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Review

Hydrogen Storage Technologies for Smart Grids applications

Stavros Lazarou [1,*] and Sofoklis Makridis [2,*]

1 Department of Electrical Engineering, Western Macedonia University of Applied Sciences, GR50100, Kozani, Greece
2 Department of Environmental and Natural Resources Management, University of Patras, GR30100, Agrinio, Greece
* Correspondence: slazaroy@teiwm.gr (S.L.); smakridis@upatras.gr (S.M.)

"A smart grid is an electricity network that can integrate in a cost efficient manner the behavior and actions of all users connected to it - generators, consumers and those that do both - in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety." *European Commission Task Force for Smart Grids*

Abstract: Electricity sector is among the main carbon emissions contributors. This sector has the potential to reduce its carbon emissions through producing electric energy from zero emitting facilities and through the optimization of the consumption in a way to better accommodate low carbon emissions. Hydrogen society per se combined with smart grids, as this is analyzed in this manuscript, can present substantial contribution towards climate change mitigation.

Keywords: smart grid; hydrogen; storage

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1. An introduction to Smart Grids and Energy Hydrogen Storage

After the Paris Agreement [1], new challenges and opportunities have emerged for the hydrogen economy. At the United Nations Framework Convention on Climate Change [2], 21st Conference of Parties, 197 member states decided to keep the planet's temperature at least 2°C below the pre-industrial levels. This objective is technically a demanding exercise that requires the implementation and the advancement of all the available technologies that can reduce carbon emissions. According to the United States Environmental Protection Agency [3] electricity sector is among the main contributors to the carbon emissions. This sector has the potential to reduce its carbon emissions through producing electric energy from zero emitting facilities and through the optimization of the consumption in a way to better accommodate low carbon emissions. Hydrogen society per se combined with smart grids, as this is analyzed in this manuscript, can present substantial contribution towards the implementation of Paris agreement.

Having mentioned the above, several technologies such as smart grids facilitate the transition towards a zero carbon emissions society because they assist the production from zero emission sources. This idea is served by a substantial number of researchers who produce knowledge on the subject [4]. Their work focuses increasingly to this specific discipline, probably incentivized by the carbon emissions mitigation policies. However, it is important to define the smart grid per se as it evolves in time on the way to meet the new requirements [5]. The smart grid idea includes hardware, software, equipment and operational procedures that facilitate the transition of the electricity system operation in a way the equipment is interconnected in a manner its information exchanges friendly and safe. In this way, the intermittent renewables with zero carbon emissions can be better accommodated and also energy efficiency measures can be easier taken to the consumers' side. Smart grids are treated on a multilayer basis since they affect policy for governments, technology for the industries and organizational patterns for utilities. On policy level the ideas circulate around basic smart grid implementation concepts. On international level [6], these include policies for reducing the burden of smart grid implementation for the utilities, the creation of incentives for dynamic pricing and smart metering, as well as the harmonization of regulatory regimes across jurisdictions. On European level, Energy Union and Third Electricity Package approaches the same issues including smart grids implementation. Especially for the European Grid an extended inventory has been produced that shows increasing penetration of smart grids across the continent [7]. As far as the specifics of the technical requirements for smart grid implementation [8] are concerned, special attention is currently given to the technologies that contribute to the security, reliability, interoperability, environmental friendliness, user interaction improvement and efficiency of the grid. To achieve these objectives, a selection of advancements is being done on storage and metering as far as hardware is concerned, control and communications as far as software is concerned [9]. An important attribute of Smart Grids is their enhanced capability to receive increased penetration of renewables and distributed generation. However, they create specific technical challenges [10] such as the increase of short-circuit current, the bi-directional flow of energy that requires advanced voltage control, differentiation for the protection and a change to the standard procedures for network planning. An important factor that facilitates the connection of renewables is the capability of smart grids to accommodate storage [11]. This attribute facilitates except from the connection of intermittent renewables the delay of the requirements for expansion of the lines.

