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Abstract

The integration of various renewable energy sources as well as the liberalization of electricity markets are established facts in modern electrical power systems. The increased share of renewable sources within power systems intensifies the supply variability and intermittency. Therefore, energy storage is deemed as one of the solutions for stabilizing the supply of electricity to maintain generation-demand balance and to guarantee uninterrupted supply of energy to users. In the context of sustainable development and energy resources depletion, the question of the growth of renewable energy electricity production is highly linked to the ability to propose new and adapted energy storage solutions. The purpose of this multidisciplinary paper is to highlight the new hydrogen production and storage technology, its efficiency and the impact of the policy context on its development. A comprehensive techno/socio/economic study of long term hydrogen based storage systems in electrical networks is addressed. The European policy concerning the different energy storage systems and hydrogen production is explicitly discussed. The state of the art of the techno-economic features of the hydrogen production and storage is introduced. Using Matlab-Simulink for a power system of rated 70 kW generator, the excess produced hydrogen during high generation periods or low demand can be sold either directly to the grid owners or as filled hydrogen bottles. The affordable use of Hydrogen-based technologies for long term electricity storage is verified.

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1. Introduction

Energy, the prime mover of economic growth, is vital to sustain a modern economic and social development. The increase in energy demand and climate change problems are two of today's defining global issues. Renewable Energy (RE) and energy efficiency (EE) offer tangible solutions for reducing Green House Gas (GHG) emissions and concomitantly providing the requested energy to billions of consumers onto the path of long-term economic and social development. The oil prices of traditional power plants are uncertain and dramatically escalating. Therefore, the corresponding volatile energy prices are impacting energy security, balance of payments, inflation, and economic growth. Thus, RE and EE technologies allows providing energy that is low-carbon, clean, safe, reliable, and independent on fuel-prices becomes necessary [1-4].

Regarding the future energy mix of European Union (EU), the target is at least 20% of electrical energy produced by RE. However, the deployment of RE sources raises the issue of the massive energetic storage due to their intermittent nature and the grid stabilization. The numerous solutions already available to achieve this role are still not satisfactory. Therefore, Hydrogen-based energy storage technologies appear and become modern competitive options. Whatever the technological maturity of this solution is – and its advantages, its development had to take into account some socio-economic aspects of the process of emergence of the new technology in energy area. One of the components of the emergence of this technology, beyond the technological criteria, is the policy support, especially the European energy policy. The authors' hypothesis is that the socio-economic expectations regarding the hydrogen use are linked to the public actors to support this new technology. Understanding the stakes of Hydrogen energy storage implies to encompass the individual identification of techno-scientific or economic or social bottlenecks and to develop a more systemic approach of the technological system emergence.

This paper main contribution aims at presenting a comprehensive techno/socio/economic study of long term hydrogen based storage systems in electrical networks. Technically, such storage system provides electrical grid with enhanced power quality and stability through its stabilizing action on the grid during the crucial period of supply-demand imbalance. Economically, the stored Hydrogen during 20 years' lifetime is explicitly affordable particularly when used for power generation in the grid. Therefore, long term electricity storage using Hydrogen-based technologies for ensuring system energy efficiency, reliability and safety with reduced carbon emissions at affordable costs is introduced.

2. European and French Energy Storage Context

The total global renewable power capacity exceeded 1,470 GW in 2012, which represents an increase of 8.5% compared to 2011. Hydropower has grown by 3% to an estimated 990 GW, while other renewables has increased by 21.5% to exceed 480 GW. Worldwide, wind power accounted for about 39% of renewable power capacity added in 2012, followed by hydropower and solar PV, each accounting for approximately 26% [5]. On the national level, the French electricity production has increased to 550.9 TWh in 2013 (a 1.7% rise compared to 2012). France has 59 nuclear reactors operated by Electricité de France (EDF), with the total capacity of over 63 GWe supplying 368 billion kWh per year (i.e. 77% of the total generated electricity that year) [6,7]. Furthermore, the share of RE, including hydraulics, has accounted for 20.7% of French consumption in 2013. In addition, As among the largest net exporters of electricity worldwide, France earns over 3000 M€ per year from electricity sales abroad [7].

