

Power-to-Gas Hydrogen: Techno-economic Assessment of Processes towards a Multi-purpose Energy Carrier

Original

Power-to-Gas Hydrogen: Techno-economic Assessment of Processes towards a Multi-purpose Energy Carrier / Ferrero, Domenico; Gamba, Martina; Lanzini, Andrea; Santarelli, Massimo. - In: ENERGY PROCEDIA. - ISSN 1876-6102. - 101:(2016), pp. 50-57. (Intervento presentato al convegno 71st Conference of the Italian Thermal Machines Engineering Association, ATI 2016 tenutosi a Politecnico di Torino, ita nel 2016) [10.1016/j.egypro.2016.11.007].

Availability:

This version is available at: 11583/2667235 since: 2017-03-17T14:58:16Z

Publisher:

Elsevier Ltd

Published

DOI:10.1016/j.egypro.2016.11.007

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16
September 2016, Turin, Italy

Power-to-Gas Hydrogen: techno-economic assessment of processes towards a multi-purpose energy carrier

Domenico Ferrero^{a*}, Martina Gamba^a, Andrea Lanzini^a, Massimo Santarelli^a

^a*Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

Abstract

The present work investigates Power-to-Gas (PtG) options for variable Renewable Electricity storage into hydrogen through low-temperature (alkaline and PEM) and high-temperature (SOEC) water electrolysis technologies. The study provides the assessment of the cost of the final product when hydrogen is employed for mobility (on-site refueling stations), electricity generation (by fuel cells in Power-to-Power systems) and grid injection in the natural gas network. Costs estimations are performed for 2013-2030 scenarios. A case study on the impact of variable Renewable Electricity storage by hydrogen generation on the Italian electricity and mobility sectors is presented.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Renewable Energy, Hydrogen Economy, Electricity storage, Power to Gas, Electrolysis, Fuel Cells, alkaline, PEM, SOEC.

1. Introduction

Variable renewable energy sources (V-RES) from wind and solar power are expected to meet an increasing share of the overall demand of electricity consumption in Europe [1]. High V-RES penetration scenarios generally will require a combination of the following strategies to maintain power grid reliability:

- the installation of new transmission lines (according to the amount of RES in the energy mix);
- the re-design of electricity distribution grid toward smart grid concepts;

* Corresponding author. Tel.: +39-011-090-4560; fax: +39-011-090-4499.
E-mail address: domenico.ferrero@polito.it

- the installation of electric energy storage (EES) options (each option can absorb only specific time scales; e.g. H₂-based, compressed-air and pumped-hydro energy storage are fit for bulk electricity storage (daily or longer), while batteries are mostly intended for voltage regulation);
- the installation of reserve power for fast ramp-up during peak load hours;
- demand response protocols.

The installation of electric energy storage (EES) systems is thus one of the possible means to provide balancing services to the grid. EES should also play a significant role in arbitrage markets, in which the revenue comes from price differences between two market prices. Energy storage charges when low-price electricity is available (e.g., during off-peak and/or night hours), and discharges it during periods of high prices. The economic reward comes from the different market prices of electricity, reduced by the losses occurring during the round-trip conversion of electricity [2].

Nomenclature

| | |
|-------|-----------------------------------|
| CAPEX | Capital Expenditure |
| EES | Electric Energy Storage |
| LCoE | Levelized cost of Electricity |
| LHV | Lower Heating Value |
| HHV | Higher Heating Value |
| OPEX | Operating Expenditure |
| PEM | Proton Exchange Membrane |
| PtG | Power-to-Gas |
| PtP | Power-to-Power |
| SOEC | Solid Oxide Electrolysis Cell |
| SOFC | Solid Oxide Fuel Cell |
| V-RES | Variable Renewable Energy Sources |

Looking at the technologies able to store large quantities of electricity (for daily, or even longer time-periods), 99% of the market is taken now in Europe from pumped-hydro energy storage (PHES). Compressed air energy storage (CAES) is also a well-proven option, which is re-gaining momentum. Both PHES and CAES suffer of geographical constraints. Pumped-hydro systems require heights of hundreds of meters to be able to store bulk energy quantities. In addition, infrastructure is required to build the water reservoirs (uphill and downhill) and to connect them via pipeline. CAES requires instead large volumetric under-ground reservoirs (e.g., salt caverns) to store the pressurized air. H₂-based energy storage systems, by contrast, are essentially geographically un-constrained and high volumetric energy densities can be easily achieved by storing electricity in a chemical fuel rather than in potential (PHES) or mechanical (CAES) energy.