Especially to the interests of this analysis, the hydrogen society is able to demonstrate substantial contribution to the sector of electricity. Several researchers have demonstrated this objective. Xing Luo, Jihong Wang, Mark Dooner and Jonathan Clarke [12] provide an analysis of the technologies that can be applied to electricity energy storage. Among them, the authors provide a comparison of the available solutions, including hydrogen storage and the challenges they can meet specifically for the United Kingdom electricity system. It appears some complementarity at least to the level of end-users and smart grid support, distribution network and system ancillary services. On the other hand, Grigorios L. Kyriakopoulos and Garyfallos Arabatzis [13] offer a broad literature review of Energy Storage Technologies. They claim that the several types of storage and specifically pumped hydro, synthetic natural gas and to the interest of this project hydrogen are the most advanced in terms of their capabilities for direct implementation. This is of paramount importance because it provides the competency to research on a neutral carbon society supported by hydrogen energy storage. Having this said, Salvatore Abate, Gabriele Centi and Siglinda Perathoner [14] provide an analysis of the benefits of chemical energy conversion to the electricity grid. They explain that hydrogen has distinctive advantages, being able to offer trading options to off-grid systems. Following this pattern of ideas, Robert Schlogl [15] provides a more generic description of the situation, being able to specifically describe the potential contribution of the chemistry in dealing with the whole energy challenge. After this, Gerda Reiter and Johannes Lindorfer [16] enter to the potential of Power-to-Gas as a tool for energy storage. David M. Bierschenk, James R. Wilson and Scott A. Barnett [17] go a step further applying reversible fuel cells for energy storage. C.H. Wendel, P. Kazempoor and R.J. Braun [18] analyze the previous concept much further proving its feasibility. Closing this bibliographical analysis, Eduardo Lopez Gonzalez, Fernando Isorna Llerena, Manuel Silva Perez, Felipe Rosa Iglesias, Jose Guerra Macho [19] demonstrate the operational capability of a hybrid power system. It appears from all the above that Hydrogen for Electricity Energy Storage has been identified among different solutions as a viable solution for energy storage. Additionally, the research acknowledges further advancements on the implementation of hydrogen technology for storage that is able to provide additional features towards the implementation of a carbon neutral society. However these advances move forward on a different level for each country.

2. The Smart Grid advancements to the electricity system

As already mentioned at the introduction, Smart Grid technology has achieved the critical mass to gradually become an applied technology. Countries around the world based on their individual requirements, resources and needs have the subject advanced on the way to better serve their interests [8, 20]. According to the Smart Grid Federation Report [20] Canada, the United States, Japan, United Kingdom, Japan and South Korea have a different key factor that affects their smart grid

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alignment. Canada needs to control an aging infrastructure, United Kingdom has increased its gas imports, Japan is in the procedure to phase out nuclear production, and South Korea to achieve higher energy efficiency. This report bases these findings on statistics produced by the International Energy Agency [21].

An issue of paramount importance, except from integrating zero carbon emission facilities is the inadequate capability of the network to serve the future requirements. Based on this situation, smart grids for the case of Canada [20] were able to dynamically rate the capacity of a given line and control widely the system. Both of these attributes increase the capability of the existing lines to transfer energy delaying new installations and optimizing the operation of the existing ones.

Transmission lines Dynamic Capacity Rating is an exercise that involves dynamic stability analysis, a wide selection of data such as of the generators, transformers and lines but also weather data and renewables intermittent production. Amro M. Farid et al [22] provide an extensive review of the situation, giving emphasis to the control of the future smart grid network. At their argumentation they explain that the study of the transmission network, due to smart grids would be unified. Having this said, any technologies applied to the transmission network can be also scaled down to the distribution level. This is exactly the pattern applied by Sara Mohtashami et al [23] in providing a method for optimizing the expansion of the distribution network with distributed generators, a situation appearing to a smart grid.

The rest of the countries such as South Korea, Ireland, Japan, United States and the European Union give more attention to the implementation of the smart grid idea in a slightly different manner [8]. These countries created smart grid projects giving more emphasis to smart metering, electric vehicles, distributed generation, demand response and to the development of advanced procedures for their control and communication across the elements. The above provide the capability to the network of being more resilient, flexible and environmentally friendly.

Closing this paragraph, it appears that the technologies seem to evolve based on the specific needs of each of the countries investing to Smart Grids. However, promising technologies, such as fuel cells for the distribution level, appear to be inadequately developed. Additionally, it remains clear that the plethora of different approaches across the countries create also issues of interoperability, harmonization and eventually standardization on a global level. International Standardization bodies and professional organizations are dealing with the above.

