Energy storage *via* synthetic fuel gases in electrical systems

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This article looks at energy storage in the form of gas (hydrogen or methane) to compensate for the variability of intermittent wind and photovoltaic production in electricity systems. (This method of storage and retrieval is known as "power-to-gas-to-power"). Energy storage for other applications, such as mobility, is not covered here.

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Hydrogen production facility using electricity generated by the Sotavento wind farm in Galicia (Spain) [1].

Any energy storage/destorage system should ideally have three essential qualities: (i) high overall efficiency, so as not to waste energy; (ii) large capacity; and (iii) long storage life, including inter-seasonal storage, to meet different needs. However, no known system meets all three of these criteria at the same time. Among the most efficient, hydraulic storage using STEPs (pumped-storage energy transfer stations) and electrochemical batteries meet the first criterion (with efficiencies of over 75% and 85% respectively), but not the other two. Conversely, storage in the form of combustible synthetic gases (hydrogen obtained by electrolysis and methane obtained by methanation of CO_2 by this hydrogen) meets the last two criteria but not the first. In the long term, however, these gases would be the best way of storing the large quantities of wind-generated and photovoltaic electricity that the grids of the future will require. The very low overall efficiency (around 20-30%) of the storage and retrieval processes using these gases currently prohibits their use and, at present, their industrialisation is a long way off. Improving these yields is therefore a key factor in their future viability, and is the subject of intense R&D worldwide.

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Advantages of storing electrical energy *using* synthetic fuel gases

This method of storage offers three major advantages… on paper.

1- Gases are decarbonised if the hydrogen is produced by electrolysis from electricity, itself decarbonised, and if the synthetic methane is obtained by methanation of the existing CO_2 by this hydrogen. Under these conditions, they meet the objective of carbon neutrality.

2- Hydrogen and methane have a theoretical capacity to store energy on a very large scale and over a long period, including interseasonally, making it possible, for example, to store photovoltaic electricity produced in abundance in the summer but is of little use at that time of year, for use in winter when photovoltaic production is very low (four times lower than in summer, on average, in our latitudes) and electricity needs are at their highest. Or to store the energy needed to cope with an almost absence of wind for ten consecutive days, as is statistically observed in Europe. As for large-scale storage, this is the result of two favourable factors: the very high energy densities of these fuel gases (see below) and the fact that their production lines can reach industrial scale.

3- Storage can take place either in the existing gas network (with no limit for methane, at a rate of 5%, which can be increased to 20% after further validation for hydrogen), or in specific storage facilities under very high pressure (up to 700 bars) for hydrogene, although the latter also poses more delicate safety problems. This makes it less easy to use than synthetic methane, even though its overall conversion efficiency (electricity → gas → electricity) is slightly higher (30% instead of 20%).

Unfortunately, such efficiencies are very low overall and constitute the major handicap of these storage methods. The underlying causes of this are analysed below on the basis of the current unit efficiencies of the many elementary energy conversions required, under optimal stable conditions and under variable operating conditions, representative of industrial reality. The progress expected from R&D, and its energy and economic consequences, are discussed later in this article.

Hydrogen route: overall efficiency at current unit efficiencies

It goes without saying that hydrogen, as an energy carrier, can be used for a wide range of applications, including chemicals and mobility. It is then used directly as required.

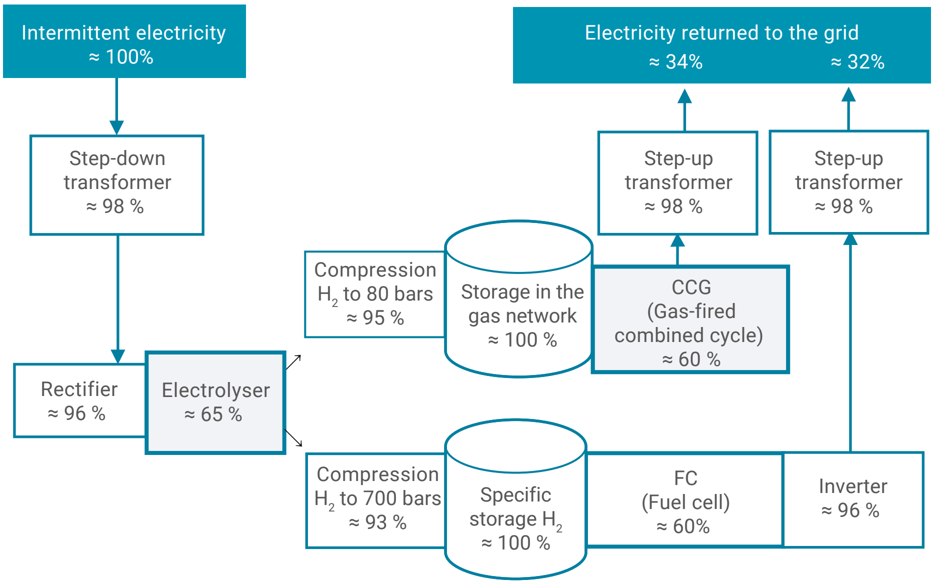
As a means of storing/unstoring energy in electricity grids, it can be used in two different ways to generate electricity again:

- either in its pure state in a fuel cell (FC for short) to directly produce direct current, which must then be transformed into alternating current to feed it into the grid;
- or in its pure state or mixed with methane in a dynamic thermomachine (combined cycle gas turbine, CCGT for short) driving an alternator which feeds directly into the grid.

The energy results for these two processes are shown in Figure 1, which shows that multiplying the unit efficiencies of the many transformations required leads to overall steady-state efficiencies of around 32% to 34%, depending on the case.

If we add to this the additional energy losses of 10 to 15% due to variable operating regimes in real use (the electrolysers do not always operate at their optimum efficiency, especially as they will be supplied by intermittent, wind or photovoltaic electricity), these overall efficiencies fall to around 28 to 30% although these are orders of magnitude.

This leads to the following conclusion: **producing 1 kWh of electricity by destoring hydrogen implies having consumed more than 3 kWh** .



1. Schematic diagram of hydrogen storage and retrieval.

Methanation process: overall efficiency at current unit efficiencies

The beginning of the conversion chain is strictly identical to that of the hydrogen route, until hydrogen is obtained (assumed to be compressed to 80 bars, which consumes electrical energy). At this stage, the hydrogen is combined with CO_2 at the same pressure, using the classic Sabatier reaction:

$$4\,H_2 + CO_2 \Rightarrow CH_4 + 2\,H_2O$$

Not only does this route add a major chemical conversion to the overall conversion chain, with its associated efficiency, but additional electrical energy must also be expended to:

- extract and purify the CO_2 (assumed here to be obtained from fossil fuel combustion fumes, which is a favourable energy assumption compared with extracting atmospheric CO_2, which would consume much more energy);
- then compress it to 80 bars.

All these additional transformations lead to new energy losses which further reduce overall efficiency, as shown in the diagram in Figure 2.

This diagram shows that multiplying the unit efficiencies of the transformations leads to an overall steady-state efficiency of around 21%, which falls to 19% under real operating conditions.

Hence the conclusion: **producing 1 kWh of electricity by destoring synthetic methane implies having consumed 5 kWh**.

These results confirm that the methanation route is even less energy-efficient than the hydrogen route. Its advantage, however, is that it is much easier to use in terms of storage (in the existing network) and transport.

Progress in R&D, but processes not yet industrialised...

In both cases (hydrogen and methane), very significant increases in overall efficiency are essential to make these storage methods viable. Is progress in sight? And if so, will it be sufficient?

Electrolysis processes are the subject of a great deal of research worldwide. One of these is the high-temperature (700-800°C) steam electrolysis process, known as the Solid Oxide Electrolyser Cell (SOEC) which seems promising in terms of efficiency (over 90% in the laboratory), but it does not cope well with variations in load...

The SOEC process can also be coupled thermally with methanation, a highly exothermic reaction that can be used to heat the steam in the electrolyser to a high temperature. Recent experiments have shown that this improves the overall efficiency of electrolysis + methanation.

Demonstrators of various sizes are currently being tested, but it will be necessary to move on to industrial-scale projects with sufficient operating experience to really calibrate the technical and economic parameters of these conversions.

In the meantime, there is a way of getting an idea of the future viability of these conversion chains by simulating their overall yields using maximum assumptions for the "industrial" unit yields of the main conversions. For example:

- for equipment with high development potential (electrolysers, methanators, fuel cells), maximum industrial yields of 90% can be achieved;
- for very technologically mature equipment, in particular combined cycle gas turbines (CCGTs), whose efficiencies will increase very little unless there is a technological breakthrough that cannot be predicted at this time, we anticipate a maximum efficiency of around 64% (currently 62% in the best case scenario);
- The efficiency of purely electrical transformation equipment (transformers, rectifiers, inverters) is already very high, and there is not much more to be gained.