The conversion of energy from electrical into chemical form through the synthesis of hydrogen – the Power-to-Gas (PtG) storage – also presents the advantage of storing electricity in a multi-purpose energy carrier. In fact, hydrogen can be either stored for deferred electricity production (i.e., EES by Power-to-Power application of PtG) or used as fuel for transportation and even injected in the existing natural gas (NG) network (even though some limitations apply on the maximum amount of H₂ gas that can be injected into the NG pipeline) [3].

Power-to-Power (PtP) systems are based on the concept of producing hydrogen via electrolysis when surplus electricity is available, thus storing energy as compressed hydrogen gas. When power demand is high, fuel cells are used to re-convert the stored hydrogen back to power. The basic technologies on which PtP systems are based are the electrochemical cells, which can be used both for water electrolysis to produce hydrogen and also for the generation of electricity from the stored hydrogen (fuel cells). Those systems in which the electrochemical cells can be operated both as electrolyzers and fuel cells are reversible PtP systems, which thus use the same device for electricity storage and hydrogen re-electrification. Recently, much attention has been drawn by the high temperature

reversible solid oxide cells (R-SOCs) [4, 5], whose round-trip efficiency has been estimated as high as 63% during charge-discharge experiments [6].

The appropriate metric to compare the economic performance of different EES plants is the levelized-of-cost-electricity (LCoE), also called the levelized-cost-of-flexibility. This metric looks at the (minimum) cost of the produced electricity (i.e., output electricity from the EES system) in order to make the investment profitable once both capital and operating costs of the plant are known, as well as the financial structure of the investment. In the limiting case in which the input price for electricity is zero (i.e., no market demand for electricity, or congestion on the transmission lines), the resulting LCoE should be lower than average electricity prices in peak-hours to make the EES plant profitable. In the study of FCH-JU released in 2015 [1], the calculated LCoE for a simulated energy intensive application with 8 hr of charge every day, and discharge for the same duration within the same day, were 24 and 49 €/MWh (2013 scenarios) for PHES and CAES, respectively.

When the hydrogen obtained by electrolysis is not re-converted to electricity, the economic performance of PtG must be evaluated by comparing the cost of H_2 with that of competing products on the market. Looking at the mobility sector, a competitive cost of H_2 fuel against gasoline and other fossil-derived fuels should be around 4 US\$/kg of H_2 (value extrapolated from [20]). According to the 2011 report from Saur and Ramsden [7], producing wind-based hydrogen via low-temperature electrolysis at about 4 \$/kg of H_2 is feasible. The current production price for the mobility sector claimed by FCH-JU is instead 13 €/kg (reference year: 2012) [8].

2. Techno-economic assessment of PtG: methodology

The present analysis is focused on the techno-economic assessment of Power-to-Gas (PtG) systems for the conversion of V-RES electricity into H_2 through water electrolysis for mobility, power generation (by fuel cells) and grid injection applications. Two scenarios were considered in the study for the estimation of the costs: the first is based on the state-of-the-art technologies for water electrolysis and fuel cells at 2013; the other is based on the projections for the investment costs of electrolyzers and fuel cells at the year 2030 given by FCHJU [1, 8].

2.1. System description

The schematic of the analyzed systems is depicted in Figure 1.