3. Smart Grid and Storage Standardization

The variety of requirements, based on a plethora of needs across the globe, leads to uneven development of smart grid technologies. However, the electricity system as a whole requires interoperability. As well as, it is already a greatly invested sector that is difficult to be replaced at once but only in sections across time when technology advances. The newer installations need to be able to operate effectively along with the existing ones but also in safe manner for people, who operate and use them. All the above attributes require being coordinated. This is achieved through standardizing procedures organized by international bodies, which are specialized to electricity systems such as the International Electrotechnical Commission (IEC) [24], the Institute of Electrical and Electronic Engineers (IEEE) [25] on global and the European Committee for Electrotechnical Standardization (CENELEC) [26], the European Committee for Standardization (CEN) [27] and the European Telecommunications Standards Institute (ETSI) [28] on European level. All the organizations above have allocated substantial resources to tackle the emerging issues of smart grids.

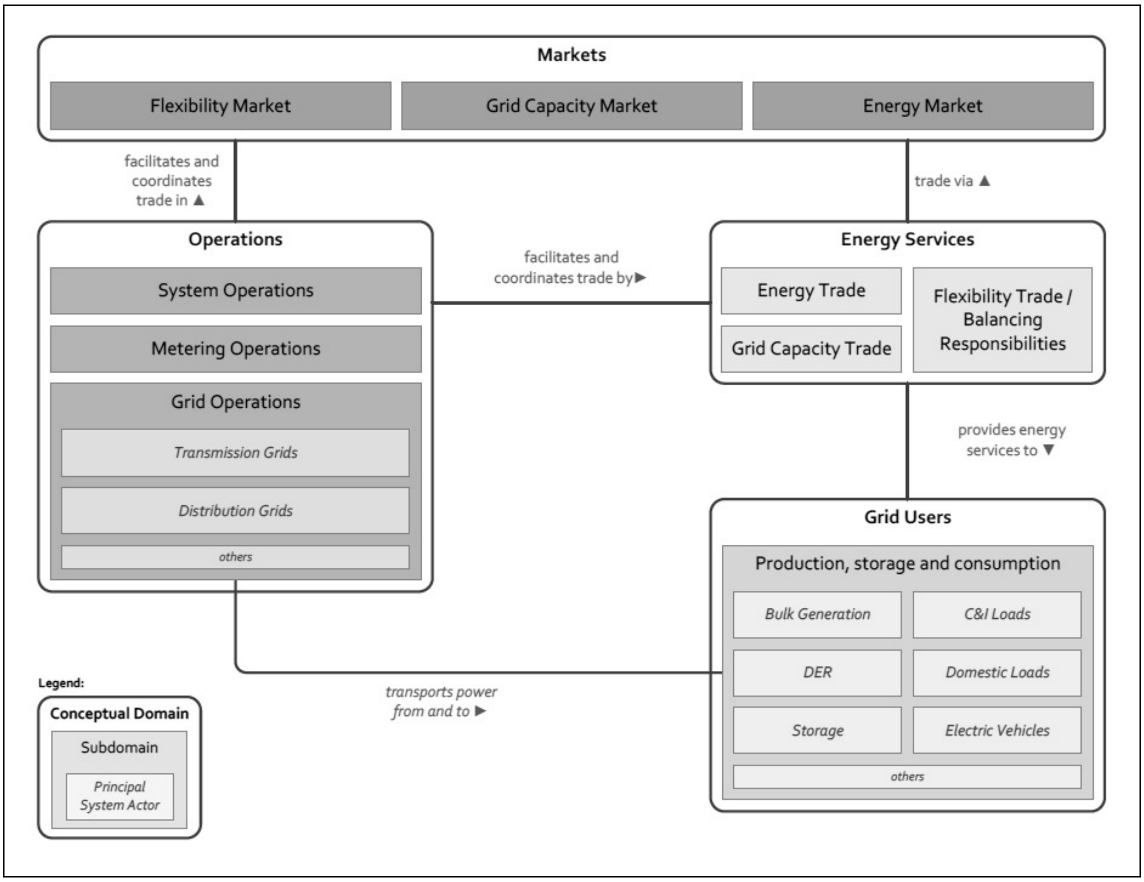

Fig 1. The European understanding of Smart Grid components (redrawn from [29])

As far CEN, CENELEC and ETSI are concerned, they have accepted the mandate from the European Commission to develop and maintain the standardization procedure for Smart Grids on European level. For this purpose these standardization bodies have described the Smart Grid concept per se, as depicted at the figure below.

According to this, there are four main parts of the whole smart grids picture representing a different selection of stakeholders involved. These are the Operations, Users, Markets and Energy Services components. The Operations include the traditional players of the energy system before smart grids. Specifically they include the utilities, the system operators on the transmission and distribution level. The above serve the grid users, who are not only consumers but also include the distributed generators as well as storage and electric vehicles. The high level operations of all stakeholders are described based on the energy services in general and the market.

