Electricity Storage, Reality and Perspectives: Feasible at Small and Medium Scales, Out of Reach at Large Scale

Summary and Conclusions

This document comprises three parts, each with increasing levels of technical content:

1/ This summary which contains the main conclusions of the study,

2/ The main body providing a global synthetic view of the main general issues associated with electricity storage. It identifies the physical and economic factors governing the efficiency and average costs of storage. Diverse technologies, either available or considered for the future, are put in perspective of the needs for storage, for different levels of quantities and time frames,

3/ More technically oriented appendixes that analyze and evaluate the technical and economic potential of storage technologies under development or being considered, but not yet mature.

The main conclusions are as follows: electricity storage covers a wide range of extremely diverse situations, in terms of the scale of the needs, of the technologies able to cope with the needs, and of the level of maturity, as well as the physical and economic performance of these technologies. It is therefore impossible to conclude in general terms. For increasing storage needs:

- Electricity storage in small/medium quantities and for very short time periods (typically daily storage capacities for domestic and tertiary uses) is already operational, even if progress is still possible. Electrochemical batteries appear increasingly as the reference technology for such applications, and active research should generate new solutions in addition to providing improvements to existing ones.

- Electricity storage for medium/large quantities and for short to medium time periods (typically for some hours to a few days for partial balancing needs of electricity grids) is also operational and effective. PHES (Pumped Hydroelectric Energy Storage) plants, are efficient and have been used during decades, they are the reference technology for higher capacities. But they require that good site conditions be available. For medium power levels, high capacity batteries are beginning to be used in some cases, due to their performance and the reduction of their cost, and because they do not require specific site conditions.

- But for massive electricity storage over long periods (typically inter-seasonal storage), there are presently no technically and economically viable solutions. Such storage is nevertheless necessary in the event of large penetration of intermittent wind and solar (PV) power, to compensate for their vanishing production over long time periods (in cases when there is no sun or wind for several consecutive days during winter anticyclonic conditions). Energy needs are indeed so important in such conditions that they cannot be fulfilled by any existing or considered storage solution today. Here are the reasons:

-- The total capacity of the existing PHES stations in continental France is not sufficient: it would be necessary to multiply this capacity by 18 to be able to store the energy needed for one day of electricity consumption during a single cold winter day. This is impossible… simply noting that their potential for capacity extension is below 20% due to site conditions.

-- Storage of compressed air in very large underground cavities does not bring the solution: besides the fact that this technology is not as mature as the pumping stations and has a lower efficiency, the capacities of underground sites would have to be tremendous: again to store the equivalent of the electricity consumption for one winter cold day, the volume of suitable cavities would be 6 times bigger than what is used today in continental France to store natural gas.

-- The inability of these two technologies to ensure mass storage for long periods is the consequence of laws of physics: indeed, the hydraulic energy of a water fall and the mechanical pressure energy both have low volumetric concentrations. These need then to be compensated by very high volumes, practically impossible to achieve. This is a physical limitation, and technological progress will not improve this fact.

-- The only solution allowing massive inter-seasonal storage is chemical storage, using the power to gas to power conversion to produce combustible gases such as hydrogen or synthetic methane. Hydrogen is produced by electrolysis of water using intermittent renewable sources; and methanation continues the process by combining hydrogen with carbon dioxide. Physics here shows that 260 times more electricity can be produced from one cubic meter of methane at 70 bars than from one cubic meter of air at the same pressure. And for hydrogen the ratio is 70 times. These values of energy densities are of the same order of magnitude as for fossil fuels.

Unfortunately these storage techniques are handicapped by a major problem: their physical and chemical transformation chains are long and complex, leading to important energy losses and very low global efficiencies when closing the loop from grid to grid. Typically, these are of the order of 30% today for hydrogen and 20% for methane. And so it means that to retrieve 1kWh of electricity at the end, one needs to input 3 kWh with the hydrogen route and 5 with the methane route.

Such very low efficiencies have other consequences: they require large electrolysis facilities designed for flow rates 3 to 5 times bigger than one would expect per usable kWh of electricity at the end. In addition, these facilities cannot operate longer than their intermittent renewable sources of electricity, 3000 hrs/year equivalent at full power, or less than 900 hrs/year if only the non-usable fraction of electricity produced by these sources is used for storage. As a result, the CAPEX of such facilities is extremely high.

To summarize, the economics of such storage techniques is impacted by various unfavourable factors, leading to a cost of final electricity to the consumer which would be 5 to 10 times higher than the actual market prices. This renders the development of such technologies economically not viable today. This even without considering the additional costs for the electricity system: it is indeed necessary to produce upstream a vast amount of electricity just to compensate for the losses during the energy conversions. This then implies important additional investment costs, important territorial footprints, etc. Except if one only focuses on using the otherwise non-usable fraction of the electricity produced by the intermittent REL, but then the storage capacities would be very limited.

Are there ways to improve? Two improvements need to be combined, beyond a reduction of the cost of the electricity used for the storage:

- Increase the efficiency. But even considering progress in R&D and technology, global efficiency factors would be limited to around 43% for hydrogen and 36% for methane (justification in Appendix 3). Which is still low.
- Reduce the investment costs. Compared to the present situation, they should be reduced by a factor 3 to 4 to ensure that the electricity from the storage could be bought on the market, when the prices would be high anyway.

In conclusion, the only possible way to get mass storage of electricity, including for inter-seasonal periods, is not economically viable today, but the necessary progress to make it viable would be extremely difficult to implement. Which makes this solution highly improbable. And so the inter-seasonal mass storage of electricity is impossible today and will probably be so for a long time. As a consequence it is impossible to do without stock energies: nuclear or natural gas.

Note that these considerations about Power to gas to power are valid for all countries in the temperate zone, whose seasons are very marked. On the other hand, the countries of the Inter-tropical zone (and a little beyond), which enjoy poorly marked seasons and strong sunshine all year round, mainly need daily storage of solar energy. This greatly reduces the quantities to be stored and eliminates the need for inter-seasonal storage. Smaller storage solutions can then be used, changing the problem completely.

Note on the power and energy units used in this document

In order to make reading more comfortable, all the units used here are adapted to the orders of magnitude concerned thus eliminating large numbers. All the units are multiples of the kW for power and of the kWh for energy.