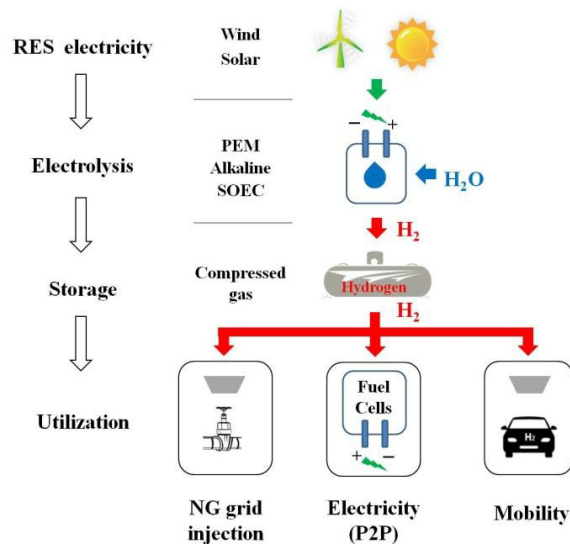


Fig. 1. Schematic of the PtG options analyzed.

In the PtG options considered, the electricity produced by variable RES is converted into hydrogen by water electrolysis and the produced hydrogen is stored in gas holders. Three different water electrolysis technologies are considered in the analysis: alkaline electrolysis, based on a low-temperature (80-90 °C) liquid electrolyte, Proton Exchange Membrane (PEM) electrolysis, based on a low-temperature (40-80 °C) solid electrolyte and high-temperature (650-850 °C) electrolysis based on solid oxide electrolysis cells (SOEC). The low-temperature technologies considered can directly produce pressurized hydrogen, while the SOEC technology is not yet mature for the operation under pressure, even if the operation up to 15 bar has been demonstrated at lab-scale [9]. A storage pressure of 20 bar is considered for the analysis, and both PEM and alkaline electrolyzers can deliver hydrogen at that pressure level. The SOEC electrolyzer is assumed to operate at ambient pressure in the 2013 scenario, thus a hydrogen compressor is considered for the SOEC-based system in order to deliver the H₂ to the storage, while the pressurized operation at 20 bar is assumed in the 2030 scenario. In all the three cases (i.e., alkaline, PEM and SOEC), pure H₂ is assumed to be available at ambient temperature at the electrolyzer outlet for the storage and/or compression. The efficiencies of the electrolysis systems have been assumed from the literature for large size (i.e., MW) systems (see Table 1), and an electrolyzer size of 10 MW (input electrical power) has been selected for the analysis. The compression stage needed in the SOEC case for the 2013 scenario has been modeled in Aspen Plus® considering an isentropic compression efficiency of 0.75 and an electro-mechanic efficiency of the compressor of 0.95 [10]. The same values of efficiencies have been assumed for all the other compressors in this work.

Three different uses of the stored hydrogen were considered in the analysis: injection in the natural gas (NG) grid, re-electrification for Power-to-Power applications and on-site vehicle fuelling for mobility.

Hydrogen injection in the NG grid is a promising option for transferring RES electricity stored in a gaseous carrier from generation areas to users using the already existing gas infrastructure and avoiding (or delaying) the construction of new power networks. In this way, an increase of the installed RES power at national level can be managed by the NG grid without generating power grid congestion issues. In the present analysis, hydrogen is available from the electrolysis section at 20 bars and directly compressed at 75 bar and injected into the NG network without intermediate storage, as it is assumed that the grid can accept at any time the H₂ injection. The compression section has been modeled in Aspen Plus® by a two-stage reciprocating compressor with intercooling.

Fuel cells are currently the only reliable and efficient option for on-site electricity production from the stored hydrogen, as gas turbines fuelled by pure hydrogen currently do not exist at commercial level and hydrogen-fuelled internal combustion engines present low efficiency and technical issues [3]. Following the same approach adopted for the electrolysis, three fuel cells technologies have been considered in the analysis: alkaline, PEM and SOFC. The three technologies operate at the same pressures and temperatures of the electrolyzers described before, and a 10 MW size (output electrical power) has been assumed. Electrochemical cells based on proton exchange membranes and solid oxides are reversible devices, and the operation of PEM and SOFC systems as both electrolyzers and fuel cells has been assumed in the present analysis. The reversible operation is a clear advantage from the economic point of view, as both electricity storage into H₂ and hydrogen re-electrification can be performed in the same device, due to the fact that electricity storage and H₂ re-use take place at different times. To the authors' knowledge, reversible alkaline systems were never investigated, thus the reversible application of this technological option has not been considered in the analysis.