The development of RE generation meets to global and European political targets. Thus, according to the United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol (KP) has set binding obligations on the industrialized countries to reduce their emissions of GHGs [1,2]. Moreover, despite a limited authority[*] at the policy level, the European Commission has tried since 2006 to establish for Member States a common and coherent European energy framework towards sustainable development objectives.

The Energy Framework is gradually built through the publication of communications and green papers setting out

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[*] Energy policy is part of the European treaties since the Treaty of Lisbon in 2007 (entered into force in December 2009). However, the competences of the European Union are relatively limited, since each member state retains its autonomy in energy policy remains. The market operates more and more at a European scale, by coupling national markets. It is the basis for the organization of exchanges between European energy suppliers. However, different national models persist to reflect specific national issues and previous choices in terms of energy mix.

the main objectives of a voluntary European policy (Integrating security of supply, market liberalization and climate change) [8], the adoption of legislation (Directives 96/92/EC, 98/30/EC, 2009/72/EC, Climate and Energy Package[†] in 2009) and the orientation of European research through the funding of research projects on priority themes (Framework Program: FP7, H2020). In an innovative way, the issue of electricity network modernization is rapidly placed at the heart of the European energy policy. Based on strategic documents published by the European Technology Platform for Electricity Networks of the Future[‡], the European Commission has defined the Smart Grid as « as a key enabler for a future low-carbon electricity system, facilitating demand-side efficiency, increasing the shares of renewables and distributed generation, and enabling electrification of transport » [9, 10]. In the context of Smart Grids development, the vital role of storage technologies –including hydrogen technology– for a progressively decarbonised European energy system is recognized [11, 12, 13,14]. Indeed, an increasing share of RE in the electricity generation leads to a growing gap between production and consumption. To overcome this problem, the use of clean Energy Storage Systems (ESSs) –especially hydrogen storage systems– become necessary for avoiding system's collapse. ESS not only compensates for the expected shortcomings of intermittent RE systems but also improves their controllability, the quality of electrical energy, and the efficiency of the entire power grid [15].

Fuel cells and hydrogen technology is one of the eight technology initiatives identified by the European Strategic Energy Technology Plan in order to change the European energy system. Looking for a consensual vision of the roles, technologies and potential applications of energy storage within the framework of EU Energy and Climate Policy, the European Commission has created or initiated the Fuel Cell and Hydrogen Joint Undertaking (FCH JU[§]) in 2008, a European Task Force on Energy storage (2009) and the European Association for storage of Energy, including manufacturers, utilities and academics bodies (2011). Workshops or research programs on the storage domain have been also developed. Accordingly, the European Commission (2012) noted in the Energy Roadmap 2050 that a new sense of urgency and collective responsibility must be brought to bear on the development of new energy infrastructure and storage capacities across Europe [16]. Then, it identifies the need for a European strategy to advance energy storage development and deployment [17]. With this document the Commission aimed to give more attention to the issues around energy storage with a view to addressing them more effectively in EU energy policy. In order to sustain this politic, the Joint Research Centre (JRC[**]), in cooperation with the R&D department of EDF, published the report "Assessing Storage Value in Electricity Markets", that presents an overview of current research on the economic drivers or barriers for electricity storage [18].

Concerning the regulation, the European Parliament (2012) included an amendment on energy storage in Horizon 2020 legislation. This amendment[††] acknowledges the importance of energy storage related research to the meeting of SET-Plan objectives. Following this amendment, the CE has set out its strategy to ensure that the EU continues to have a world-class technology and innovation sector to tackle the challenges for 2020 and beyond [19]. So, European Commission and European Parliament recognize the role that fuel-cell and hydrogen technology - as a storage technology - can play in the future energy system. Even if the Energy European policy is recent, the European commission tries to build a framework to promote storage technologies, including hydrogen initiatives. Following this European policy, the French government seeks for more than 20% share of renewables in gross electricity production of 2020.

