Alkaline and high-temperature electrolysis for nuclear hydrogen production

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Abstract

In anticipation to energy world evolution in the coming decades, we will discuss the role that hydrogen can play in the future energy systems.

Facing strong energy demand growth in the transport field, expected oil production limitation and climate change constraints, the oil industry has to raise difficult challenges requiring short-term actions. Hydrogen being a key molecule for this industry, we will show how nuclear produced hydrogen can contribute to resolve some of the oil industry challenges, within a compatible time frame with the inertia of climate mechanisms.

Technical solutions to produce hydrogen using nuclear energy and electrolysis will then be described. We will describe the relevant characteristics of alkaline electrolyser technology. Using results of nuclear-aided petrochemical processes technico-economic studies, we will show that synthetic fuels are accessible at reasonable costs.

We will also discuss the limitations of these technological solutions and describe which improvements and evolutions can be expected and looked for, as regards both the nuclear industry and electrolyser technologies. For the latter, we will discuss both alkaline and high-temperature electrolysis. The evolutions to be looked for should minimise development efforts, therefore we will argue why advanced thermal integration should be studied in order to avoid too-stringent requirements on both the nuclear reactor and the electrolyser. Remaining challenges will be discussed.

As a result, our paper will show how and why the nuclear industry, and specifically AREVA, will be able with relatively limited developments to massively decarbonise transportation from well to wheel, through a variety of applications.

Towards an evolution of the energy systems, linked to transportation and fuels

Three incompatible constraints make inevitable a major transformation of the energy systems. First, the strong growth of the energy demand in transportation, driven by population growth and economic growth. Second, the peak oil, or to say the least the production plateau expected by 2020 around 100 Mbl/d. This plateau implies that an alternative source of energy than oil from wells will be required to satisfy demand. And third, the climate change issue, which imposes to quickly and drastically reduce greenhouse gas emissions. This constraint is particularly strong on the oil and automobile industries.

This analysis is now shared by a growing number of players in the energy industry. And it is, naturally, around fuel and transport industries that major evolutions will occur. The challenges that these two industries will have to face can be summarised in four main questions:

- How to reduce CO_2 emissions released during fuels production?
- What kind of energy source could be used in the oil and petrochemical industry tomorrow?
- How to satisfy the fuel demand? That is, with which sources of energy and which carbon sources. Will it be necessary to resort to synthetic fuels?
- The reduction of carbon footprint vehicles is necessary in order to protect the growth potential of car manufacturers, how will the vehicles motorisation evolve? Will electrification take a big share and if yes, when?

It should be noted that for air, sea and truck transportation, electrification is not conceivable. For these applications, the only CO_2 emissions reduction option that will not limit growth will be in the use of clean fuels or synfuels.

Clean production of hydrogen as an opportunity for clean fuel

The oil industry has to enrich crude oil with hydrogen to produce lighter petroleum products. Today, the vast majority of hydrogen in refineries is produced by steam methane reforming, this production accounts for approximately 1% (~0.3 Gt) of the CO_2 world emissions. For comparison, it is approximately equal to 15% of avoided CO_2 emissions thanks to the world nuclear reactors fleet. Besides, the tradition Fischer-Tropsch process to produce synfuels has a poor conversion yield and is a large CO_2 emitter: one-third of the resource is used to produce the hydrogen required for the process, when another third is used to produce the energy required for the process. Two-thirds of the carbon resource is therefore converted directly into CO_2, and not into fuel.

Reducing the environmental impact of fossil fuel and synthetic fuel production requires a massive production of clean hydrogen which water electrolysis technology can offer: in water electrolysis, electricity enables breaking water molecules into its elementary components hydrogen and oxygen. In the case where the electricity is produced free of CO_2 emissions hydrogen is also produced CO_2 free.