On the global level, the International Electrotechnical Committee has established a wide basis to create the standards that describe Smart Grids' operation. It distinguishes the components of smart grids to the different levels of transmission, distribution, distributed generation, consumption and communication. IEC categorizes the need of further developing smart grids to aging infrastructures, intermittent renewables, low cost of energy, issues of sustainability and societal changes. Sustainability is of paramount importance since it includes the emerging questions of carbon emissions reduction when the societal changes require the abolishment of the traditional energy monopolies to unbundled entities.

4. The advantages of installing hydrogen storage facilities to smart grids

Hydrogen storage facilities were developed to the level to be considered a technology advanced enough to be implemented [30]. However there are still challenges. The main advantage of their implementation remains their much higher to thermal engines efficiency. For installations of the same small or medium capacity, where thermal reciprocal engines or turbines are used, the system efficiency is much lower compared to fuel cells. As a matter of fact, fuel cells demonstrate three different types of phenomena that create losses and reduce their efficiency. These are the ohmic, activation and concentration losses, for which more information can be found at [31]. A common characteristic to the majority of electric circuits and components is the ohmic losses. They appear due to electrons flow and the resistance of the interconnections, cables etc. Specifically for fuel cells, the ohmic losses are low. Additionally, activation or reaction rate losses are connected to the chemical reaction per se. They are also relatively low but still existing. The concentration losses are connected to the reduction of the concentration caused by the depletion of reactants on the surface of the fuel cell electrodes. The concentration losses are also considered as low. Having mentioned the above, it is possible that fuel cell installations of low or medium capacity to be able to deliver much higher efficiency compared to any alternative. The situation can be different though for large power plants of hundreds of megawatts where turbines are able to achieve high efficiency level at reasonable costs. This is the reason of proposing at this manuscript, solutions to be applied to the smart grid rather than the transmission system level, however complementarity exists.

An additional feature of the fuel cells is their reduced maintenance requirements due to the absence of moving parts compared to the main competing technology. Internal combustion engines are able to offer long operating life, however they require frequent maintenance, change of parts and fluids. The maintenance reduces their capability to be installed in remote places and also the fluids need to be properly disposed for environmental reasons. The low maintenance also is consistent to high system reliability.

Fuel cells are able to withstand immediate load changes from stand still. Thermal engines, due to premature metal aging, need to be warmed before delivering their full capacity. This situation provides distinctive advantages for specific applications such as covering the needs of the intermittent renewables. On the other hand, their capability to deliver for long time their full load is an advantage compared to battery systems.

Fuel cell installations can be used to produce except from electric energy and heat, but also for the so-called cogeneration or combined heat and power (CHP) procedure. The produced heat can be used for residential or industrial purposes. It is on average of low cost, given that this energy otherwise would have been disposed to the atmosphere. CHP is able to increase the total efficiency of the system, however the production of heat is a by-product that is not always consumed. This may happen, as an example, at the countries of which moderate climate prevails or there are low industrial energy requirements.

Hydrogen storage can be successfully combined with the existing gas distribution network. C.H. Wendel, P. Kazempoor and R.J. Braun [18] describe such a solution. In this specific case the authors propose the installation of a reversible fuel cell that is able to produce electricity from the gas network and vice versa. This solution can effectively exploit the adjacent network however it cannot be applied to remote installations. The main advantage compared to alternatives is the unlimited potential for energy amount to be stored and withdrawn from the network.