The use of hydrogen for mobility purposes in electric vehicles driven by fuel cells engines is the third application included in the analysis. An on-site refueling station sized for an average refueling rate of 1000 kg/day has been selected [11]. A gas storage (20 bar) has been assumed between the electrolyzer and the refueling station, as hydrogen is produced when there is RES availability, while demand occurs during the whole year. Inside the station, hydrogen is compressed to 875 bar by a five stage intercooled compressor and stored into dispensers for vehicle injection. The efficiency of the refueling station has been calculated by simulating the system in Aspen Plus®.

2.2. Methodology and assumptions

The techno-economic assessment of the selected PtG options is based on known values of energy efficiency and investment cost of each section of the system. The efficiencies of electrolysis and fuel cell sections have been taken from the literature looking at large size systems (i.e., MW size). All the values used in our analysis are listed in Table 1 (efficiency values include both electrochemical conversion and parasite consumption from balance of plant,

i.e., heat exchangers, gas blowers, etc.). The specific electricity consumptions of hydrogen compression sections evaluated by energy simulations are: 2.2 kWh/kgH₂ for SOEC hydrogen compression (from 1 bar to 20 bar) in the 2013 scenario, 0.73 kWh/kgH₂ for grid injection and 2.5 kWh/kgH₂ for the refueling station.

Table 1. Efficiency and investment costs (CAPEX) of electrolysis and fuel cell technologies.

| Technology | Electrolysis efficiency | Fuel cell efficiency | CAPEX 2013 (€/kW) | CAPEX 2030 (€/kW) |
|------------|-------------------------|-----------------------|------------------------------------------------|-------------------------------------------|
| Alkaline | 71% ^a [3] | 60% ^b [13] | 1200 ^c [1] – 3000 ^d [13] | 370 ^c [1] – 925 ^{d,e} |
| PEM | 63% ^a [3] | 56% ^b [15] | 2320 [1] | 250 [1] |
| SOC | 82% ^a [14] | 50% ^b [14] | 6000 [8] | 500 [8] |

^a HHV basis ^b LHV basis ^c Electrolysis ^d Fuel cell ^e Extrapolated value

The profitability of the PtP application has been evaluated using the metric known as Levelized Cost of Electricity (LCoE) [1]. The LCoE takes into account all the actualized investment (CAPEX) and operating (OPEX) costs of the electricity conversion to hydrogen, gas storage, compression and reconversion to electricity, and puts them in relation with the amount of energy (i.e., electricity) produced by the system. The LCoE thus evaluates the total costs per MWh of product of the PtG system, and it is calculated as follows:

$$LCoE = \frac{\sum_t ((CAPEX + OPEX + Fuel)_t \cdot (1+r)^{-t})}{\sum_t (Electricity_t \cdot (1+r)^{-t})} \quad (1)$$

where *Fuel* is the cost of fuel, which is considered zero in the analysis, as the PtG system is assumed to be feed by surplus electricity produced by RES that cannot be delivered to the grid, and *r* is the discount rate (5% assumed). The profitability of PtG applications for mobility and grid injection has been evaluated in a similar way, by using the amount of produced hydrogen instead of the electricity. The CAPEX for electrolysis and fuel cell systems has been evaluated from the literature, while the cost of hydrogen storage and compressors by using cost functions of equipments [12]. The CAPEX values depend on the size of the equipments, and all the system components sizes have been selected in order to be suitable for a plant based on a 10 MW_{el} electrolyzer. The CAPEX of electrolyzers and fuel cells expressed per unit of power are reported in Table 1 with the related references.