On this basis, it is then possible to recalculate maximum overall yields, which are summarised in Table 1.

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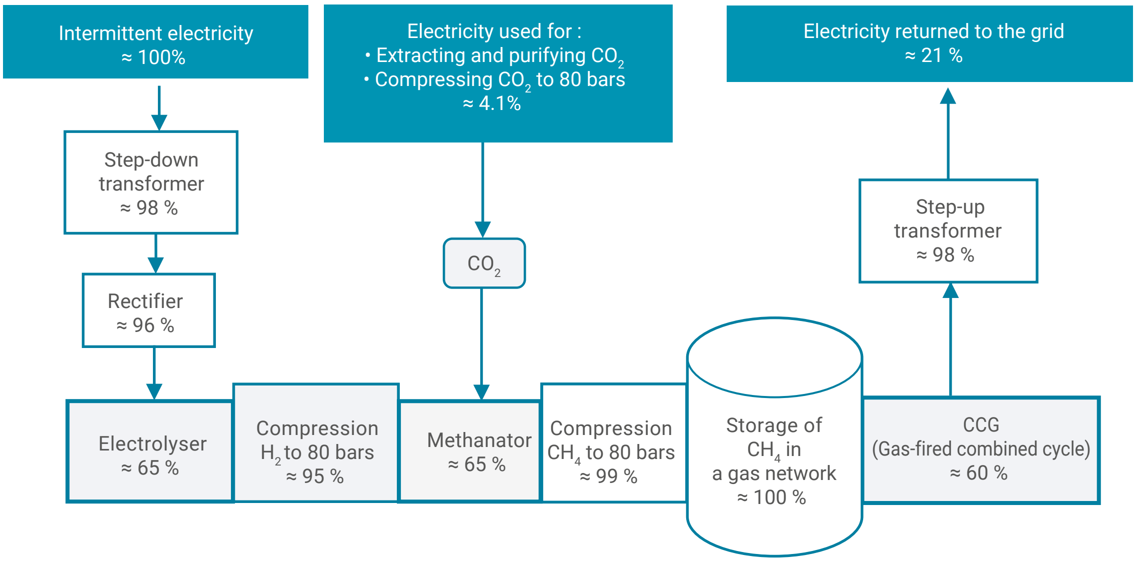

2. Schematic diagram of methane storage and retrieval.

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To sum up, in an industrial context in which the unit efficiencies of the main energy conversions (those involving changes in the form of energy) do not exceed 90% (which is already a lot), it seems very difficult to do better than double the current operational efficiencies of H_2 with a heat pump and CH_4 with a CCGT, and increase the efficiency of H_2 with a CCGT by 50%...

The overall yields of these conversion chains will therefore remain intrinsically limited. The basic reason is the excessive number of energy conversions necessary especially for the CH_4.

When limited yields and low load factors combine to have negative economic effects...

Limited yields are not the only weakness of these storage methods. The fact that they are powered by intermittent electricity (which is their primary purpose) also puts them at a huge disadvantage, as these sources of electricity have low "load factors" (i.e. "equivalent operating time at full power") on an annual average for mainland France, 22 to 23% for onshore wind power and 13% for photovoltaic power (16% in the south of France, less than 11% in the north).

If these intermittent sources are to develop significantly, there are only two ways of using the electricity they produce for storage purposes, on the understanding that immediate needs must in all cases be met as a matter of priority.

1- Or use surpluses from wind and photovoltaic that are not immediately available for consumption or export. We can roughly estimate that these surpluses could be available for around 10% of the time, or 900 hours a year. In this case, the electricity used for storage could be very cheap, or even free. But then the electrolysers would work very little and the cost of hydrogen would be affected by depreciation charges.
2- Or build additional resources dedicated to storage, as the existing resources are insufficient. In this case, the maximum load factor of the storage systems cannot exceed the sum of the "load factors" of the resources deployed, i.e. 22 + 13 = 35%, corresponding to a maximum of 3,000 hours per year. In this case, the electricity used for storage must be paid for at its normal selling price. In addition, as intermittent production varies greatly, the electrolysers need to be oversized to capture the maximum amount of intermittent electricity produced. Amortisation costs are lower than in the previous case, but electricity is not free and it is necessary to buy three or five times more (for hydrogen and methane, respectively) than it will be possible to resell.