Power units used:
kW; **MW** (1 MW = 1 000 kW); **GW** (1 GW = 1 000 MW); **TW** (1 TW = 1 000 GW)

Energy units used:
kWh; **MWh** (1 MWh = 1 000 kWh); **GWh** (1 GWh = 1 000 MWh); **TWh** (1 TWh = 1 000 GWh)

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1 - Why Store Electricity?

The growing need for electricity storage is a direct consequence of the emergence of intermittent renewable electricity generators, namely wind turbines and photo-voltaic (PV) panels. Indeed, it is the only way in which a **random and intermittent production** can be made to match **instantaneous consumption needs, the two being largely uncorrelated**.

Massive storage is, moreover, **vital** to face up to meteorological episodes during which wind and/or sun insolation can be about nonexistent **during several consecutive days** (up to ten consecutive days for wind observed in Germany during the 2016/2017 winter). As stocks cannot be rebuilt during such episodes, mass storage must, in addition, be **INTER-SEASONAL**, the more so that solar PV yields 4 times less in the winter, when it is most needed, than in the summer.

Moreover, electricity storage makes environmental sense only if it mitigates **CO_2 emissions from fossil fueled backup production means**.

2- Some Physical Reminders to Shed Light on what Follows...

The expression "**electricity storage**" is a language shortcut that reflects reality imperfectly. Indeed, **electricity *per se*** (i.e. putting electrons in motion in a conductor) **can be stored only at a small**

scale in capacitors, those with the largest storage capacities being called **supercapacitors** their storage capacity still remaining **quite modest** (a few ten kWh at most).

In **all other cases**, the **electricity has to be transformed to another form of energy** which can then be **stored in much larger quantities**, to be subsequently **transformed back to electricity** when the need arises. However, any transformation, whether physical, chemical, electro-chemical, etc. from one form of energy to another **entails energy losses**, generally as heat. These successive transformations, then, always translate into an efficiency that is less than one. This is a crucial issue since a **1 kWh electricity "storage" will yield less than 1 kWh: today between 0.9 kWh at best and hardly 0.2 kWh** (see below), depending on the nature of the energy conversions involved.

It is easy to understand, then, that the **charge-discharge cycle efficiency** is a major determining factor of the cost of **discharged electricity**. The other factors are the amortization of **investments made in the creation of the charge-discharge** installations and **their use ratio** (or **load factor**).

Thus, the characteristics of an "**ideal**" storage system can be determined. It should combine

- **High efficiency**
- Low **investment and operating cost,** along with a **long-life time**.
- Small **environmental** impact, from construction, through operation, to dismantling: no GHG or other polluting agent emissions; limited use of natural space; limited nuisance to the surroundings (noise, eyesore, etc..); no landscape destruction; no competition with other economic activities, etc.
- For **massive storage**, in particular **inter-seasonal** storage, a sufficiently **large energy density** so as to limit the volumes required, an issue that **conditions large scale storage deployment**.
- For **mobile** applications and, to a lesser degree for **domestic** applications, a small weight and/or volume and consequently, a **large per unit mass and/or per unit volume energy density** but at **small scales**.

Are storage technologies available today that satisfy all these criteria? A negative answer to this question will not be a surprise. Well, chances are that it will remain negative as the constraint is determined by the fundamental laws of science whose limits cannot be overcome: science is not all powerful... We must, then be content with the best solutions and the optimal compromises (depending on circumstances) between the above parameters and an additional but essential constraint: the scale of the storage needs which can vary considerably with the requirements. This leads to very different technological solutions able to fulfill these requirements.

3 - The Required Storage Scale, a Crucial Issue

The simplest approach to this question is through **real life examples** and a survey of the technologies available or considered capable of fulfilling the requirements. A few examples can be mentioned:

- **Storage capacity to cover the needs of an average day's consumption of specific electricity for a medium sized household.**

A household's average **specific electricity** consumption (the consumption dedicated to uses that cannot be satisfied by any other form of energy (lighting, household appliances, audiovisual devices, computers, etc..., excluding heating devices, then) is presently on the order of 2,400 kWh/year or 6.6 kWh/day.

If one day's consumption is to be stored with a battery whose charge-discharge cycle efficiency (including from-grid/back-to-grid conversion electronics) is on the order of 85%, the battery's **operational** capacity has to be at least 6.6/0.85 ≈ 8 kWh rounded value. For 2 days, this capacity has to be doubled, and so on.

Note: For comparison, and to give a ballpark idea, the most recent mid-range electric cars are equipped with 40 kWh to 50 kWh batteries giving an autonomy range of 250 km to 350 km depending on the traffic and the ambient temperature. The batteries in top-range much more expensive models have capacities which can be twice that.

- **Storage capacity required for an isolated grid in the DOM (Département d'Outre Mer) islands.**

If we take **Martinique and Guadeloupe** as our examples, their average daily consumption is about 4 and 5 GWh/day respectively. Can such quantities be stored? The two industrially mature technologies are **PHES (Pumped Hydroelectric Energy Storage)** the only large scale storage technology available today, and **batteries**:

- PHES storage would be at the appropriate scale (mainland France boasts PHES plants of the right size). However, the geographical layout of either island does not allow in any way the creation of the high level reservoir required, using the ocean as the low level reservoir. The impossibility here lies in the **lack of suitable physical space** and in the fact that **hydraulic energy density is poor**: **4 metric tons of water falling 100 meters** (large height difference for a seaside installation) will yield **1 kWh**, the efficiency of the hydraulic turbine included. Moreover, considering the risks of seepage, storing salt water at an altitude can, in the event of leaks, pollute the water tables and cause major damage to the natural drinkable water system of these small territories.

- Storage in **Lithium-Ion batteries** (today, the ones with the best performance) is possible in theory but it would be very expensive! At their current cost (≈ 200 €/kWh minimum for very large industry-grade batteries, cf. Appendix 1) and considering a 0.85 global charge-discharge cycle efficiency, the dimension required would lead to an investment on the order of **1 billion €** (0.95 bil € and 1.2 bil € respectively in rounded numbers).

Thus, even starting from these very modest levels of consumption (roughly 300 times less than the average consumption in mainland France), physical and economic limits are encountered. And that, to store the average demand of just one day.

- **Storage capacity need for the national (mainland France) grid.**

The scale, here, changes completely, the more so that France being in a temperate climate zone, winter demand is much larger than the mean demand (as opposed to the islands mentioned above where the demand changes little over the year). It is the **winter demand**, then, that d**etermines the storage capacity required**. On a cold winter day, a demand amounting to **1,800 GWh/day** is not exceptional. This is **400 fold** the average daily demand of the islands we discussed. Can such a large amount of energy be stored? Here again, the storage solutions currently available give an idea of the size of the difficulty.

