017.
- [115] Dawoud B, Amer E, Gross D. Life cycle energy and environmental analysis of a microgrid power pavilion. *Int J Energy Res* 2007;31:135–47. doi:10.1002/er.
- [116] Vafaei M, Kazerani M. Optimal unit-sizing of a wind-hydrogen-diesel microgrid system for a remote community. *IEEE PES Trondheim PowerTech Power Technol. a Sustain. Soc. POWERTECH 2011*, 2011, p. 1–7. doi:10.1109/PTC.2011.6019412.
- [117] Niknam T, Golestaneh F, Malekpour AR. Probabilistic model of polymer exchange fuel cell power plants for hydrogen, thermal and electrical energy management. *J Power Sources* 2013;229:285–98. doi:10.1016/j.jpowsour.2012.11.052.
- [118] Perna A, Minutillo M, Jannelli E. Hydrogen from intermittent renewable energy sources as gasification medium in integrated waste gasification combined cycle power plants: A performance comparison. *Energy* 2016;94:457–65. doi:10.1016/j.energy.2015.10.143.
- [119] Spencer JD, Moton JM, Gibbons WT, Gluesenkamp K, Ahmed II, Taverner AM, et al. Design of a combined heat, hydrogen, and power plant from university campus waste streams. *Int J Hydrogen Energy* 2013;38:4889–900. doi:10.1016/j.ijhydene.2013.02.021.
- [120] Ming Kwok JJ, Yu N, Karimi I a., Lee DY. Microgrid scheduling for reliable, cost-effective, and environmentally friendly energy management. *Ind Eng Chem Res* 2013;52:142–51. doi:10.1021/ie3006897.
- [121] Litchy a. J, Young C, Pourmousavi S a., Nehrir MH. Technology selection and unit sizing for a combined heat and power microgrid: Comparison of WebOpt and HOMER application programs. *North Am. Power Symp. NAPS 2012*, 2012. doi:10.1109/NAPS.2012.6336337.
- [122] Alavi F, Park Lee E, van de Wouw N, De Schutter B, Lukszo Z. Fuel cell cars in a microgrid for synergies between hydrogen and electricity networks. *Appl Energy* 2017;192:296–304. doi:10.1016/j.apenergy.2016.10.084.
- [123] El-Emam RS, Dincer I. Assessment and Evolutionary Based Multi-Objective Optimization of a Novel Renewable-Based Polygeneration Energy System. *J Energy Resour Technol* 2016;139:012003. doi:10.1115/1.4033625.
- [124] Gabrielli P, Gazzani M, Martelli E, Mazzotti M. Optimal design of multi-energy systems with seasonal storage. *Appl Energy* 2017;219:408–24. doi:10.1016/j.apenergy.2017.07.142.
- [125] Allman A, Daoutidis P. Optimal design of synergistic distributed renewable fuel and

- power systems. *Renew Energy* 2017;100:78–89. doi:10.1016/j.renene.2016.03.051.
- [126] Vidal M, Martín L, Martín M. Optimal Integration of a Concentrated Solar Plant Facility with a Biomass Based Polygeneration System. 24th Eur. Symp. Comput. Aided Process Eng. – ESCAPE 24, vol. 33, Elsevier; 2014, p. 1603–8. doi:10.1016/B978-0-444-63455-9.50102-1.
- [127] Hakimi SM, Moghaddas-Tafreshi SM, Moosavian SM, Rahim N a., Selvaraj J. Optimization of a Reliable Combined Cooling, Heat and Power Microgrid System. CEAT 2013 - IEEE Conf. Clean Energy Technol., 2013, p. 7–12. doi:10.1109/CEAT.2013.6775590.
- [128] Proietto R, Arnone D, Bertoncini M, Rossi A, La Cascia D, Miceli R, et al. A novel heuristics-based energy management system for a multi-carrier hub enriched with solid hydrogen storage. 5th Int. Conf. Futur. energy Syst., 2014, p. 231–2. doi:10.1145/2602044.2602081.
- [129] Pazouki S, Haghifam M-R, Olamaei J. Short term scheduling of multi carrier systems through interruptible load and Energy Storage toward future sustainable energy needs. 8th Int. Conf. Electr. Electron. Eng., 2013, p. 77–81. doi:10.1109/ELECO.2013.6713807.
- [130] Zafra-Cabeza A, Del Real A, Arce A, Camacho EF, Ridao M a., Bordons C. A risk-based strategy for power system optimization. 49th IEEE Conf. Decis. Control, 2010, p. 1905–10. doi:10.1109/CDC.2010.5717218.