In 2013, the French government launched the national debate on energetic transition. Concerning the development

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† The climate and energy package is a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020. These targets, known as the "20-20-20" targets, set a 20% reduction in EU greenhouse gas emissions from 1990 levels; raising the share of EU energy consumption produced from renewable resources to 20%; and a 20% improvement in the EU's energy efficiency.
‡ The European Technology Platform for Electricity Networks of the Future also called ETP Smart Grids was initiated by the European Commission in 2005. It is the key European forum for the crystallization of policy and technology research and development pathways for the smart grids sector, as well as the link between EU-level related initiatives. It published many documents promoting its strategic vision for the development of European electricity networks of the future [11, 12, 13]. These roadmaps give an increasing role to the energy storage (i.e. hydrogen storage): from « important » to « a high-priority research topic ».
§ It was established by Council Regulation (EC) 521/2008 as a public-private partnership between the European Commission and Europe's fuel-cell and hydrogen industry and research communities.
** EU's in-house science service.
†† Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure.

of the fuel cell, studies have shown three distinct periods in France. Inside these developments, the dominant role of the government in the guidance of public research, the lack of effective industrial research, the competition from electric batteries as well as the resistance of the dominant technological paradigm (vehicles with internal combustion engine) all contributed to a relative failure of FC dissemination as stated by Belot and Picard [20]. In the current context of the energy transition, hydrogen does not seem to have any problem with the public acceptability. However, the conditions for its diffusion are not created because of the lack of opportunities of its technology markets and the low investment of the government which limits the development of infrastructure and maintains the fossil fuels. In August 2014, the French roadmap leaves little room for hydrogen and the proposed energetic policy [21]. It recommends "conducting further R&D work on electrolysers and fuel cells before considering their substantive or experimental deployment. An impact assessment of hydrogen solutions must take into account, among other things, the economic consequences on other energy sectors (gas, electricity, fuels) and the safety issues" [21, p.1]. Once again, it seems that the French hydrogen turn is not taken. If hype and disappointment characterized the life of new technology [22], this is particularly true for the hydrogen in France [20]. More generally, these barriers are similar to those of the ESS, that are (i) regulations and utility processes that disfavour energy storage, (ii) costs, (iii) lack of awareness of the benefits [23]. Consequently one of the major questions is to assess the hydrogen storage system energy efficiency and its capacity to challenge the grid stability.

3. Energy Storage Systems

As highlighted by the European Commission, energy storage becomes a key element in achieving goals in energy sustainability that lead to energy and cost savings. Electricity transmission and contribution sector (power quality and energy management) and transport sector are the potential areas where ESS can be fully utilized [23,24]. ESS enhances the existing power plant and at the same time prevents expensive upgrades [25]. ESS could act as a regulator that manages the fluctuations of electricity from RE resources. In the literature, various types of energy storage can be used such as: compressed air energy storage (CAES), flywheel energy storage (FES), pumped hydro energy storage (PHES), battery energy storage (BES), flow battery energy storage (FBES), superconducting magnetic energy storage (SMES), super capacitor energy storage (SCES), hydrogen energy storage, synthetic fuels, and thermal energy storage (TES) [25]. ESS technologies can be used for different application depending on various characteristics such as: specific parameters such as: energy and power density, response time, cost and economies scale, lifetime, monitoring and control equipment, efficiency and operating constraint [21,25,26].

A suitable energy storage system should have a number of properties: (a) high gravimetric and volumetric energy and power densities, (b) easy deployment and integration with RE sources and the existing energy network, (c) high energy efficiency, (d) economic viability in storing large amount of energy, (e) extended life span and reliability of the systems and components, and (f) safe in operation [27-29]. Table 1 presents a brief comparison between the different types of ESSs. Obviously, ESSs can be employed for either power-intensive (power for relatively short periods of time) or energy-intensive (energy for relatively long periods of time) applications. Among energy storage systems, batteries are the most common choice for short-term storage. However for longer-term energy storage, their application might be inappropriate owing to their low energy storage density and unavoidable self-discharge [2]. In this respect, it is clear that Energy storage systems based on hydrogen technologies are one of the most interesting options [2-4]. In hydrogen storage systems, excess electricity can be converted to hydrogen through an electrolyser (EL) and stored in pressurized tanks. The stored hydrogen can later be used to produce electricity in a Fuel Cell (FC) as explained by Cau et al. (2014) [27].