Simple economic calculations, based on realistic investments of the order of €1,000/kW installed for each of the main components of the conversion chains (electrolysers, methanators, fuel cells, combined gas cycles) assumed to be amortised in 20 to 25 years with financing rates of around 3 to 5%, the cost of destored electricity can be as high as €300/MWh for hydrogen and up to €500/MWh for methanation, depending on production conditions. That's six to ten times the average wholesale electricity prices on the markets in 2019. It's easy to see that no business model is currently viable under these conditions.

What would happen with improved yields, which could at best be doubled as indicated above? These costs would automatically be halved, bringing them to less than €150 and €250/MWh respectively. This is still not enough to make an economic model viable... In addition, the investment costs of the conversion lines would have to be halved (hydrogen route) or tripled (methanation route) for the costs of electricity from storage to become saleable when market prices reach or exceed a hundred euros per MWh. This happens during periods of high demand, which raises two questions: will it be possible to reduce investment costs to such an extent? And will there be enough hours of the year when market prices are high enough to place electricity from storage? Given the current state of knowledge, no one is in a position to answer these very complex questions.

Performance Route	Performance **electrolyser**	Performance V_{FC}	Performance **methanator**	Performance **CCG**	Overall performance at optimum content route	Overall operational performance **(at variable route)**
H_2 **+ FC**	65 ↗ **90 %**	60 ↗ **90 %**	-	-	32 ↗ ≈ **65 %**	28 ↗ **≈ 57 %**
H_2 **+ CCG**	65 ↗ **90 %**	-	-	60 ↗ **64 %**	34 ↗ ≈ **50 %**	30 ↗ **≈ 44 %**
CH_4 **+ CCG**	65 ↗ **90 %**	-	65 ↗ **90 %**	60 ↗ **64 %**	21 ↗ ≈ **42 %**	19 ↗ **≈ 37 %**

Table 1. **Current and expected efficiencies of hydrogen + fuel cells (FC), hydrogen + combined cycle gas turbine (CCGT), and methane + combined cycle gas turbine (CCGT).**

And yet, only the storage of electricity using fuel gases is capable of meeting the mass inter-seasonal needs...

This is the result of the laws of physics and chemistry, and more specifically of the energy densities of the different physical or chemical forms taken by energy. Storing very large quantities of energy means having sufficiently concentrated forms of energy so as not to increase the volumes occupied beyond what is materially and/or economically feasible.

However, there are very large differences between the energy densities per m^3 of material that can be converted back into electricity using current industrial methods:

- Hydraulic potential energy (water from dams), i.e. 1 m^3 of water falling 700 m driving a hydraulic turbine and an alternator: ≈ 1.7 kWh ;
- Pneumatic potential energy (compressed air stored in underground cavities), i.e. 1m^3 of compressed air at 70 bars expanded to 20 bars, driving a compressed air motor and alternator: ≈ 1.8 kWh ;
- Chemical potential energy of hydrogen fuel gas, i.e. 1 m^3 of hydrogen compressed to 70 bars burnt in a combined cycle: ≈ 125 kWh ;
- Chemical potential energy of methane fuel gas, i.e. 1 m^3 of methane compressed to 70 bars burnt in a combined cycle: ≈ 415 kWh.

So, for the same volume, combustible gases (hydrogen and methane) store 70 to 230 times more potential energy than water in dams or compressed air in underground cavities.

Let's look at a few figures to illustrate the scale of the challenge of mass storage on the French electricity grid:

- on a very cold winter's day (24 hours), the country's electricity consumption is typically between 1.7 and 2 TWh;
- All of France's six PSH plants, despite their huge size, can only store... 0.1 TWh! We would therefore need to build 17 to 20 times as many to supply the country with electricity for a single day... This is totally unrealistic, since the realistic growth potential is of the order of a factor equal to 1.2 ;
- on the other hand, this amount of electricity could be produced using around 2.5% of the natural gas reserves stored every year in the country's underground caverns. This gas could be replaced by synthetic methane in the same proportion. In reality, we would need to store the equivalent of at least ten days' worth of gas to get through the winter, or 25% of the capacity of current underground storage facilities. This would still be physically accessible, but would mean building additional underground storage capacity.

Conclusion

The only energy forms capable of storing electricity on the very large scale required to meet the country's electricity consumption each winter for ten or so very cold days are synthetic fuel gases. The solution sometimes mooted of going as far as synthetic liquid fuels from these gases, which is technically possible, would increase the number of physical transformations and therefore further degrade efficiency.