- [131] Li B, Roche R, Miraoui A. Sizing of a stand-alone microgrid considering electric power , cooling / heating and hydrogen. *PowerTech* 2017, 2017.
- [132] Hakimi SM, Moghaddas-Tafreshi SM, Moosavian SM, Rahim N a., Selvaraj J. Optimization of a reliable combined heat and power microgrid considered uncertainty. CEAT 2013 - IEEE Conf. Clean Energy Technol., 2013, p. 7–12. doi:10.1109/CEAT.2013.6775590.
- [133] Cau G, Cocco D, Lucariello M, Petrollese M. Optimal generation scheduling for a hybrid stand-alone power system using renewable energy sources and hydrogen storage. 27th Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst. ECOS 2014, 2014.
- [134] Liu W, Wang D, Yu X, Jia H, Wang W, Yang X, et al. Optimal Scheduling of Multi-Source Microgrid Considering Power to Gas Technology and Wind Power Uncertainty. *Energy Procedia* 2017;143:668–73. doi:10.1016/j.egypro.2017.12.744.
- [135] Nelson DB, Nehrir MH, Wang C. Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. *Renew Energy* 2006;31:1641–56. doi:10.1016/j.renene.2005.08.031.
- [136] Khan MJ, Iqbal MT. Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. *Renew Energy* 2005;30:835–54. doi:10.1016/j.renene.2004.09.001.
- [137] Türkay BE, Telli AY. Economic analysis of standalone and grid connected hybrid energy systems. *Renew Energy* 2011;36:1931–43. doi:10.1016/j.renene.2010.12.007.
- [138] Abedi S, Alimardani a., Gharehpetian GB, Riahy GH, Hosseini SH. A comprehensive method for optimal power management and design of hybrid RES-based autonomous energy systems. *Renew Sustain Energy Rev* 2012;16:1577–87. doi:10.1016/j.rser.2011.11.030.
- [139] Feroldi D, Zumoffen D. Sizing methodology for hybrid systems based on multiple renewable power sources integrated to the energy management strategy. *Int J*

- Hydrogen Energy 2014;39:8609–20. doi:10.1016/j.ijhydene.2014.01.003.
- [140] Mostofi F, Shayeghi H. Feasibility and Optimal Reliable Design of Renewable Hybrid Energy System for Rural Electrification in Iran. *Int J Renew Energy Res* 2012;2:574–82.
- [141] Das D, Esmaili R, Xu L, Nichols D. An optimal design of a grid connected hybrid wind/photovoltaic/fuel cell system for distributed energy production. *IECON Proc. (Industrial Electron. Conf., vol. 2005, 2005, p. 2499–504.* doi:10.1109/IECON.2005.1569298.
- [142] Fazelpour F, Soltani N, Rosen M a. Economic analysis of standalone hybrid energy systems for application in Tehran, Iran. *Int J Hydrogen Energy* 2016;41:7732–43. doi:10.1016/j.ijhydene.2016.01.113.
- [143] Maleki A, Hafeznia H, Rosen M a., Pourfayaz F. Optimization of a grid-connected hybrid solar-wind-hydrogen CHP system for residential applications by efficient metaheuristic approaches. *Appl Therm Eng* 2017;123:1263–77. doi:10.1016/j.applthermaleng.2017.05.100.
- [144] Khare V, Nema S, Baredar P. Optimization of hydrogen based hybrid renewable energy system using HOMER, BB-BC and GAMBIT. *Int J Hydrogen Energy* 2016;41:16743–51. doi:10.1016/j.ijhydene.2016.06.228.
- [145] Rouholamini M, Mohammadian M. Heuristic-based power management of a grid-connected hybrid energy system combined with hydrogen storage. *Renew Energy* 2016;96:354–65. doi:10.1016/j.renene.2016.04.085.
- [146] Hacatoglu K, Dincer I, Rosen M a. Sustainability assessment of a hybrid energy system with hydrogen-based storage. *Int J Hydrogen Energy* 2015;40:1559–68. doi:10.1016/j.ijhydene.2014.11.079.
- [147] Ri YB, Cell DMH. Optimal Design and Performance Evaluation of A Grid Independent Hybrid Micro Hydro-Solar-Wind? Fuel Cell Energy System Using Meta-Heuristic Techniques. 1st Int. Conf. Non Conv. Energy (ICONCE 2014) Optim., 2014, p. 89–93.
- [148] Türkay B, Telli a. Y. An economic analysis of grid-connected hybrid energy systems. *Energy Sources, Part B Econ Plan Policy* 2011;6:228–41. doi:10.1080/15567241003614529.