The investment costs for PEM and SOC technology are assumed to be the same for fuel cells and electrolyzers, since reversible cells have been selected, and thus the equipment is the same for both electrolysis and fuel cell operation. The alkaline system has different costs as the electrolyzer and fuel cell are different devices. The size of the fuel cell system is also considered to be 10 MW_{el}, assuming that electrochemical systems can operate with a total reversibility. The CAPEX values selected for 2013 are the highest in the ranges reported by the Fuel Cells and Hydrogen Joint Undertaking (FCHJU) [1, 8], in order to perform a conservative analysis for the today's scenario. The values adopted for 2030 are in the lower range of the costs, in order to present an optimistic scenario for 2030. The CAPEX of hydrogen compressors has been estimated to be 2100 €/kW_{fluid} [12], the storage cost is 225 €/m³ [12] (storage dimensioned for one week storage of a 10 MW_{el} electrolyzer), and the total CAPEX of the refueling station is 3.2 M€ (1000 kgH₂/day size) [11, 12]. The annual OPEX has been assumed to be the 2% of the CAPEX for all the equipments, following FCHJU assumptions [1]. The lifetime of equipments is assumed to be 20 years.

The evaluation of the energy commodity produced by the PtG system (i.e., electricity for PtP, H₂ for mobility or grid injection) requires to know the yearly operating hours in order to calculate the amount of electricity/hydrogen generated during the lifetime of the system. Variable RES are not available for all the hours of the year, and consequently the installed electrolyzer capacity cannot be fully exploited during the lifetime of the system. For the Italian scenario, variable RES currently have a capacity factor near 20% [16-17]. This means that the installed RES power in Italy is fully exploited for a number of hours equivalent to 20% of the total hours of the year. In the analysis it is assumed that the electrolyzer works at full power for this number of hours, and the electricity/hydrogen produced is calculated consequently by taking into account also the efficiency of electrolysis, compression and re-electrification processes. In fact, it is assumed in the calculations that all the energy consumed in the PtG processes

analyzed is provided only by RES, thus a part of the electricity provided by wind or sun to the PtG system is consumed in the transformation processes and it is not available in the useful product.

3. Results and discussion

Results are presented for a today's scenario, for which efficiencies and costs have been calculated using literature data of state-of-the-art technologies in 2013, and for an optimistic scenario in which the costs of electrolyzers and fuel cells have been estimated at 2030 following FCHJU projections. The potential impact of hydrogen-based PtG on the actual Italian energy system is also assessed.

3.1. Electricity generation (PtP)

The calculated LCoEs for stored electricity are presented in Table 2 for both scenarios.

Table 2. Final cost of stored electricity: 2013 and 2030 scenarios.

| PtP 2013 (€/MWh _{el}) | | Fuel Cell | | | PtP 2030 (€/MWh _{el}) | | Fuel Cell | | |
|------------------------------------|----------|-----------|-----|------|------------------------------------|----------|-----------|-----|------|
| | | Alkaline | PEM | SOFC | | | Alkaline | PEM | SOFC |
| Electrolysis | Alkaline | 356 | 332 | 559 | Electrolysis | Alkaline | 117 | 84 | 106 |
| | PEM | 569 | 433 | 815 | | PEM | 103 | 56 | 91 |
| | SOEC | 901 | 916 | 882 | | SOEC | 116 | 84 | 78 |

The LCoEs evaluated for all the combinations of technologies in the 2013 scenario are sensibly higher than that of PHES (18-42 €/MWh_{el}) and CAES (27-49 €/MWh_{el}) estimated by FCHJU for the same year [1]. The lowest LCoE (332 €/MWh_{el}) is achieved for a PtP system based on alkaline electrolysis and PEM fuel cells, mainly due to the high efficiency and low CAPEX of the alkaline electrolyzer. Moreover, alkaline and PEM electrolyzers operate in pressurized conditions, thus avoiding the need for hydrogen compression for the storage. The LCoE of alkaline-PEM combination is comparable with the less optimistic cost evaluations at 2013 provided by FCHJU for PtP systems based on NaS, V-Flow and Lead batteries (238-379 €/MWh_{el}) [1]. The options that involve SOC cells have the highest LCoEs due to the very high investment cost for SOC technology today and to the atmospheric operation that impose an expensive compression for hydrogen storage. The LCoEs evaluated for SOC-based PtP options are even higher than the today's less optimistic cost evaluations for Li-ion batteries (573-754 €/MWh_{el}) [1].