- The total capacity of the **6 PHES installations** that mainland France enjoys, although their power/capacities per unit storage are very substantial, can store, at best, roughly **100 GWh**. This is equivalent to ... the demand for **1 hour 20 minutes** on a very cold winter day! Thus, the current PHES capacity would have to be multiplied by at least 18. This is physically out of reach, practically all the suitable geographical sites being already occupied (at most, only a 20% increase would be possible, or **20 GWh**: not anywhere near the scale at issue!).

- Resorting to **batteries** is no more realistic. Indeed, 1,800 GWh worth of Lithium-Ion batteries would cost a trifle ... **360 billion €** with current prices. All this, for a **10 year** life span and subsequent replacement. Even **supposing** (according to current projections which are grounded on extrapolations with no guarantee, see Appendix 1) that the price of these batteries will effectively **be divided by 4** (down to 50 €/kWh) by 2030, the bill would still reach **90 bil €**! Not to mention the limited resources for Lithium and other rare metals used to manufacture these batteries, nor the problematic handling of their wastes.

The **limits** are both **physical** and **economic**. All this to fulfill the storage requirements... to meet the demand for **one single cold winter day**! This being, in any case, very **insufficient insofar as both wind and sun can be practically lacking for over 5 to 7 consecutive days and even more**!

However, **partial charge-discharge cycles**, **limited** both in **<u>quantity and in duration</u>**, are realistic for the **mainland grid**. A frequent occurrence is the feed-in of discharge energy to cover the demand peaks, otherwise covered at high cost by dedicated peak demand power plants whose production costs are very high.

For example, the existing PHES plants, provided their high altitude reservoirs are sufficiently filled, can provide up to 5 GW instantaneous power during the 7:00 PM demand peak, between 6:00 PM and 8:00 PM while discharging only about 7 to 8 GWh. Similarly, the batteries of a large fleet of electric vehicles could be used for the same purpose, after having been charged during the day at their owner's work site. But this will concern limited amounts of energy and time, with a discharge over short time spans of a few hours, the vehicle batteries having to be fully charged for use the next morning.

In short, the **mass storage issue**, at the **single day scale** and *a fortiori* the **multi-day scale remains unresolved**. Are there **other solutions, whether identified or envisioned,** that could potentially meet the need? This is discussed in the next paragraph, after a brief overview of possible storage technologies.

<u>4 - Overview of the Main Storage Solutions Identified or Envisioned.</u>

- **Overview of the storage possibilities, arranged according to increasing capacity**

<u>* Small storage capacities</u> (a few kWh to several ten kWh, extending to a few hundred kWh)

This category includes:

- **Supercapacitors,** up to a few ten kWh for very specific applications requiring extremely large instantaneous discharge power. For example, fast charge for urban electricity-powered buses, receiving a partial recharge in less than a minute at each bus stop.

- **Flywheels**, limited to a few ten kWh in general because they accumulate small amounts of energy despite their large mass and high rotation speed. Multiple machines allow higher capacities but their economic competitiveness is increasingly confronted to that of electrochemical batteries.

- **Electrochemical batteries**, easily adaptable to various capacities, they have progressed a great deal (and continue to do so) in terms of their capacity to cost ratio. As a consequence, they are the most frequently used storage device within this capacity range.

<u>* Medium scale storage capacities</u> (several hundred kWh to a few MWh).

This category includes essentially:

- Again, **electrochemical batteries,** whose increasingly competitive cost, supported by a very dynamic R&D, allows to consider them a viable economic model in this capacity range.

- **Compressed air storage** in ground reservoirs, still poorly developed because it is limited in capacity and costly.

- Small or medium sized **PHES**, a well proven industry-grade solution that represents a competitive economic model.

* **<u>Large scale and very large scale storage capacities</u>** (a few GWh to several ten or hundred GWh, extending to several TWh).

This is an **altogether different domain,** in terms of **physical limits for the larger capacities** (mass storage) and in terms of **new potential applications** such as **inter-seasonal storage** which is inaccessible to the preceding categories.

This category includes:

- **Large PHES** with both **large instantaneous power and large capacity** as mentioned above but their capacity is very **far from being sufficient for mass inter-seasonal storage** (see above).

- Very large volume **compressed air energy storage** in **underground cavities**.

- **Chemical storage** in the form of fuel gas, **hydrogen** or **synthetic natural gas (power to gas to power).**

These last two chemical storage solutions, at the stage of a few industry-grade installations (the first one) and of small size demonstrators (the second), are discussed in more depth in the next paragraphs. Indeed, some people deem them to be solutions for the future. What exactly are the facts?

- **Compressed Air Energy Storage - CAES**

Compressed air energy storage consists in compressing air with electricity during low demand periods (off-peak) and/or excess production episodes and storing this compressed air in very large underground cavities (because of volume and cost considerations), to later expand it in turbines and generate electricity when it is needed.

There are **three kinds of CAES technologies**, as detailed in Appendix 2. Very few plants using this technology have been built as of today and none exceeds the performance of a medium sized PHES in terms of instantaneous power, storage capacity and efficiency; the efficiency of the CAES type with the best performance (which is ... not yet built) does not exceed 70% compared to a PHES's 75% to 80%.

Taking things further in an attempt to draw an overall view of this **technology's potential**, a **comparison** with **existing underground natural gas storage facilities** shows that, to **store a single day's intensive winter demand**, the size of the necessary underground cavities would have to be about ... **6 times the volume** of the (already very large) natural gas storage cavities in which 3 months' worth of gas consumption can be stored. This is way beyond realistic thinking... and leaves the CAES technology in the category of **small to medium scale storage capacity**, insofar as it can be proved economically competitive compared to the other technologies available.

Here, we put our finger on the **physical limits** and on the fact that **the density of pressure mechanical energy** is small, much smaller than that of **chemical** energy; natural gas is capable of generating **400 times as much electrical energy as compressed air for the same storage volume**. That is the reason why **chemical energy** in the form of fuels is the **only energy** which allows, **physically, mass storage**, including **inter-seasonal** storage (see "Power to gas to power" below and Appendix 3).

