Alliance Nationale de Coordination de la Recherche pour l'Énergie

Decarbonization Wedges Exercise

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POWER-TO-HYDROGEN TECHNOLOGIES AND APPLICATIONS (HYDROGEN AND SYNGAS)

The rapid development of VRE[1] creates a context in which the adjustment of electricity supply and demand becomes a major issue. Increasing VRE capacities will more and more frequently lead to oversupply while satisfying demand will require significant backup capacities. Using electric oversupply to create a transportable energy vector —in the form of hydrogen or synthetic natural gas— thus appears to be a potential option for developing robust decarbonized electricity systems.

1. State of the art and current development

Power to H_2

This technology is based on water electrolysis that can be performed using different types of electrolyzers: alkaline technology, PEM and HTVE technology. Hydrogen production through methane reforming is broadly used in industry for chemical applications but it is not taken into account in the following analysis. The resulting hydrogen can in turn be used for GtP[2] (energy recovery), for direct injection of H_2 in gas networks (hythane) or methane production in methanation processes using captured CO_2 as a carbon source —for transportation etc.

Technology 1.1: Alkaline electrolysis
Electrolysis is a process which transforms water into H_2. Alkaline electrolysis involves a liquid electrolyte. Plants lifetime is highly sensitive to power flow variations and for the moment these systems are not suitable for connection to renewable energy sources.

Technology 1.2: PEM[3] electrolysis
PEM electrolysis does not involve a liquid electrolyte as protons migrate through the polymer electrolyte membrane. PEM produces high purity hydrogen.

Technology 1.3: High temperature vapor electrolysis (HTVE) or steam electrolysis
This technology involves transforming vapor into H_2: this releases oxygen ions, which close the circuit. HTVE reduces power consumption and increases efficiency. The process is reversible as the same device can be used for electrolysis (with SOEC[4]) or power production (SOFC[5]).

Technology 1.4: Power to syngas through co-electrolysis
The co-electrolysis of CO_2/H_2O at high temperature produces syngas —a mixture of H_2 and CO— which can be used for chemicals, synthetic diesel, methanol, etc. It is based on SOEC technology and can produce both electricity and thermal energy through cogeneration. If the temperature is above 650°C, co-electrolysis can produce a small mole fraction of methane.

H_2 to applications

Once Hydrogen produced from VRE, its uses and applications are very large, hydrogen is a flexible energy carrier? Different possible pathways are:

- Hydrogen to Mobility: hydrogen transported and distributed to hydrogen refueling stations to refuel fuel cell vehicles

[1] VRE: Variable Renewable Energy
[2] GtP: Gas to Power
[3] PEM: Proton Exchange Membrane
[4] SOEC: Solid Oxide Electrolyzer Cell
[5] SOFC: Solid Oxide Fuel Cell

- Hydrogen to Power: to refurnish electricity to the grid through a fuel cell or a gas turbine; PEMFC or SOFC technologies will be used. In some cases Hydrogen will be transported and used directly in a decentralized or residential fuel cells for electricity supply or CHP applications.
- Hydrogen to Gas: hydrogen is injected directly to the natural gas grid(with a limit due to material compatibility) or use of Hythane for mobility
- Hydrogen to Industry: use “green hydrogen” or low carbon hydrogen for the needs of industry: heavy industry, refineries or petrochemical industry, synfuels or biofuels(final use mobility) etc…

Technology 2.1: PEMFC (PEM Fuel Cells) for stationary applications
This technology uses the reverse process of PEM. PEMFC uses temperatures below 100°C. This technology has several possible applications —e.g. transports, APU[6], mobile and stationary applications, backup power.

Technology 2.2: SOFC for stationary applications
This technology uses the reverse process of HTVE. Solid Oxide Fuel Cells have many advantages: high efficiency and, thanks to its high operating temperature —600-900°C—, fuel flexibility.

H_2 to syngas

Hydrogen can also be used to produce synthetic methane. Methanation gives more flexibility to the “power to H_2” stage and it enables CO_2 recycling and recovery

Technology 3.1: Catalytic methanation
Methane production using catalytic reaction (CO_2,H_2 -> CH_4,H_2O) is already developed. The usual conditions include a temperature from 250 to 550°C and a pressure from 10 to 50 bar. This technology requires high CO_2 purity and induces low flexibility.

Technology 3.2: Biological methanation
Biological methanation also involves producing methane but contrary to catalytic methanation, biological methanation involves microorganisms. Biological methanation is at the research or pilot stage. It operates at low temperature —40 to 60°C— with a pressure from 1 to 20 bar. Biological methanation is more flexible than catalytic reaction —thanks to fast start-stop operations— and high tolerance to impurities.

2. Maturity level and technological perspectives

The main criterion for large development is the cost of H_2 production and thus the cost of the electricity involved.

In the early stages of development other dimensions than mere economic assessment should be considered. These conditions include environmental co-benefits, power delivery security, energy system flexibility, new industries and systems development, etc.

Maturity of Power-to-Gas technologies (hydrogen and syngas)

Methodological information:

The maturity level is the TRL, reduced to 5 levels with market deployment enclosed in the higher TRL classes; maturity level scaling: 0 = none; 1 = fundamental research; 2 = R&D; 3 = demonstrator; 4 = low deployment; 5 = large deployment.