The 2030 scenario shows sensibly lower LCoEs. In particular, the PtP systems based on reversible PEM and SOC achieve very low LCoEs (respectively 56 and 78 €/MWh_{el}). These costs are competitive also with the optimistic FCHJU projections at 2030 for energy-intensive applications with CAES and batteries (37-76 €/MWh_{el}), with the exception of PHES that still achieves the lowest LCoE (24 €/MWh_{el}). The strong reduction of investment costs and the projected SOC capability of working under pressure are the drivers of the LCoE reduction for R-SOC based PtP systems.

3.2. Mobility and Grid injection

The fuel cost of hydrogen for mobility and grid injection applications is presented in Table 3 for both scenarios. The hydrogen produced for grid injection has the lowest costs in all the scenarios and for all the electrolysis technologies, due to the lower investment cost for the grid injection system with respect to the vehicle refueling option that requires higher pressures and consequently costlier equipments.

In the today's scenario (2013) the hydrogen produced by alkaline electrolysis achieves the lowest cost (5.0 €/kg H₂), which nearly complies the competitive target cost of 4 US\$/kg of H₂ [20]. It is worth noting that the on-site hydrogen refueling has been considered in the analysis performed, while supplying the hydrogen to fueling stations distributed on the national territory through road transport or by dedicated pipelines will add the cost of hydrogen transport from the generation facility to the refueling station.

Table 3. RES-produced hydrogen cost for mobility and grid injection: 2013 and 2030 scenarios.

| Hydrogen cost €/kg H ₂ (€/kWh) | | 2013 scenario | | 2030 scenario | |
|----------------------------------------------|----------|---------------|----------------|---------------|----------------|
| | | Mobility | Grid Injection | Mobility | Grid Injection |
| Electrolysis | Alkaline | 5.0 (0.15) | 3.8 (0.11) | 2.3 (0.07) | 1.2 (0.04) |
| | PEM | 9.6 (0.29) | 8.1 (0.24) | 2.0 (0.06) | 1.0 (0.03) |
| | SOEC | 16.8 (0.50) | 14.9 (0.45) | 2.3 (0.07) | 1.2 (0.04) |

In the future scenario (2030) the cost of hydrogen will be very similar for all the technological options, with a very strong cost reduction (90%) for the SOEC-based option. Cost values of 2.0-2.3 €/kg for mobility and 1.0-1.2 €/kg for grid injection are evaluated. It is worth noting that the transportation of hydrogen in the existing natural gas infrastructure entails several issues which could be sources of additional costs. The main ones are gas leakage and higher energy consumption for pipeline delivery through compression with respect to methane – due to the lower density of hydrogen – and also lower durability of pipeline materials exposed to hydrogen [21]. The estimation of additional transport costs depends on hydrogen fraction and grid architecture, and was not included in this work.

3.3. Impact of hydrogen-based PtG on the Italian energy system

The impact of the PtG options analyzed in the present Italian electricity and mobility sectors has been assessed. The total V-RES power capacity (i.e., solar and wind) installed in Italy at 2015 is 28 GW [18]. Assuming that V-RES capacity is doubled and all the new installed power is connected to hydrogen-based PtP systems in order to avoid congestion of the electricity network, we calculated the fraction of the fossil electricity (217 TWh in 2013 [19]) that the new RES will substitute; results are shown in Table 4 for all the electrochemical technologies assessed in this work. The best PtP option is that based on SOEC and alkaline fuel cells, which can lead to the highest RES integration – 22.8 TWh, corresponding to 10% of fossil electricity substituted – with 46% of round-trip efficiency.