- **Power to gas to power**

Energy storage in the form of synthetic natural gas is based on the production of hydrogen via water electrolysis, the electricity being produced mostly by **intermittent renewable sources**, i.e. the sources that are **not controllable** (with controllable production plants which can, by definition, adapt their production to the demand, the storage needs are much smaller and resorting to synthetic natural gas production is not useful). The hydrogen thus produced, but an energy vector, can then be used to different ends:

* Propulsion of zero emission vehicles, hydrogen fuel producing water as its only waste.

* Transitional storage for re-use in electricity production. This storage can take place within the existing natural gas transport and distribution network (up to a 6% concentration and, thanks to minor adaptations but hindsight is lacking, up to about 20% under the provision of additional analysis and complementary validations which remain to be done) or, otherwise, in dedicated storage facilities.

* Transformation to **synthetic natural gas** by combining it with CO_2. This is the **methanation** (or **hydrogenation**) process (not to be confused with **anaerobic digestion** which is the production of **bio-methane** through a **biological transformation** of plant or animal wastes). The methane thus obtained can then be injected in unlimited proportion directly in the natural gas network (itself containing 90 % or more methane) and used either as a fuel, or to produce electricity (leaks, however, must be avoided at all cost, the global warming potential of methane being much larger than that of CO_2).

In short, "**power to gas to power**" covers two different sets of transformations, the first steps of the process being the same.

Electricity → Hydrogen → Electricity (Hydrogen route)

Electricity → Hydrogen → Methane → Electricity (Methanation route)

The **methanation** technology is presented by some as **THE solution**. Indeed, it is graced with two undeniable major advantages: as just stated, the feasibility of direct storage in the existing gas distribution network, for several months if necessary (**inter-seasonal storage**), a real economic benefit; and, just as important, the prospect of reaching **industry-grade sizes** that would provide the **physical capacity** to meet the **mass storage** needs. But is that enough?

Unfortunately, however, these two technologies suffer from a **major drawback**: a **very poor global conversion efficiency**, which is, today, about **30% for the hydrogen route** and 2**0% for the methanation route, "from network to network**" (see Appendix 3). **In concrete terms, this means that for 1 kWh electricity retrieved, more than 3 have to be consumed in the hydrogen route, and 5 in the methanation route!**

Here again, we are confronted to the **physical limits** but also to the **limits of chemistry**, unlike the technologies base on **mechanical** transformations, whether hydraulic or pneumatic. The **efficiency** limits of the physical and chemical transformations involved in these technologies are due to both the main transformations with their limited efficiency and to the annex transformations whose individual efficiency may be very good but whose multiplicity weighs on the overall efficiency.

Add to that a circumstance specific to **chemical** or **physicochemical** transformations that is not so prevalent in **mechanical** transformations, whether hydraulic or pneumatic: **they deal poorly with the highly fluctuating transitional regimes** inherent to **intermittent electricity** generators, namely wind turbines and PV panels. Such fluctuations remove them from their **optimal efficiency operating range** and **increase** the global conversion efficiency losses This is true in particular of water **electrolysis**.

Additionally, this poor efficiency has a major economic impact for two reasons whose negative effects add up, because it imposes:

* **Oversized facilities** since the some **3 to 5 kWh of input electricity** required to retrieve **1 kWh of output electricity** have to be used **whenever they are available**; coming from non-controllable wind or PV generators, they are **fatal**.

* The **purchase of these 3 to 5 kWh of electricity input in order to sell 1 kWh only, whose sale price will have to cover the cost of the purchase**.

Given that wind and PV sources produce only during a small percentage of the time in terms of full capacity output equivalent (load factor about 23% for wind and 13% for PV) the same will hold for the installations, those doing the electrolysis in particular. As a consequence, their amortization will be harder to achieve, the more so that there is a risk that their life span will be shortened because of discontinuous operation. And this further increases the costs.

With present efficiencies, investment costs and purchase price of electricity produced by wind turbines (a minimum of about 70 €/MWh) and given the short operating times of the installations (< 3000 hours/year) the costs of the discharged electricity **lie roughly around**:

* ≈ **300 €/MWh** for the hydrogen route

* ≈ **500 €/MWh** for the methanation route

Note that even supposing that only the **intermittent electricity surplus,** therefore **cost free electricity**, is used, the global costs are about the same because, then, the installations **operate during even less time in the year**, (< 900 hours to set a value) so that the amortization costs rocket.

Needless to say that these costs are **exorbitant**: roughly **5 to 10 times above the mean spot market prices** which frequently ranged between **45 €/MWh and 60 €/MWh during the 2018 winter**. This means that there is **NO VIABLE ECONOMIC MODEL** at this time (and probably there will not be in the near future - see below) for this type of storage.

Add to this very negative assessment the **damaging systemic consequences** of very large energy losses in these systems: indeed, these have to be compensated by a**dditional upstream electricity production** amounting to, **for each discharged kWh**, 3 - 1 = **2kWh** for the hydrogen route and 5 - 1 = **4 kWh** for the methanation route. While the **cost** of this additional production is already included in the global costs quoted above, such is not the case for the **related systemic effects**: the **power production potential has to be increased**, entailing large **additional investment** costs for the public. Not to mention the negative impact of such installations on the environment, landscape, etc.

What are the improvement margins? They lie in a combination of an **efficiency improvement** and a **very significant reduction of the investment costs.** Based on the estimations quoted in Appendix 3:

* The **maximum efficiencies that can reasonably be hoped for are on the order of 43% for the hydrogen route and 36% for the methanation route**. It's an improvement over what we have now but still small.

* The current **investment cost of the installations** would, moreover, have to be **divided by 3 or even 4 for the cost of the discharged electricity to come near the market prices when they are high, in times of large demand. Is this realistic?**

In short, these estimations lead not only to the conclusion that, today, this type of storage is not viable as an economic model, but also show that the likelihood of reaching a viable economic model in the future is very uncertain, if electricity prices are to remain economically sustainable for the consumers, whether they be households or businesses. Meanwhile, it is IMPOSSIBLE TO DO WITHOUT STOCK ENERGIES: nuclear power whose operation does not emit CO_2, and/or natural gas which, even though it is the least CO_2 intensive fossil fuel per unit energy, would increase CO_2 emissions massively and is at any rate not a sustainable solution as it would be economically ruinous for France's commercial balance, natural gas being entirely imported.