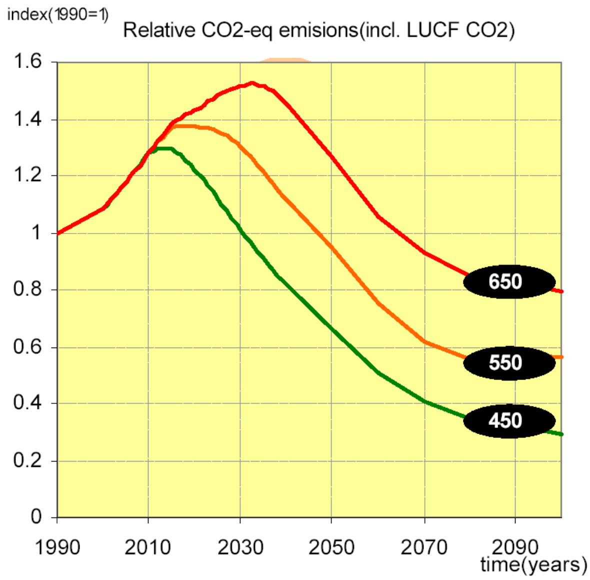
In a generic way, the challenges which the oil and automobile industries are facing can be dealt with by using nuclear power, via:

- the use of hydrogen stemming from water electrolysis as a replacement to hydrogen stemming from fossil raw material or from methane;
- the use of the co-produced oxygen;
- the direct use of electricity and\or nuclear heat in petrochemical processes.

These generic interfaces are applicable in all of the oil industry processes: synthesis of fuels, refining, and heavy oil production. As a result, clean massive hydrogen production is a technology enabling substantial CO_2 abatements in the oil industry (Boardman, 2008; Forsberg, 2009).

As illustrated in Figure 1, the timing for CO_2 emissions reductions is crucial to the evolution of climate. Besides, CO_2 emissions from the transportation sector have to be reduced massively and quickly if the climate is to be protected. It is therefore of major importance that technologies able to go at commercial scale in due time are made available.

Figure 1: A sense of emergency: climate change impacts are very different depending on how fast we start to reduce CO_2 emissions due to the inertia of climate mechanisms

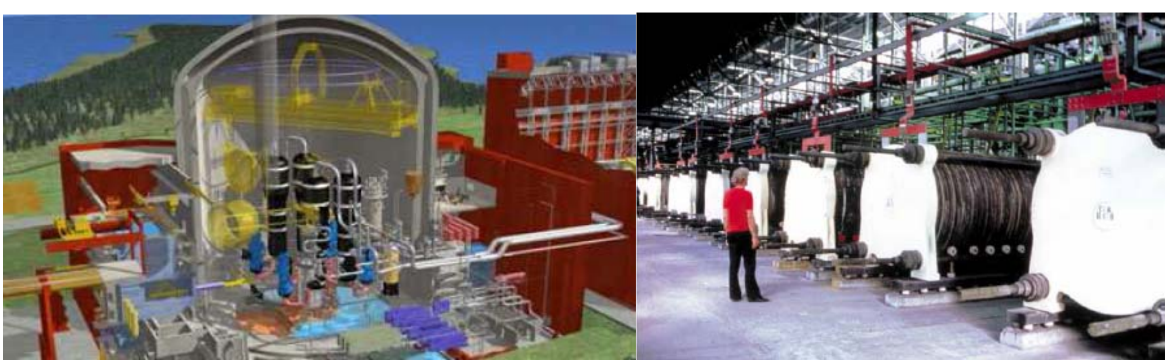


The CO_2 capture and sequestration cannot meet these challenges since the expected time frame for deployment would be longer than are time horizons authorised for CO_2 emissions reduction, for which should also be considered the uncertainties lying in the world geological storage capacity. We will show in the next section that this is not the case with nuclear and electrolysis.

Clean fuels are at hand

Technically speaking, hydrogen can be massively produced without CO_2 emissions in the short term as light water reactors and alkaline electrolysis technologies are available and mature. Companies like Hydrogen Technologies (StatoilHydro Group) have been selling these products for many years, see Figure 2. These existing technologies still have room for improvement; they are, thus, solutions for the mid-term. Some companies are currently working to improve the performances and economics of alkaline electrolysis (Bourgeois, 2008). They could be supplanted, in the long run, by not yet available technologies: for example, high-temperature nuclear reactors and high-temperature electrolysis, or even thermochemical processes driven by high-temperature heat from nuclear plants if their development succeeded.

Figure 2: Light water reactors such as EPR™ and alkaline electrolysis such as Hydrogen Technologies' method are well established technologies to produce CO_2-free hydrogen



Considering process integration, a typical synfuel process like CtL can be modified to use hydrogen and oxygen produced from water electrolysis using nuclear energy, and to use also directly some electricity. This process evolutions, sketched on Figure 3, lead to quite energy efficient layouts as some very energy intensive pieces of equipments are removed, the air separation unit (ASU) being the most important one. The idea of the modified process is to turn every carbon entering the process into fuel, the energy and all of the hydrogen coming from nuclear and water. Therefore the CO shift is removed too, as there is no need to produce hydrogen from the coal enabling all CO molecules to go to the Fischer Tropsch unit.