	2015	2020	2030	2040	2050
Alkaline electrolysis	4	4-5	5	5	5
PEM electrolysis	3	3-4	4	5	5
HTVE	2	3-4	4	5	5
Co-electrolysis	2	3-4	4	5	5
PEMFC stationnary	5	5	5	5	5
SOFC	3	3	4	5	5
Catalytic methanation	2-3	2-3	3	4-5	5
Biological methanation	4	4-5	5	5	5

For alkaline electrolysis, the behavior in transient regime must be improved. PEM is under progress, like almost all other PtG[7] technologies: indeed they will only reach maturity by 2030-2040.

Potential development of Power-to-Gas technologies (hydrogen and syngas)

Methodological information:

Potential development is measured as the percentage of the technology's contribution to environmental protection. This means evaluating, in terms of carbon emissions and of carbon emissions reduction, to what extent this new technology can contribute to limiting temperature increase to 2°C above pre-industrial level according to the time horizon considered in this study. Potential development scaling: 0 = not significant; 1 = significant (i.e. more than 1% of global emissions reduction) in some countries; 2 = significant on the global scale; 3 = very significant on the global scale (i.e. up to 3% of global emissions reduction); 4 = major technology vs. climate change (i.e. more than 3% of global emissions reduction).

	2020	2030	2040	2050
Electrolysis	0	1	3	4
Fuel cells stationnary	0	1	2	3
Methanation	0	0	1	2

3. Technological, economic and social bottlenecks

Methodological information:

The following table ranks the bottlenecks according to their impact on the development of the technology. A bottleneck ranking at 6 on the scale will hinder or stall the deployment of the technology compared with bottlenecks ranking at 1; conversely, a bottleneck ranking at 1 will hinder the deployment of the technology much less than bottlenecks ranking at 6. Note that the ranking is relative, meaning that a bottleneck ranking at 6 is not necessarily hard to remove; conversely, a bottleneck ranking at 1 is not necessarily easy to remove. Technologies rank according to: research, finance, regulations, resources & environment, security and acceptability. The table also contains keywords associated with each bottleneck.

Technology		Research & technological bottlenecks	Economy and Financial bottlenecks (investment, risks)	Regulation & institutional environment	Resources & environmental impacts (including scarcity of raw materials, water, land, climate)	Safety & security (impacts on health, people and security assets)	Socio-technical feasibility
PtHydrogen (electrolysis)	Rank	6	5	4	2	3	1
	Key-words	Power-Efficiency-Lifetime	Industrialization Scaling up CAPEX reduction - business models	Rules – authorization processes / implementation agreement	Materials recycling - Life cycle assessment	Explosive nature of Hydrogen	Public acceptance
H_2 to power (Stationnary fuel cells)	Rank	5	6	2	3	4	1
	Key-words	Power-Efficiency-Lifetime	CAPEX reduction - business models	Rules – authorization processes / implementation agreement	Scarce material (Platinum) Materials recycling - Life cycle assessment	Explosive nature of Hydrogen	Public acceptance
H_2 to syngas (methanation)	Rank	5	6	2	3	4	1
	Key-words	Power-Efficiency-Lifetime	CAPEX reduction - business models	Rules – authorization processes / implementation agreement	Materials recycling - Life cycle assessment	Explosive nature of hydrogen	Public acceptance

Hydrogen has weak points, such as overall efficiency, business models —high CAPEX—, current regulations and safety considerations. Reducing upfront costs and CAPEX while increasing the system size, the efficiency and the lifetime of systems are the main current challenges.

There are still many technological bottlenecks to overcome, among which material efficiency, system design, manufacturing process, ability to perform dynamic operations.

[7] PtGH: Power to Hydrogen

The development of the technology depends on crosscutting activities —for example: H_2 storage and distribution (refueling stations) at small and large scale, safety, testing procedures, recycling (and life cycling analysis) and rules (authorization processes/implementation agreement, etc.).

Potential radical and incremental innovations

Methodological information:

The following table lists the nature of innovations needed to overcome the bottlenecks mentioned earlier. There are two types of innovations: I stands for 'incremental innovation' (i.e. improving existing products and processes) and R stands for 'radical innovation' (i.e. developing new products and processes).

Technology		**Research & technological innovations**	**Economy and Financial innovations** (investment, risk)	**Regulation & institutional environment**	**Resources & environmental impacts** (including scarcity of raw materials, water, land, climate)	**Safety & security** (impacts on health, people and security assets)	**Socio-technical feasibility**
PtG	I or R	I and R	R	R	I	I	I
	Key-words	Need for research and demonstrators	Long term investment Long term ROI	Different for each country			
Stationnary	I or R	R	I	R	I	I	I
	Key-words			Different for each country			
H_2 to syngas	I or R	R	I	R	I	I	I
	Key-words			Different for each country			

Overcoming the bottlenecks mentioned in the table above may be achieved through:

Demonstration projects: they will be needed until 2020 or 2025 to prove the cost-effectiveness of these technologies and to test the business models;

Basic research activities: they are absolutely necessary to obtain innovations, either radical or incremental. Supports and funding of research depend on states policy and on existing industries.