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References

[1] LE STOCKAGE DE L'ÉLECTRICITE - Un défi pour la transition énergétique - Ouvrage collectif de 16 chercheurs d'EDF/R&D spécialistes du domaine; *Electricity Storage - A Challenge*

for the Energy Transition - Collective work by 16 researchers from EDF/R&D, experts in the domain.- Lavoisier, Juin 2017

[2] Pertes énergétiques du schéma « Power to gas + Gas to power » - Georges Sapy - Site de Sauvons Le Climat - Septembre 2015; *Energy Losses in the Power to Gas + Gas to Power Scheme* by Georges Sapy - Save the Climate internet site.

[3] Estimations de l'Institut Fraunhofer concernant les rendements globaux « électricité → hydrogène ou méthane → électricité »; *Estimations from the Fraunhofer Institute of the Global "Electricity → Hydrogen or Methane → Electricity" Efficiency* - Selon source V. Boulanger dans : Stockage d'électricité. Énergie et Climat n° 45 - 1er Mai 2012.

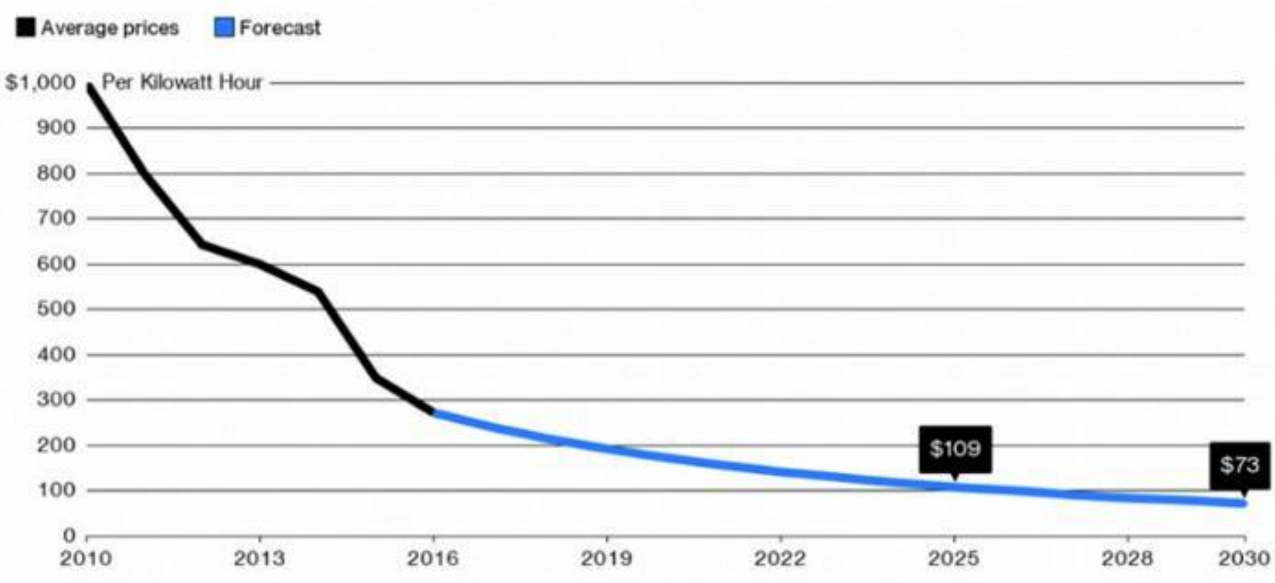
[4] Y a-t-il place pour l'hydrogène dans la transition énergétique ? *Does Hydrogen Have a Place in the Energy Transition?* Etienne Beeker - France Stratégie - Août 2014.

[5] Infrastructures gazières - Description générale; *Gas Network Infrastructures - General Description* - Commission de régulation de l'énergie (CRE).

[6] Panorama du stockage souterrain de l'énergie; *Overview of Underground Energy Storage* - Patrick de Laguérie - Ecole des Ponts / ParisTech - 25 novembre 2014.

[7] Le stockage massif de l'énergie; *Very Large Scale Energy Storage* – Panorama 2013 – IFP Energies nouvelles

Appendix 1: Estimated cost of Lithium-Ion batteries in $/kWh



(Source: Bloomberg New Energy - July 2017)

Cost estimations according to the above curve and comparison with other data sources:

* In 2017 (above curve): ≈ 230 $/kWh ≈ **200 €/kWh**

* End 2017, batteries delivered by Elon Musk for the Southern Australian grid (129 MWh for 30 M$) ≈ 233 $/kWh ≈ **200 €/kWh**

* In 2030 (above curve) 73 $/kWh ≈ **50 €/kWh**

Appendix 2: Compressed Air Energy Storage (CAES)

There are **three types of CAES technology**:

- **Gas CAES**

During expansion (which naturally produces cold), the air is reheated by gas combustion (the most frequent reheating mode, wherefore the name, gas CAES) in order to obtain more energy. **This is not a sustainable solution**, however, if **fossil gas is used** (using renewable gas obtained through anaerobic digestion {bio-methane} or through methanation {synthetic natural gas} is not necessarily the best way to use these gases which will be available in limited quantities).

Other variants of CAES, then, must be considered (see below) even though gas CAES is presently the most mature of the CAES technologies, the only one to this day that has been implemented in operational industrial facilities or has given rise to industrial-scale projects (see below the list of existing industrial installations and of projected plants). Note also that second generation gas CAES installations are being explored but their economic future seems uncertain.

In terms of their **instantaneous-power/energy-storage-capacity** performance, the size of existing or projected gas CAESs is comparable to that of **small to medium sized PHESs**. **They are thus in no way capable of large scale storage, even less of inter-seasonal storage**. As for their **efficiency**, it is at best on the order of 55%.

- **Adiabatic CAES**

The adiabatic system has about the same global structure, the difference being that **it does away with the heating fuel** and replaces it with **a heat storage system that holds the naturally produced compression heat** and **returns** it during the **expansion phase**, reheating the air fed into the turbines.

In terms of **performance**, **improved efficiency**, then, can be expected (up to about **65%** in theory) but no industrial-scale system of this type is in operation at this time. As for their **instantaneous-power/energy-storage-capacity,** installations equivalent to a large PHES can be envisaged. **But this still does not correspond to mass storage needs nor, *a fortiori*, to inter-seasonal storage: storing the heat generated during compression over several months would be very expensive**. Finally, it appears that R&D on this type of CAES is slackening due to uncertainties concerning their economic model.

- **Isothermal CAES**

Again, the system's global structure is about the same but, here, there is an attempt to **extract the heat during compression** (and not at the **end of the compression** as in adiabatic CAES) so as to r**educe the compression energy**, thus **increasing the efficiency**. Similarly, during expansion, the **air cooling is limited** thanks to heat transfer, from heat stored during compression or by heat exchange with the environment, **as the expansion progresses**.