Table 4. Fraction of fossil electricity substituted by V-RES integrated through H₂-based PtP.

| Share of fossil electricity substituted by V-RES | | Fuel Cell | | |
|-----------------------------------------------------|----------|-----------|------|------|
| | | Alkaline | PEM | SOFC |
| Electrolysis | Alkaline | 8.2% | 7.7% | 6.9% |
| | PEM | 7.3% | 6.8% | 6.1% |
| | SOEC | 10.5% | 9.8% | 8.7% |

Looking at the transportation sector, 245 TWh of fossil fuels (gasoline and diesel) were consumed in Italy during 2013 [19]. The calculated V-RES capacity that is required to produce the equivalent hydrogen is 252 GW for PtG based on alkaline electrolysis, 280 GW for PEM-based PtG and 182 GW for SOEC-based PtG, with an assumed capacity factor of 20% for the RES. This means that a full conversion of the transport sector to hydrogen mobility will require the installation of at least 6.5 times of the actual V-RES capacity, if the most efficient electrolysis option (SOEC) is considered for H₂ production.

4. Conclusions

The work investigated Power-to-Gas options for variable RES storage into hydrogen through low-temperature (alkaline and PEM) and high-temperature (SOEC) water electrolysis technologies. A techno-economic assessment was performed for three different applications of the RES-produced hydrogen: injection in the natural gas (NG) grid, re-electrification (PtP) and on-site vehicle fuelling for mobility. The LCoE of stored energy has been estimated for the three applications in two scenarios, one based on the state-of-the-art technologies for water electrolysis and fuel cells in 2013, and the other based on costs projection from FCHJU for electrolyzers and fuel cells at the year 2030.

The results show that in the 2013 scenario, the Power-to-Power system based on alkaline electrolysis and PEM fuel cells represent the most cost-effective solution, which can compete with EES systems based on batteries (i.e., NaS, V-Flow and Lead batteries) achieving an LCoE of 332 €/MWh_{el} for the stored electricity. This cost is far higher than that of large-scale electricity storage systems based on CAES and PHES, and incentives are needed to promote the introduction of hydrogen-based EES on large-scale. In the mobility sector, the today's scenario (2013) shows a cost of 5.0 €/kg for the hydrogen produced by alkaline electrolysis, which is already nearly competitive on the market if vehicle refueling is performed on-site (i.e., where hydrogen is generated). Hydrogen injection in the NG grid presents lower costs in all the scenarios with respect to vehicle refueling, due to the lower investment cost of the grid injection system that requires lower pressures and consequently cheaper equipments.

The 2030 scenario shows sensibly lower LCoEs, in particular for PtP systems based on reversible PEM and SOC technology (respectively 56 and 78 €/MWh_{el}). Their cost values are competitive also with the optimistic FCHJU projections at 2030 for energy-intensive applications with CAES and batteries (37-76 €/MWh_{el}), with the exception of PHES that still achieves the lower LCoE (24 €/MWh_{el}). In the 2030 scenario, the cost of hydrogen for mobility and grid injection will be very similar for all the technological options, with a very strong cost reduction (90%) for the SOEC-based option. Cost values of 2.0-2.3 €/kg for mobility and 1.0-1.2 €/kg for grid injection were calculated.

The impact of hydrogen-based PtP on the actual Italian electricity sector was also assessed. The best PtP option for RES integration is based on SOEC electrolysis and alkaline fuel cells that achieves 46% of round-trip efficiency.