Table 1: Comparison between the different types of ESSs [27].

Technology	Capital cost ($/kWh)	Durability (Year)	Power density (W kg^{-1})	Gravimetric energy density (Wh kg^{-1})	Energy Efficiency (%)
Li-ion battery	600-2500	5-20	100-5000	75-250	85-90
Super-capacitor	300-2000	20+	500-5000	0.05-30	97
Pumped-hydro	5-100	40-100	-	0.5-1.5	70-87
Hydrogen	2-20	30	-	400-1000	-
Flywheel	1000-5000	15-20	400-1600	5-130	80-99
Pressurized air	2-50	20-100	-	30-60	40-80

3.1. Hydrogen Systems

The hydrogen atom is the lightest, simplest and most common element in the universe. However, it occurs only in combination with other elements, primarily with oxygen in water and with carbon, nitrogen and oxygen in living materials and fossil fuels. Hydrogen is not a primary source of energy. However, it becomes an attractive energy carrier when split from these other elements by using a source of energy. Hydrogen, as clean energy carrier, is considered to be the clean fuel of future particularly for energy storage and transport [29,30]. The energy storage capacity of hydrogen is excellent because calculations show that one kilogram of hydrogen contains approximately 33 kWh of energy [30,31]. The advantages of hydrogen are: (i) energy security by reducing oil imports, (ii) sustainability by taking advantage of the RE sources, (iii) less pollution and better urban air quality by producing near-zero carbon, hydrocarbon, GHG and NOx emissions at the point of use, and (iv) economic viability by potentially shaping the future global energy markets. Therefore, Hydrogen is a worldwide-accepted clean energy carrier as it is source-independent and has a high energy content per mass compared to petroleum as listed in Table 2 [27-32]. Although there are some nitrogen oxides produced during high temperature combustion, environmental pollutant can be fully removed during low temperature utilization such as by fuel cells. Hydroelectricity-Hydrogen Energy System (HHES) can be used for energy to remote or isolated areas such as rural villages, hotels, frontier regions and islands [27-32].

Table 2: Comparison between Hydrogen and different fuel as source of energy [27-29].

Fuel	Energy content (MJ/kg)	Fuel	Energy content (MJ/kg)
Hydrogen	120	Ethanol	29.6
Liquefied natural gas	54.4	Methanol	19.7
Propane	49.6	Coke	27
Automotive gasoline	46.4	Wood (dry)	16.2
Automotive diesel	45.6	Bagasse	9.6

3.2. State of the Art

Assessing the economics of storage implies developing and using models. In its "state of the art" on assessing storage value in electricity markets, JRC (2013) identifies two approaches: "Engineering models" and "System approaches" [17]. The first ones focus on assessing the techno-economic performance of one specific technology, in a given system context, without assessing its impact on the system. This corresponds to the view of a storage producer trying to maximize its gains. The second ones, "System models", usually aims at finding a least cost solution for the supply of energy services under a number of constraints which could be policies or infrastructure limitations. In this perspective, a number of authors study how to deliver more than one service in order to construct profitable business models for storage. Note that system models do not aim at modelling an individual actor's behaviour. Unfortunately, JRC does not focus on hydrogen storage.

Many researchers have observed and modelled hydrogen storage systems based on FC technology, the studies [29,33,34] outlined a review of energy storage options for Ireland including the use of hydrogen and FC and discussed the key strategy for improving low-temperature Proton Exchange Membrane (PEM) FC performance and durability. The transition toward a hydrogen-based energy system, the "hydrogen economy", has been illustrated [35-41]. Midilli et al. [38] reviewed the basics and fundamentals related to hydrogen as a fuel and its importance to the development of a sustainable future. Afgan et al. reviewed the potential of multi-criteria assessment of hydrogen production from RE in 2007 considering multi-criteria method based on performance, market, environment and social indicators. The multi-criteria procedure for evaluation of hydrogen energy systems proves that the sustainability index rating is an effective tool for decision making [42]. Due to high inflammability, adequate safety measures should be taken during the production, storage, and use of H_2 fuel. Dutta (2014) has introduced the storage and production methods of hydrogen. The necessity of the safety program, public awareness and acceptability has been discussed [28] and this paper follows this challenge. The research proposed by Becherif et al. (2010) has dealt with the state space modelling and control of DC hybrid sources. The system under study has been composed of a FC, PVs and a battery. The passivity-based control technique has been applied with the stability proof for the suggested control law. Adequate simulation and experimental have been illustrated [43].