- [149] Tudu B, Majumder S, Mandal KK, Chakraborty N. Optimal unit sizing of stand-alone renewable hybrid energy system using bees algorithm. *Int. Conf. Energy, Autom. Signal, ICEAS - 2011, 2011, p. 600–5.* doi:10.1109/ICEAS.2011.6147175.
- [150] Fazelpour F, Soltani N, Shariatzadeh M, Rosen M a. Feasibility of satisfying electrical energy needs with hybrid stand alone systems for application in Tehran, Iran. *IEEE 15th Int. Conf. Environ. Electr. Eng., 2015, p. 1587–92.* doi:10.1109/EEEIC.2015.7165408.
- [151] Papaioannou IT, Purvins A, Shropshire D, Carlsson J. Role of a Hybrid Energy System Comprising a Small/Medium-Sized Nuclear Reactor and a Biomass Processing Plant in a Scenario with a High Deployment of Onshore Wind Farms. *J Energy Eng* 2014;140:04013005. doi:10.1061/(ASCE)EY.1943-7897.0000142.
- [152] Rouholamini M, Mohammadian M. Grid-price-dependent energy management of a building supplied by a multisource system integrated with hydrogen. *Int J Eng Trans A Basics* 2016;29:40–8. doi:10.5829/idosi.ije.2016.29.01a.06.
- [153] Vatankhah Barenji R, Ghadiri Nejad M, Asghari I. Optimally sized design of a wind/photovoltaic/fuel cell off-grid hybrid energy system by modified-gray wolf

- optimization algorithm. *Energy Environ* 2018;0958305X1876813.  
doi:10.1177/0958305X18768130.
- [154] Badea G, Felseghi R, Aschilean I, Bolboaca A, Muresan D, Soimosan T, et al. Energen System for Power Supply of Passive House. 2nd Int. Conf. Math. Comput. Sci. Ind. MCSI 2015, 2016, p. 24–31. doi:10.1109/MCSI.2015.31.
- [155] Maniyali Y, Almansoori A, Fowler M, Elkamel A. Energy Hub Based on Nuclear Energy and Hydrogen Energy Storage. *Ind Eng Chem Res* 2013;52:7470–81. doi:10.1021/ie302161n.
- [156] AlRafea K, Fowler M, Elkamel A, Hajimiragha A. Integration of renewable energy sources into combined cycle power plants through electrolysis generated hydrogen in a new designed energy hub. *Int J Hydrogen Energy* 2016;41:16718–28. doi:10.1016/j.ijhydene.2016.06.256.
- [157] Lacko R, Drobnič B, Mori M, Sekavčnik M, Vidmar M. Stand-alone renewable combined heat and power system with hydrogen technologies for household application. *Energy* 2014;77:164–70. doi:10.1016/j.energy.2014.05.110.
- [158] Lacko R, Drobnič B, Sekavčnik M, Mori M. Hydrogen energy system with renewables for isolated households: The optimal system design, numerical analysis and experimental evaluation. *Energy Build* 2014;80:106–13. doi:10.1016/j.enbuild.2014.04.009.
- [159] Wang C, Nehrir MH. Power management of a stand-alone wind/photovoltaic/fuel cell energy system. *IEEE Trans. Energy Convers.*, vol. 23, 2008, p. 957–67. doi:10.1109/TEC.2007.914200.
- [160] Dufo-López R, Bernal-Agustín JL. Multi-objective design of PV-wind-diesel-hydrogen-battery systems. *Renew Energy* 2008;33:2559–72. doi:10.1016/j.renene.2008.02.027.
- [161] García P, Torreglosa JP, Fernández LM, Jurado F. Optimal energy management system for stand-alone wind turbine/photovoltaic/ hydrogen/battery hybrid system with supervisory control based on fuzzy logic. *Int J Hydrogen Energy* 2013;38:14146–58. doi:10.1016/j.ijhydene.2013.08.106.
- [162] Torkkeli A. Dynamic Real-Time Optimization and Control of a Hybrid Energy System Milana. *AIChE J* 2014;60:2546–56. doi:10.1002/aic.
- [163] Kalinci Y, Dincer I, Hepbasli A. Energy and exergy analyses of a hybrid hydrogen energy system: A case study for Bozcaada. *Int J Hydrogen Energy* 2017;42:2492–503. doi:10.1016/j.ijhydene.2016.02.048.