In terms of **performance**, the expected **efficiency** is very high (better than that of adiabatic CAES, up to roughly **70%**) but the **capacity range considered for this kind of CAES is very much below that of gas or adiabatic CAES** (a few MW maximum for storage times of a few hours) because of technological considerations: it is difficult, in practice, to come near the theoretical isothermal evolution which implies **continuous evacuation of the heat** generated in the compressors, or **continuous heating of the air expanding** in the turbine. Studies for **small scale** solutions are ongoing but it seems it will prove difficult to extrapolate to large scale facilities, i.e. to large throughput. **Isothermal CAES, then, is no at all adapted to mass energy storage.**

- **Does the CAES Technology Offer a Potential for Extension to Mass Energy Storage?**

This question comes naturally to mind after this brief overview of the various types of CAES. Indeed, the **possibility of using large underground cavities** can lead to hopes that mass storage solutions can be found, despite the geological constraints and the potential scarcity of such cavities adapted to the need. But is this realistic?

An indirect method to get an idea of the possibilities is to refer to the **underground natural gas storage facilities in operation**. In France, there are currently about fifteen underground natural gas storage installations whose **total usable volume is 11.7 billion Nm^3** (normalized m^3 defined at: 0°C; 1 bar absolute) and whose **maximum** storage pressures (depending on the mechanical resistance and air tightness of the underground reservoirs) range from a little under 50 bars to 140 bars, with a number of them in the range 60 to 70 bars. With this global capacity, about **132 TWh natural gas** can be stored.

The **potential mechanical energy** that could be obtained from the **compression of 11.7 billion Nm^3 of air at a maximum pressure of 70 bars** (the typical pressure possibility of the average underground cavities) stored in cavities with the **same global volume** as the existing volume for natural gas, can be easily grossly approximated. The maximum energy writes as:

Wp = P * V * Ln P1/P2 with P1 = 1 bar and P2 = 70 bars

Working this out, we obtain Ln 70 ≈ 4.25: **W ≈ 1.38 TWh**

However, this **potential** energy is **not totally retrievable** for two reasons whose effects add up:

* **The storage cavity cannot be completely emptied**: indeed, a turbine that works from the expansion of compressed air can produce sufficient power only if the upstream pressure is itself sufficient. Making the **realistic assumption** that the minimum operational pressure is about 20 bars, the **maximum retrievable energy is the energy in the storage when the internal pressure decreases from 70 bars to 20 bars**. The residual energy for an internal pressure of 20 bars is:

Wr = P * V * Ln P1/P2 with P1 = 1 bar and P2 = 20 bars

Working this out, we obtain Ln 20 ≈ 3:**W ≈ 0.98 TWh**

The really recoverable energy, given this technological constraint, is then down to:

1.38 - 0.98 = **0.4 TWh**

* Next, the amount of energy recovered depends on t**he type of expansion**, whether it is with or without **heat** recovery:

- In the case of an adiabatic expansion with **integral heat recovery**, mimicking a theoretical **isothermal** expansion, we will make the simple assumption that the full **0.4 TWh** quoted above are recovered.

- In the case of an adiabatic expansion with **no heat recovery whatsoever**, a situation very **far removed** from an isothermal expansion, the **share of recoverable energy** can be **roughly approximated** by the simplified equation:

Wa ≈ 2.5 * P * V (the 2.5 factor is applicable to the diatomic gases in the air)

If we reconcile **very simply** the above 2.5 coefficient with the mean of the isothermal expansion coefficients given above, i.e. (4.25 + 3) / 2 ≈ 3.62 we get a ratio on the order of 2.5 / 3.62 ≈ 0.7 which means that with this type of expansion, the recoverable energy is only 0.4 * 0.7 = **0.28 TWh.**

* The two previous estimates are **high and low theoretical thermodynamic** values. To include **industrial reality**:

- As recovering **all the heat** is difficult in an industrial context the amount of heat retrieved in reality lies somewhere between the two extreme values; we will make a **simple assumption** that the energy recovered is the mean between the high and low estimations, that is **0.34 TWh**.

- In addition, the **efficiency of the machines** must be included: the turbine's **mechanical** efficiency (≈ 0.90 %) and the alternator's **electrical** efficiency (≈ 0.98 %) combined result in an **electromechanical efficiency** that amounts to 0.90 * 0.98 ≈ **0.88** approximately.

The **electrical energy** finally fed into the grid is thus reduced to 0.34 * 0.88 ≈ **0.3 TWh**

These results call for several comments:

- First, and this deserves to be stressed, note that these results are only **gross approximations,** given that they are obtained with very simplified calculations. They aim only at highlighting the **orders of magnitude**, they have no claim to precise values. These orders of magnitude, however, do allow the formulation of clear conclusions:

* **Compressed air storage in a volume totaling the equivalent of the already considerable underground cavities presently used for natural gas storage would not allow to store more than roughly 0.3/1.8 = 1/6th of one day's demand on a winter day with intensive demand (1.8 TWh, see above)! This is way off the mark and leads to the conclusion that <u>compressed air storage is unable to ensure mass storage and, *a fortiori*, inter-seasonal storage</u>.**

* Why this a result? Its origin must be understood: it is due to the fact that the **energy density of pressure mechanical energy is insufficient**. This is a **fundamental cause which proceeds from LIMITS due to PHYSICS and is therefore not susceptible to change with technological advances**.

Note: To make this quite clear, we compare the energy obtainable by storing an equal volume, in this instance that of the underground natural gas storage, of compressed air and of natural gas:

- The compressed air can generate **0.3 TWh** electricity (see above).

The 132 TWh of natural gas can generate roughly 132 * 0.6 ≈ **79 TWh** electricity, assuming all the gas is used to fuel combined cycle facilities with about 60 % efficiency.