4. System Under Study

As shown in Fig. 1, the system under study comprises two main parts as follow: the network which includes the power generation and demand, and the ELS/FC system. The network power plants can be either conventional or a multi-source system with renewable plants (i.e. WE, PV, etc).
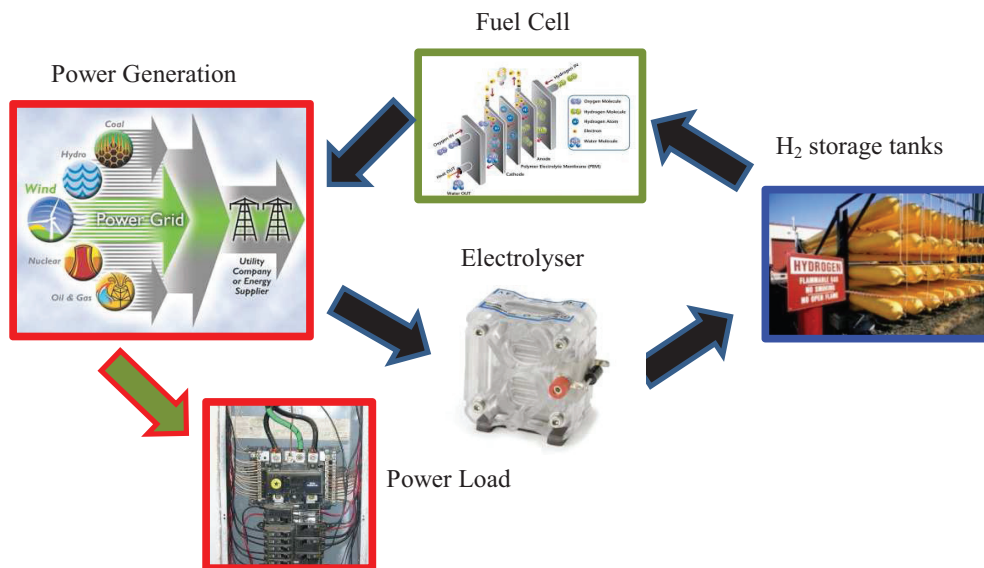

Fig. 1: System under study.

The PEM electrolysers has a thin polymer membrane (Nafion®) sandwiched between the anode and the cathode. The membrane contains the electrolyte and allows the conduction of H^+ ions from the anode to the cathode. It also separates hydrogen and oxygen. PEM electrolysers are small in size due to higher current densities (1-2A/cm^2) when compared to alkaline electrolysers and have power efficiencies in the range of 50-90 %. Their start up/shut-down time and response time are short since there is no recirculation of the electrolyte and they have a reduced mass. PEM electrolysers can also operate at high pressures, reducing the need for auxiliary compression. These benefits over alkaline electrolysers make them to be well suited for standalone systems [44,45]. Using the low heat value the necessary power requested to obtain one kilogramme of hydrogen is 33.3kWh/kg H_2. The relationship between the production rate per hour, the number of electrolyser cells η_C and the electrolyser stack current I_{ELS} is [46,47]:

$$H_2 \left(\frac{kg}{h}\right) = 7.5816 \frac{\eta_C \, I_{ELS}}{ZF} \tag{1}$$

where Z is the number of electrons per transferred per mole of H_2O (Z=2e⁻), F is Faraday constant (F= 96485 C/mol), η_C refers to the number of cells in series, I_{ELS} (A) = i (A/cm²)* A_{ELS} (cm²) with A_{ELS} is the active area of electrodes and its value for typical PEM electrolyser is about 100 cm².