- [164] Calise F, Figaj RD, Massarotti N, Mauro A, Vanoli L. Polygeneration system based on PEMFC, CPVT and electrolyzer: Dynamic simulation and energetic and economic analysis. *Appl Energy* 2017;192:530–42. doi:10.1016/j.apenergy.2016.08.018.
- [165] Moradi H, Esfahanian M, Abtahi A, Zilouchian A. Modeling a hybrid microgrid using probabilistic reconfiguration under system uncertainties. *Energies* 2017;10:1–17. doi:10.3390/en10091430.
- [166] Karavas CS, Arvanitis K, Papadakis G. A game theory approach to multi-agent decentralized energy management of autonomous polygeneration microgrids. *Energies* 2017;10. doi:10.3390/en10111756.
- [167] Dong W, Li Y, Xiang J. Optimal sizing of a stand-alone hybrid power system based on battery/hydrogen with an improved ant colony optimization. *Energies* 2016;9. doi:10.3390/en9100785.

- [168] Yang D. Day-Ahead Dispatch Model of Electro-Thermal Integrated Energy System with Power to Gas Function. *Appl Sci* 2017;7:1–12. doi:10.3390/app7121326.
- [169] Badea G, Felseghi R, Raboaca M, Ashchilean I, Bolboaca A, Mureshan D, et al. Techno-economical Analysis of Hybrid PV-WT-Hydrogen FC System for a Residential Building with Low Power Consumption. *Probl Reg Energ* 2016;32:78–84.
- [170] Khalid F, Dincer I, Rosen MA. Analysis and assessment of an integrated hydrogen energy system. *Int J Hydrogen Energy* 2016;41:7960–7. doi:10.1016/j.ijhydene.2015.12.221.
- [171] Khalid F, Aydin M, Dincer I, Rosen MA. Comparative assessment of two integrated hydrogen energy systems using electrolyzers and fuel cells. *Int J Hydrogen Energy* 2016;41:19836–46. doi:10.1016/j.ijhydene.2016.08.121.
- [172] Kalinci Y, Hepbasli A, Dincer I. Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. *Int J Hydrogen Energy* 2015;40:7652–64. doi:10.1016/j.ijhydene.2014.10.147.
- [173] Caliskan H, Dincer I, Hepbasli A. Energy, exergy and sustainability analyses of hybrid renewable energy based hydrogen and electricity production and storage systems: Modeling and case study. *Appl Therm Eng* 2013;61:784–98. doi:10.1016/j.applthermaleng.2012.04.026.
- [174] Cau G, Cocco D, Petrollese M. Modeling and simulation of an isolated hybrid micro-grid with hydrogen production and storage. *Energy Procedia* 2014;45:12–21. doi:10.1016/j.egypro.2014.01.003.
- [175] Giannakoudis G, Papadopoulos AI, Seferlisa P, Voutetakis S. On the systematic design and optimization under uncertainty of a hybrid power generation system using renewable energy sources and hydrogen storage. *Comput Aided Chem Eng* 2010;28:907–12. doi:10.1016/S1570-7946(10)28152-X.
- [176] Zhang W, Han D, Sun W, Li H, Tan Y, Yan Z, et al. Optimal Operation of Wind-Solar-Hydrogen Storage System Based on Energy Hub. *IEEE Conf. Energy Internet Energy Syst. Integr.*, 2017, p. 2–6.
- [177] Tzamalīs G, Zouliās EI, Stamatakis E, Varkaraki E, Lois E, Zannikos F. Techno-economic analysis of an autonomous power system integrating hydrogen technology as energy storage medium. *Renew Energy* 2011;36:118–24. doi:10.1016/j.renene.2010.06.006.
- [178] Zhang W, Maleki A, Rosen MA, Liu J. Optimization with a simulated annealing algorithm of a hybrid system for renewable energy including battery and hydrogen storage. *Energy* 2018;163:191–207. doi:10.1016/j.energy.2018.08.112.
- [179] Duman AC, Güler Ö. Techno-economic analysis of off-grid PV/wind/fuel cell hybrid system combinations with a comparison of regularly and seasonally occupied households. *Sustain Cities Soc* 2018;42:107–26. doi:10.1016/j.scs.2018.06.029.
- [180] Schwartz T, Stevens G, Jakobi T, Deneff S, Ramirez L, Wulf V, et al. What people do with consumption feedback: A long-term living lab study of a home energy management system. *Interact Comput* 2015;27:551–76. doi:10.1093/iwc/iwu009.
- [181] Kelly J, Knottenbelt W. Does disaggregated electricity feedback reduce domestic electricity consumption? A systematic review of the literature. *3rd Int. NILM Work.*, Vancouver: 2016.