References

- [1] Fuel Cell and Hydrogen Joint Undertaking (FCH-JU). Commercialisation of energy storage in Europe. Final Report, 2015.
- [2] M. Kintner-Meyer, P. Balducci, W. Colella, M. Elizondo, C. Jin, T. Nguyen, V. Viswanathan, and Y. Zhang. National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase 1, WECC. Pacific Northwest National Laboratory: Richland, WA, 2012.
- [3] G. Gahleitner. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *Int. J. Hydrogen Energy* 2013; 38(5): 2039–2061.
- [4] D. Ferrero, A. Lanzini, P. Leone, and M. Santarelli. Reversible operation of solid oxide cells under electrolysis and fuel cell modes: Experimental study and model validation. *Chem. Eng. J.* 2015; 274:143–155.
- [5] S. H. Jensen, C. Graves, M. Mogensen, C. Wendel, R. Braun, G. Hughes, Z. Gao, and S. a. Barnett. Large-scale electricity storage utilizing reversible solid oxide cells combined with underground storage of CO₂ and CH₄. *Energy Environ. Sci.* 2015; 8:2471–2479.
- [6] Graves, C., Ebbesen, S. D., Jensen, S. H., Simonsen, S. B., and Mogensen, M. B. Eliminating degradation in solid oxide electrochemical cells by reversible operation. *Nature materials* 2015; 14(2):239-244.
- [7] G. Saur and T. Ramsden. Wind Electrolysis: Hydrogen Cost Optimization. Contract 303, 2011.
- [8] Fuel Cell and Hydrogen Joint Undertaking (FCH-JU). Multi - Annual Work Plan 2014 - 2020. [Online]. Available: http://ec.europa.eu/research/participants/data/ref/h2020/other/legal/jtis/fch-multi-workplan_en.pdf. [Accessed: 12-Jun-2016].
- [9] O'Brien, J. E., Zhang, X., Housley, G. K., DeWall, K., Moore-McAteer, L., and Tao, G. High temperature electrolysis pressurized experiment design, operation, and results. Report for US Department of Energy Office of Nuclear Energy Under Contract DE-AC07-05ID14517, 2012.
- [10] Giglio, E., Lanzini, A., Santarelli, M. and Leone, P. Synthetic natural gas via integrated high-temperature electrolysis and methanation: Part I—Energy performance. *Journal of Energy Storage* 2015; 1:22-37.
- [11] Parks, G., Boyd, R., Cornish, J., and Remick, R. Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration. No. NREL/BK-6A10-58564. National Renewable Energy Laboratory (NREL), Golden, CO., 2014.
- [12] Turton, R., Bailie, R.C., Whiting, W.B., and Shaeiwitz, J.A. Analysis, synthesis and design of chemical processes. Pearson Education, 2008.
- [13] Schiller, H. Demonstration of 500 kWe alkaline fuel cell system with heat capture. [Online]. Available: [http://www.fch.europa.eu/sites/default/files/5-POWER-UP_update151111%20\(ID%202848023\)%20\(ID%202848602\).pdf](http://www.fch.europa.eu/sites/default/files/5-POWER-UP_update151111%20(ID%202848023)%20(ID%202848602).pdf). [Accessed: 12-Jun-2016].
- [14] Technical datasheet. [Online]. Available: <http://www.sunfire.de/en/products-technology/reversible-generator>. [Accessed: 12-Jun-2016].
- [15] Verhage, A. J. L., Erik Middelma, and A. J. G. Manders. Power generation with PEM fuel cells at a chlor-alkali plant. Seminar Advances in Dutch Hydrogen and Fuel Cell Research 2008, 22.
- [16] IEA. Wind annual report 2011. Available: http://www.wind.energy.gov/pdfs/iea_wind_2011_annual_report.pdf. [Accessed: 12-Jun-2016].
- [17] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2014. [Online]. Available: http://www.irena.org/documentdownloads/publications/irena_re_power_costs_2014_report.pdf. [Accessed: 12-Jun-2016].
- [18] GSE. Energia da fonti rinnovabili in Italia. Dati preliminari 2015. Available: <http://www.gse.it>. [Accessed: 12-Jun-2016].
- [19] IEA Statistics. Italy: Indicators for 2013. [Online]. Available: <http://www.iea.org/statistics/>. [Accessed: 12-Jun-2016].
- [20] AFDC. Average Retail Fuel Prices in the U.S. [Online]. Available: <http://www.afdc.energy.gov/fuels/prices.html>. [Accessed: 12-Jun-2016].
- [21] Melaina M.W., Antonia O., and Penev M. Blending hydrogen into natural gas pipeline networks: a review of key issues. *Contract*, 303, 275-300, 2013.