The FC, illustrated in Fig. 2, is an electrochemical energy converter that converts chemical energy of fuel directly into DC electricity. Conversely this is not the case of conventional processes of electricity generation which convert classical fuels through several energy conversion steps generally including mechanical and thermal energies. Several types of fuel cells exist: Polymer Electrolyte Membrane FC (PEMFC), alkaline FC, phosphoric FC, molten carbonate FC, solid oxide FC, which are in different stages of development. At 400 K, hydrogen has a Lower Heating Value (LHV) of 242.847 kJ/mol, and with 37% efficiency, a 50 kW FC system would require about 0.55 mol or 1.1 g of usable hydrogen gas per second. This corresponds approximately 2000 mol or 4 kg of usable hydrogen per hour [49]. Its dimensions for 205 kW are about 2.5m wide, 1.6m deep and 1.33m height [50].

The electrolyser in the ELS/FC has been used as a part of dump load. If there is any excess power generation, the electrolyser turns on to produce hydrogen gas, which is delivered to the hydrogen storage tanks. If the H_2 storage tanks become full, the excess power will be diverted to another dump load. In case of a deficit in power generation, the FC begins to produce electrical energy for the load using hydrogen gas from the H_2 tanks. The energy management methodology for the hydrogen storage and production for the system under study is demonstrated for the different conditions in Fig. 2 respectively.
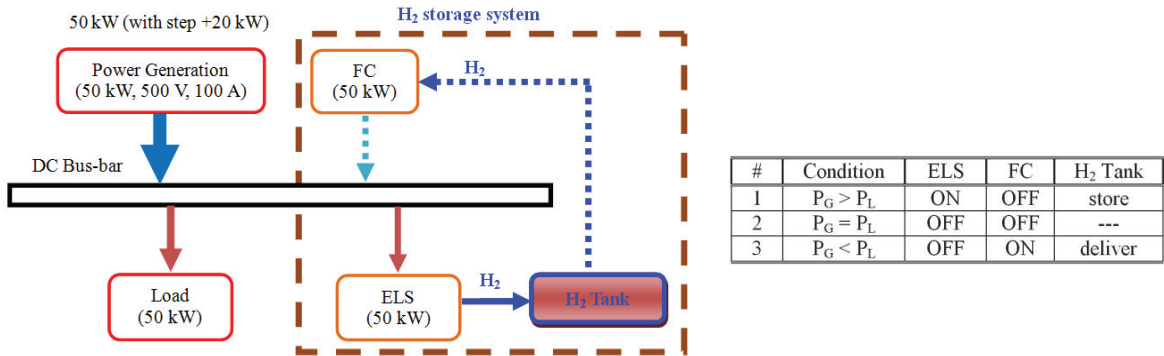

#	Condition	ELS	FC	H_2 Tank
1	$P_G > P_L$	ON	OFF	store
2	$P_G = P_L$	OFF	OFF	---
3	$P_G < P_L$	OFF	ON	deliver

Fig. 2: Energy management methodology for H_2 storage/generation.