The ratio between the two is then 79 / 0.3 ≈ **260 approximately**, a considerable number which shows that **chemical energy density** (that of natural gas in the present case) is much larger than the energy density of compressed air. More generally, sorting storage methods according to increasing **energy density per unit volume**, the following approximate results are obtained, in **kWh of electricity generated**, **industrial** efficiencies of the conversion to **electricity** included:

- PHES: 1 m^3 of water falling 400 m to drive a hydraulic turbine: ≈ **1 kWh**

- **CAES:** 1 m^3 of air compressed at 70 bars and expanded to 20 bars in an air turbine: ≈ **1.8 kWh**

- **Hydrogen:** 1 m^3 of hydrogen compressed at 70 bars burned in a combined cycle facility: ≈ **125 kWh**

- Natural gas: 1 m^3 of natural gas compressed at 70 bars burned in a combined cycle facility: ≈ **475 kWh**

This energy density hierarchy allows a classification of the various solution according to their **ability to ensure mass storage.** And makes clear the fundamental **limits of PHESs and CAES**, **chemical storage in the form of fuel gas** being alone capable of mass storage, as discussed in Appendix 3 below.

- **Existing Industrial Facilities and Projects**

There are around ten CAESs worldwide, all of the **gas type**, of which **only two** have been **producing for a long time**, the others being at the **project stage** or abandoned. Among the most important we can list:

* **Humtorf** plant (Germany - **1979**): 290 MW - 3 h storage - 45 to 70 bar compression.

* **McIntosh** plant (USA - **1991**): **110 MW** - 26 h storage - 45 to 75 bar compression.

* **PG&E Project** (USA - around 2020/2021): **300 MW** - 10 h storage.

* **APEX Project** (USA - around 2020/2021): **317 MW**

*** Norton Project** (USA): **2 700 MW** - 16 h storage - 55 to 110 bar compression - dropped because of uncertain financial viability.

As can be seen, the industrial experience feedback is quite limited and the operational or projected facilities remain rather small (the largest having been dropped for the time being). In any case, they are not at the scale of mass storage.

Appendix 3: Power to Gas to Power

As results from the preceding discussion, **chemical storage in the form of fuel gases appears to be the only candidate capable of fulfilling the needs of mass storage**, **inter-seasonal** storage included. But is this sufficient to make it an ideal candidate?

- **Efficiency, the Major Weak Point of this Type of Storage**

Despite the advantages detailed in the main body of this document, the two Power to gas to power routes suffer from a major weakness: **the very large number of physical and chemical transformations involved in the processes, more so in the methanation process**, as will appear below:

* **Hydrogen route**: **7 transformations**: GRID → Voltage drop → current rectifier for the electrolysis → water electrolysis → Hydrogen compression for storage → Hydrogen combustion in a combined cycle plant →Voltage hike → GRID

* **Methanation route: 11 transformations:** GRID → Voltage drop → current rectifier for the electrolysis → water electrolysis → Hydrogen compression for storage → CO_2 recovery from industrial smoke → CO_2 compression → Hydrogen + CO_2 methanation chemical reaction → Methane compression for storage in the natural gas network → Methane combustion in a combined cycle plant → Voltage hike → GRID

Of course, for some of these transformations, the individual efficiency is large, even very large, but the efficiencies **add up** and combine with **the worst efficiency losses incurred in the main transformations:** water electrolysis, CO_2 recovery, methanation chemical reaction and methane or hydrogen combustion: **the more numerous the energy transformations, the smaller the global**

efficiency; this, too, is a fundamental law of physics! Here is indeed the case, power to gas to power accumulates many more energy transformations than the **other storage methods**.

Add to this an important feature: the electrolyzers receive their **electricity** from wind and/or PV power, therefore **intermittent and greatly variable power when it does not vanish altogether.** They undergo **a large number of transitory excursions** and are **mostly operated in regimes remote from their optimal efficiency,** further deteriorating the global efficiency of the successive transformations. This effect is anything but trivial and can **occasion the loss of an additional 10 to 15 efficiency points, and even more**.

All told, then, the global efficiency of these "**grid to grid"** transformations is very small and can be estimated according to the values summarized in the table below, taken from two studies (references [2] and [3]). They consider two time frames: the present situation and a future one at a date that is not easily determined but could be around 2030-2035.

Indeed, new electrolysis processes with better performances are being developed, such as **improved alkaline** electrolysis, **PEM** electrolysis, and **SOFC** electrolysis; the latter are the more innovative; they are still at the R&D stage and/or at the very small demonstrator stage. It will take some time before they reach a **proven industrial-scale** stage, provided the studies confirm these processes are interesting.

Moreover, improvements of the efficiency of the methanation reaction itself should also be possible. However, this transformation implies the availability of a sufficiently concentrated CO_2 source so as to minimize the energy consumed for its extraction, this being very large in any case. Add to this the smaller but still significant energy expenditure for purification and intermediate storage.

In the study of reference [2], the **individual efficiency of the main transformations** considered is the following:

- Current situation: efficiency of the **standard alkaline electrolysis: 65%**; efficiency of the **methanation reaction: 60% to 70%**; efficiency of the combined cycle to generate electricity from **synthetic gas: 60%**. Furthermore, additional energy losses amounting to **10% to 15%** are included to take in consideration the large number of transients which remove the installations from their optimal efficiency operating regime.

- Future situation imagined: electrolysis efficiency improvement via the i**mproved alkaline process or any other process** reaching an efficiency of up to **80% to 90%**; similarly improved **methanation reaction** to reach an **80%** efficiency; unchanged efficiency of the combined cycle to generate electricity from synthetic gas: **60%.**

In the study of reference [3] which also bears on the future global efficiencies of these processes, the individual efficiencies are not quoted, however, except for the combined cycle efficiency which is here again **60%.**

Estimation of the overall maximum efficiencies that could be obtained, taking industrial realities in consideration: it is possible to reach an estimation by applying the methodology used in the study of reference [2] and **taking the individual efficiency of the main transformations** to a likely upper limit from an industrial perspective: efficiency of the **electrolysis** and of the **methanation** reaction raised to **90%;** efficiency of the combined cycle raised to **62%** (a world record today, in stable optimal regime; given that the technology is largely mature, future progress in terms of efficiency can be but asymptotic).

On these grounds, the following table summarizing the global efficiencies can be established:

Transformation	Hydrogen route	Methanation route
Operational efficiencies obtained in Ref [2] study	Present: 29 - 31 % **Future: 36 - 43 %**	Present: 17 - 20 % **Future: 27 - 32 %**
Efficiencies obtained by **Fraunhofer Institute** quoted in Ref [3]	**Future: 34 - 44 %**	**Future: 30 - 38 %**
Rounded **mean** efficiencies obtained in [2] and [3]	Present: ≈ 30 % Future: ≈ 40 %	Present: ≈ 20 % Future: ≈ 32 %
Estimated maximum **operational** efficiencies	Future: 42 - 44 %	Future: 35 - 37 %
Average of the maximum operational efficiencies	Future: ≈ 43 %	Future: ≈ 36 %

The two sets of estimations [2] and [3] are overall consistent and sufficiently close to allow establishing averages that are correct representations of the **orders of magnitude**. The values obtained are very close to the maximum realistic values that can be reasonably hoped for, namely **about 43 % for the hydrogen route and 36 % for the methanation route**. This remains globally a **very mediocre performance since to be able to discharge 1 kWh of electricity, it is still 2.3 kWh in the hydrogen route and 2.8 kWh in the methanation route that will have to be "consumed"**. It is an improvement over today's performance, but the amount of wasted energy is still very large, with economic consequences that are not negligible.