Figure 3: Traditional coal-to-liquid process

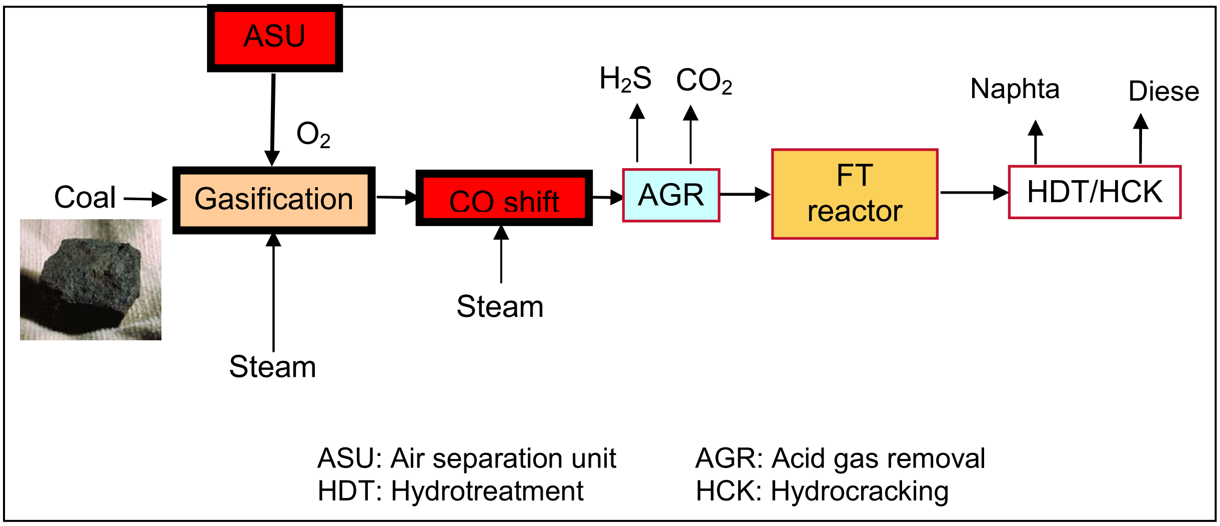
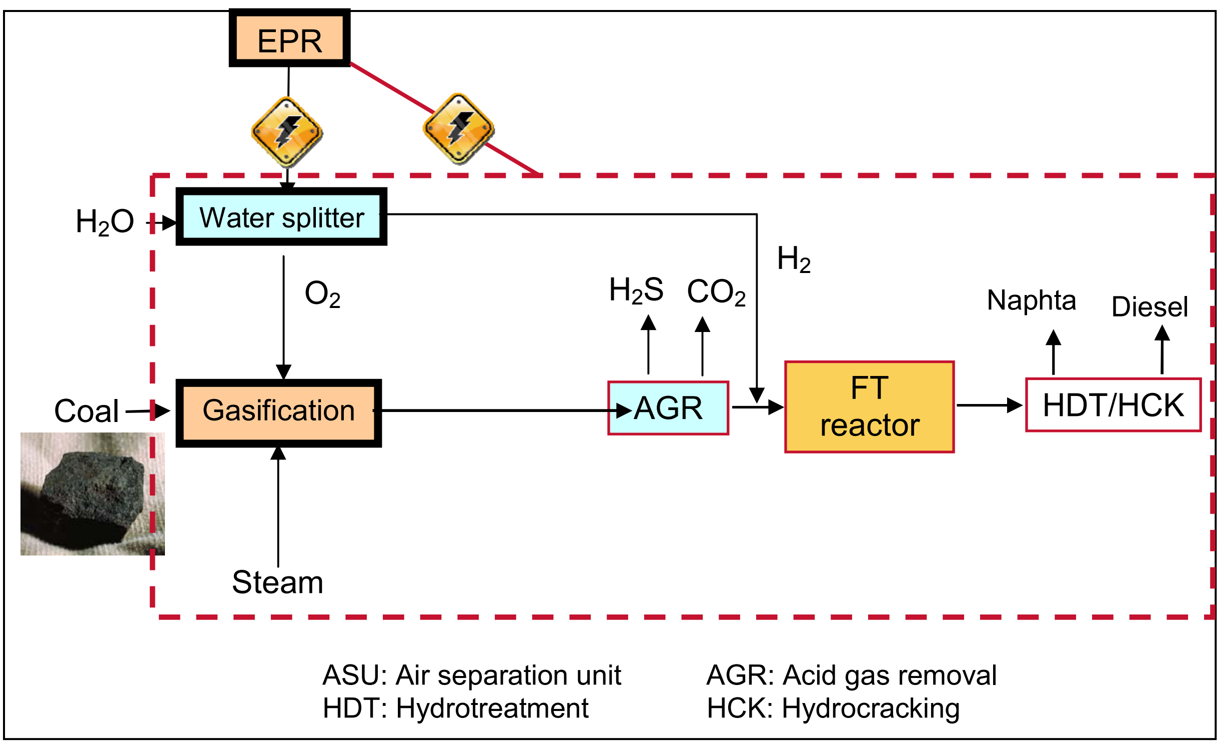