5. Simulation Results

After developing the EMR system overall model shown in Fig. 3, Matlab-simulations have been performed in order to determine the quantity of stored hydrogen, oxygen and water [51, 52]. The power generation is considered to be instantaneously stepped up from 50 kW to 70 kW at t=500 s. Accordingly, the quantity of the stored hydrogen and oxygen are approximately 27 and 3 bottles respectively as depicted in Fig. 4. The hydrogen bottle comprises 800 gm of Hydrogen, 50l at moderate pressure of 200 bars during the next limited 500s. If compressed under high pressure of 700 bars, about 10 bottles of Hydrogen can be attained of 5kg each. If the hydrogen is liquefied, 16 bottles of volume 84l including 6 kg H_2 are attained. The price of the bottle depends on the state of hydrogen within (gas, liquid, etc.) and the pressure at which the hydrogen is compressed. However, the price of less than 10 €/kg of Hydrogen will be hopefully expected for 2020. Therefore, the stored hydrogen quantity can either be used during high demand periods (lack of national generation) or re-sold to the grid with affordable prices to cover the overall storage system expenses. At the end of the simulation, the quantity of water delivered by electrolyser at both the cathode and the anode become 0.364 m^3. These quantities of oxygen and water can be used for both medical purposes and drug production.
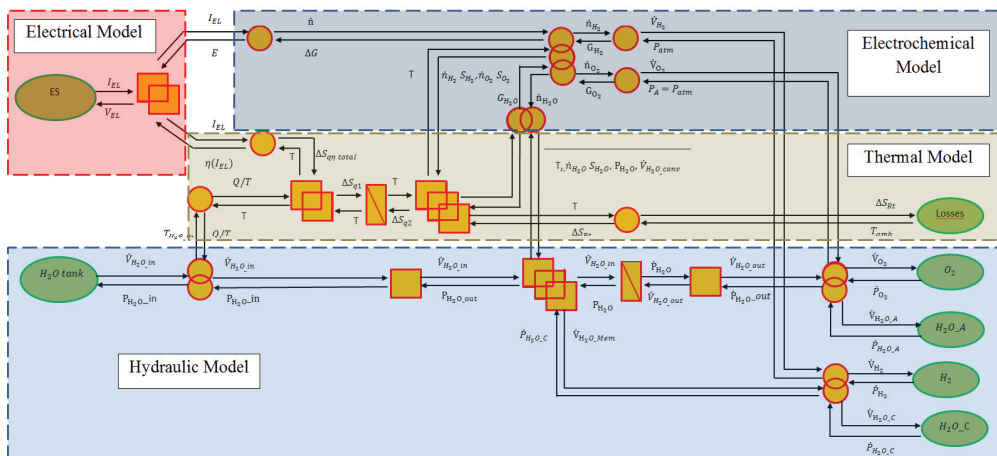

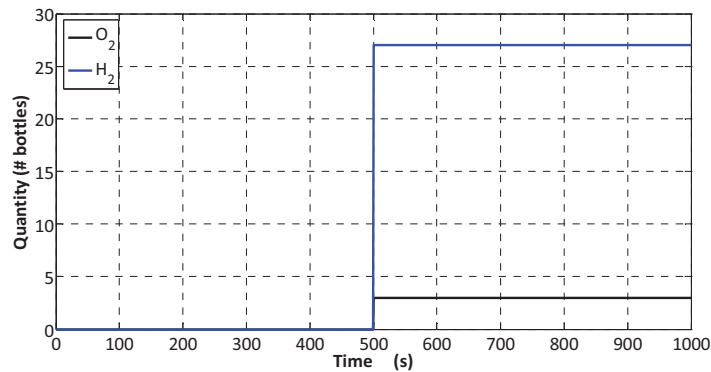Fig. 3: The overall EMR model for the system under study [51]

Fig. 4: H_2 and O_2 produced in case of excess power generation.

6. Conclusion

Understanding the stakes of Hydrogen storage solution implies to identify the techno-scientific, economic or social bottlenecks and to develop a more systemic approach of the technological system emergence. In this perspective, the criteria method based on performance, market, environment and social indicators needs to be completed with other components as service and social factors. Therefore, the notion of business model and particularly the Service, Technology, Organization and Finance (STOF) model, will be useful. Indeed, Business model can help for converting ideas and the hydrogen storage systems technology into economic value [53]. Even if there is no consensus among researchers either about the number and nature of components or about frameworks that organize elements, the STOF business model approach is particularly interesting in analyzing hydrogen storage systems, because it considers the service definition in terms of the customer value proposition as the starting point for any business model. The service definition acts as a reference for the other domains [54].

Hydrogen storage systems become a mature option not only for power system stabilization during generation-demand imbalances but also for economic profits in consequence of excess hydrogen and oxygen production. The locally produced hydrogen can be sold either directly to the national grid (in watt-hours) or to the public users for hydrogen cars or microgrids in the form of compressed hydrogen bottles. Due to the fact that technology does not spread alone, it is necessary to understand how a technical innovation is built and fits in society. Consequently, attention should be directed towards the forms of interconnection (alliances, competition, cooperation) between the actors and the discrepancies involved by the confrontation of different logics (political, commercial, scientific) that intersect and fit together.

Acknowledgements

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