- **The Onerous Economic Consequences of very Small Efficiencies**

From the economical point of view, very small energy conversion efficiencies represent two kinds of major negative consequences whose effects potentiate each other:

* <u>First consequence</u>: As has been mentioned already in several occasions, it is necessary to **"consume" much more electricity during the storage phase than will be recoverable during the discharge phase**. Thus, **to be able to recover 1 kWh, the energy consumed is**:

- **With the hydrogen route, more than 3 kWh** today, still **2.3** in the future, at best.

- **With the methanation route: about 5 kWh** today, still **2.8** in the future, at best.

The price of the electricity consumed, **multiplied by the above factors**, obviously contributes an additional cost to the **specific cost of the recovery installations**, in the assessment of the **final storage cost**.

* <u>Second consequence</u>: The **storage/recovery installations have to be significantly oversized**. Indeed, taking as an example the methanation route as it is today, t**o recover 1 kWh of electricity during destocking, it is practically 5 kWh that have to be electrolyzed!** As the installations have to be **<u>prepared to use wind or PV power whenever it becomes available</u>**, t**he electrolysis capability must be 5 times larger than the recovery capability to keep the setup running! This considerably augments the necessary investments which, moreover, can be amortized only by the sale of recovered electricity, i.e. an amount 5 times smaller...**

- **The very Difficult Amortization of Installations Powered by Sources with a Small Capacity Factor (CF)**

The storage/recovery installations considered being, by construction, powered only by wind and/or PV renewable sources, their capacity factor cannot exceed that of the sources that power them. Two main situations can occur:

* <u>First case</u>: The storage/recovery installations are powered by dedicated wind and/or PV devices. The capacity factors being on average 22% for wind power and 13% for PV, the overall capacity factor of the storage/recovery installations is **necessarily limited to 22 + 13 = 35 % at best**, representing roughly 3 000 hours/year (1/3 of the year) in full power output equivalent. In this scheme, the electricity consumed must of course be purchased **at the sale price that applies to the dedicated generator's production**.

* <u>Second case</u>: The storage/recovery installations are powered by the wind and/or PV **surplus** production that finds no buyer for instantaneous consumption or exportation. In this case, a realistic estimation, given the feedback acquired from countries well equipped with wind or PV production, shows this surplus to be available **about 10 % of the time at most**, i.e. during less than 900 hours in full power output equivalent. We can, moreover, make the simplifying assumption that this surplus production **sells at practically no cost**.

These two cases show that there is no good solution: either the installations operate over longer times, favorable to amortization, but the electricity intended for storage must be paid for, or the latter can be obtained for free but the amortization rests on shorter operating times, increasing the cost considerably. Be that as it may, the amortization of industrial installations operating a maximum of 3 000 hours/year is, at best, very expensive.

- **Technical and Economic Synthesis, Current Situation**

Based on the current efficiencies and investment costs, this type of storage accumulates severe economic disadvantages: much more electricity than can be recovered has to be purchased, the installations have to be significantly oversized, their amortization is all the more difficult that operating times are short or very short so that fixed operating costs soar to very high levels which, added to the purchase of the upstream electricity, make the recoverable electricity so very expensive that it cannot be sold except during a few ultra-peak demand hours in the year: THIS SOLUTION IS NOT ECONOMICALLY SUSTAINABLE.

Note: more specifically, with today's efficiencies and use times of the installations (load factors, see above), and the sale price of wind power (about 70 €/MWh) the electricity recovered costs roughly:

* ≈ **300 €/MWh** with the hydrogen route

* ≈ **500 €/MWh** with the methanation route.

This holds for the two situations examined above: electricity purchased at 70 €/MWh and installations operating during 3000 hours/year; or electricity from surplus production gotten for free but installations operating during only 900 hours/year. In passing, this demonstrates the financial impact of insufficient amortization for the installations.

- **What Prospects for a Cost Reduction of the Electricity Recovered?**

Reducing the cost of the electricity recovered implies both that the **efficiencies** be improved and that the **investment costs** of the installations be reduced. What can we hope for?

* Regarding the **future efficiencies**, with the (optimistic) hypothesis that the maximum estimated efficiencies quoted above are **within reach**, we would shift from about **30% to 43%** (improvement factor ≈ **1.43**) with the hydrogen route and from about **20% to 36%** (improvement factor ≈ **1.8**) with the methanation route.

* Regarding the **installation investment costs** in the distant future, projections are much more problematic and uncertain. Only by building **scenarios** can the **necessary cost reduction factors be estimated that would make these solutions viable**, compared to the **cost of the recovered electricity** (in rounded €/MWh in the table below):

Investment cost reduction factor (hypotheses)	Factor 2	Factor 3	Factor 4
Hydrogen	300/(1.43 * 2) ≈ **105**	300/(1.43 * 3) ≈ **70**	300/(1.43 * 4) ≈ **52**
Methanation	500/(1.8 * 2) ≈ **140**	500/(1.8 * 3) ≈ **93**	500/(1.8 * 4) ≈ **70**

This very simplified simulation shows that it is a division by **at least 3, if not 4,** that must be achieved on the current investment costs if a **sale price of the recovered electricity comparable to the high market prices of intensive demand periods is to be obtained**.

Is such a reduction of the investment costs realistic? Answering this question is all the more difficult that the current costs of industrial-grade electrolysis installations are more or less known only in the case of the **current alkaline process**. In all likelihood, they can be roughly extrapolated for the **improved alkaline process, but what of the PEM and SOFC processes which are still in the R&D stage?** Moreover, a number of technological shells still need to be cracked; plus, the **PEM** process, for example, uses rare metals (therefore expensive materials) such as platinum and iridium. Finally, as far as investment costs are concerned, only **industrial experience** is really credible... and enables investments to be made on solid grounds.