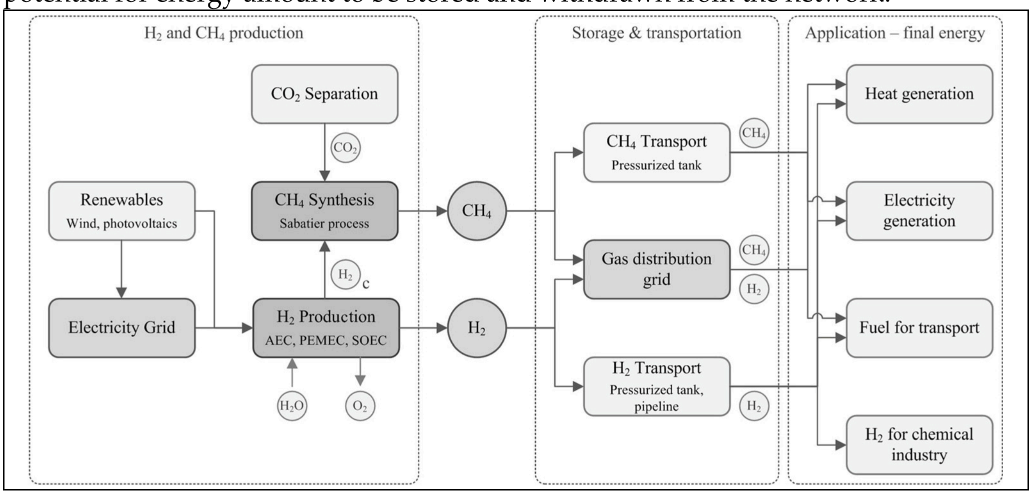

Fig 2. Power to gas system and its pathways (redrawn from [16])

Figure 2 depicts the selection of pathways for hydrogen and methane storage. It is a cyclical procedure since the produced from electric energy material is eventually consumed to produce the same type of energy. However, this transformation provides distinctive advantages to storage and transportation. As a matter of fact the electricity system without storage needs to consume all the energy it produces or in other words to adequately satisfy the consumption. On the other hand, energy production from renewables remains intermittent, which is not always consistent to the consumption in every given time. Hydrogen storage can be a valuable solution to this challenge since it provides unlimited storage capability and the option of producing energy using the gas distribution system even if there is shortage of already stored energy.

5. Expected complementarity of hydrogen technologies for smart grids with the renewables' installations

Hydrogen technology is able to deliver unique solutions to complex problems for the implementation of wider basis for renewables installation. As a matter of fact, hydrogen technology can be applied to remote installations where any other alternatives are not feasible. Offshore deep-sea renewables may be too remote to be directly connected to the electricity grid or they move to different sites based on the requirements. Marine technology has shown the utility of these solutions. Floating wind turbine installations may use hydrogen to store the produced energy that can be collected to be transferred to the mainland without the need of long distance electricity grids.

Additionally to the above, where the importance of hydrogen arises due to the absence of electricity network, the technology can be applied in support of the ancillary services. The electricity networks need to be able to deliver the energy required by the loads immediately and to cover the transmission and distribution losses. In the case this requirement is not fulfilled, the lack of available power stalls the system creating blackouts. The transmission system operators, to be able to control the lack of power, apply a group of services called ancillaries. In this case, the energy producers receive a compensation to keep their facilities operating without producing energy, in order to be able to withstand immediately the loss of power due to a fault coming from another producer. Up to recently, storage of electric energy had been too costly to be widely implemented, however the technology of today is able to offer additional opportunities to this direction. As a matter of fact, utilities are installing storage facilities at the distribution system level to meet peak demands without the need of keeping reserves. On the other hand, fuel cells are able to deliver these services but they introduce different behavior. Batteries are able to deliver peak loads for shorter time, when fuel cells, especially when connected to the gas distribution network are able to deliver consistently their installed capacity for long time.

Another important feature of fuel cells installations is their capability to produce methane and hydrogen to be fed to the gas network as a means of storing energy. The wide installation of renewable energy installations and their intermittency create new challenges to the electricity system. Renewables, most of the time, do not produce their installed capacity due to the absence of wind or solar irradiation at that point. This situation creates the need of the installation of excessive installed capacity to meet the daily needs if they need to be met by renewables. The existing technology proposes curtailment. During this procedure, when the energy system is not able to absorb the produced energy, the producers from renewables are called to stall. This situation can lead to energy prices below zero. To avoid such extreme situations, a solution could be to install reversible fuel cell systems. In this case, the excessive energy is not disposed to the atmosphere but it is transferred to the gas network for immediate or future consumption.

The last but not least important contribution that fuel cells can have to the electricity network is connected to their capability to deliver high efficiency with relatively small installations. This creates the opportunity to connect to the distribution level and deliver power near the consumption. This creates lower transmission and distribution losses, contributes to the reduction of the need for network expansion and maintains relatively high production efficiency. The benefits are environmental, societal and on the energy security level. Environmental due to the reduction of losses, societal due to the opposition of the society to the installation of new transmission and distribution lines and energy secure since they produce energy on high efficiency.

6. Conclusions and future proposed work

Closing this manuscript, it appears that hydrogen technology presents extensive complementarity with the smart grids. Fuel cells can be used to mitigate the consequences of intermittent renewables installation, to store energy produced remotely and to facilitate the operation of the existing grid delaying its expansion. However, all the above are not applied to the degree required due to technical challenges. These are the issues to be further investigated.

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