However, this physical response, which involves colossal investments, leads to a dead end: the absence of a viable economic model for this type of storage, given current technologies and prospects. However, with the massive development of wind and photovoltaic sources beyond 2035 in France, and no doubt earlier in other countries, mass and inter-seasonal storage will become essential to ensure a secure electricity supply. But what if they are not economically viable when the time comes?

Unless we want to plunge the country (and Europe) into darkness or subject electricity consumers to very high prices, we will have to continue to rely on a large proportion of stock energy, enabling us to produce electricity when it's needed, not just when there's wind or sun. There are only two sources of stock energy that have the physical capacity to meet the scale of the variable needs that will arise: nuclear power, whose production emits no CO_2, and natural gas, the lowest-emitting fossil fuel, which nevertheless emits around 440g of CO_2 per kWh of electricity produced in the best-case scenario. But this CO_2 would have to be captured and sequestered to prevent it from being released into the atmosphere. Capture technologies do exist (see the article by F. Delprat-Jannaud, p. 78), but they consume a lot of energy and sequestration raises difficult issues, including safety. Finally, the use of natural gas is accompanied by methane leaks (methane is the main component of natural gas), a gas that has a warming power 80 times greater than CO_2 in 20 years' time. From a climate and economic point of view, this solution is far less efficient than nuclear power. France's National Low Carbon Strategy (SNBC) has not identified carbon capture and sequestration as a possible solution.

In the absence of an economically sustainable solution for inter-seasonal mass storage, we will have to choose between nuclear power and global warming... ▮

> “we will have to choose between nuclear power and global warming...”

1• M. Rey Porto *et al.*, “H_2 production in Sotavento wind farm”, Proceedings of the 18th World Hydrogen Energy Conference 2010 (Essen). ISBN: 978-3-89336-653-8.

An energy carrier in tune with the times: hydrogen

In addition to its use as a means of storing electricity in 'power-to-gas-to-power', discussed in Georges Sapy's previous article, the dihydrogen molecule now appears to be the ideal energy carrier, capable of replacing fossil fuels in their main applications, either in heat production or transport.

The various French and European hydrogen plans have three distinct objectives: (1) the production of carbon-free hydrogen for current non-energy industrial uses (refining, ammonia, fertilisers, etc .); (2) the development of energy uses for hydrogen (heavy mobility, heating, etc.); (3) facilitating the integration of renewables into the electricity mix.); Table 1 summarises the orders of magnitude and production targets .

Producing all this hydrogen, for both current industrial uses and new energy uses in a carbon-free way, represents an enormous challenge. Water electrolysis is the preferred method of production, but the energy cost of this process is around seven times higher than that of steam reforming methane, which is currently 95% used. To produce one kg of hydrogen by electrolysis, you need to consume around 55 kWh of electrical energy. The cost of production depends not only on the low-carbon electricity used, but also on the cost of the electrolyzers and their maintenance. While the current cost per kg of dihydrogen produced by steam reforming of natural gas is between €1.5 and €2, that produced by electrolysis is in the €3-9/kg range. To become economically competitive, this production of low-carbon hydrogen by electrolyse would have to satisfy the following conditions[(a)]:

- electrolysers must operate at full load for as long as possible throughout the year, to limit the oversizing of installations;
- electrolysers must ensure regular and continuous production for the industry;
- the electrical system must be able to deliver the huge amount of electricity required. ▮

	France	European Union	World
Current non-energy industrial uses	0.9 Mt	9 Mt	~ 100 Mt
Electrolysis production targets for 2030-2035 : • Industriels uses - Energy uses (heavy mobility, gas networks) Electrolysis requirements.	**0.63 Mt** 0.4 Mt 0.23 Mt 6.5 GW, 35 TWh	**12-17.5 Mt** 3 Mt	
2050 targets and electricity requirements, electrolysis capacity	20% final energy (2016): 8 Mt, 440 TWh, 70 GW	24% final energy (2018): 65 Mt, 3600 TWh	528 Mt H_2 equiv. (cf. IEA NZE scenario)
Managing the intermittency of renewable energies (beyond 2035)	Note: three days of total *backup* (= 5 TWh) → 0.25 Mt, 14 TWh, 2 GW		

Table 1. **Hydrogen production and use targets in France, the European Unionand the rest of the world.**

(a) For a more detailed analysis, see for example
- G . Bonhomme, https://cutt.ly/conversation_debat_lhydrogene, and
- G. Bonhomme, https://cutt.ly/articles_des_emerites_2021 .