Figure 4: Coal-to-liquid process coupled to a nuclear energy source



Economically speaking, synthetic fuels are accessible with a cost sharply less than USD 150/bl, which compares fairly with the USD 120/bl cost of traditional CtL processes.

Besides, it is possible to turn refineries quasi-CO_2 free thanks to the supply of hydrogen, oxygen and clean electricity. On the basis of the early 2008 economic conditions (high level of fossil fuels prices, around USD 140/bl) and considering nuclear electricity costs at around EUR 55/MW, such modified refineries are more profitable than conventional ones.

Besides, in comparison to usual processes, the use of nuclear power in the synfuel production processes allows to drastically increase conversion yield:

- using biomass, conversion ratio is doubled;
- using coal, conversion ratio is tripled.

With such substantial gains, BtL becomes a viable option (the needed agricultural or forest areas being strongly reduced) and coal-to-liquids can also be reconsidered (CO_2 emissions being strongly reduced). As an immediate consequence, the perspectives of deployment of more generally XtL processes can be reconsidered as less pressure is exerted on resources. Moreover, nuclear plants not only provide hydrogen to the petrochemical processes, but oxygen and electricity as well.

Finally, it is crucial to note that the cost of synfuel barrels is strongly dependent on the cost of electricity. In a very capital-intensive case such as the nuclear power, the cost of the synfuel barrels is therefore very sensitive to the capital cost.

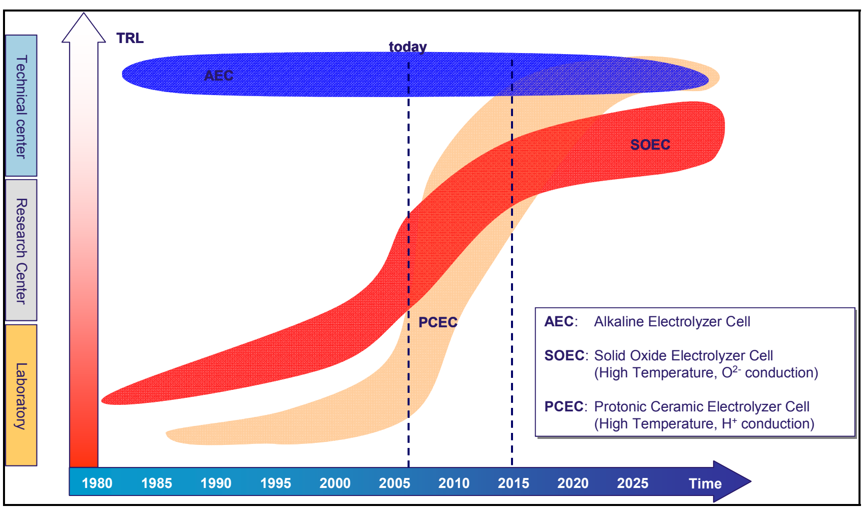
Another attractive option is to seize the opportunity for producing hydrogen via alkaline electrolyses from electricity consumption during off-peak periods. Purchasing electricity at low cost during off-peak periods makes possible to reduce hydrogen production costs and leads to considerable savings. However, coupling the production of hydrogen by electrolysis with low electricity price leads to a discontinuous process. The petrochemical processes being continuous, a hydrogen temporary storage has to be included in the system.

As a result, the nuclear option can, in the short term, enable large CO_2 emission reductions based on available light water reactors and alkaline electrolysis technologies. The economic attractiveness of this solution depends on the electricity cost but also on the CO_2 and natural gas prices.

High-temperature technologies

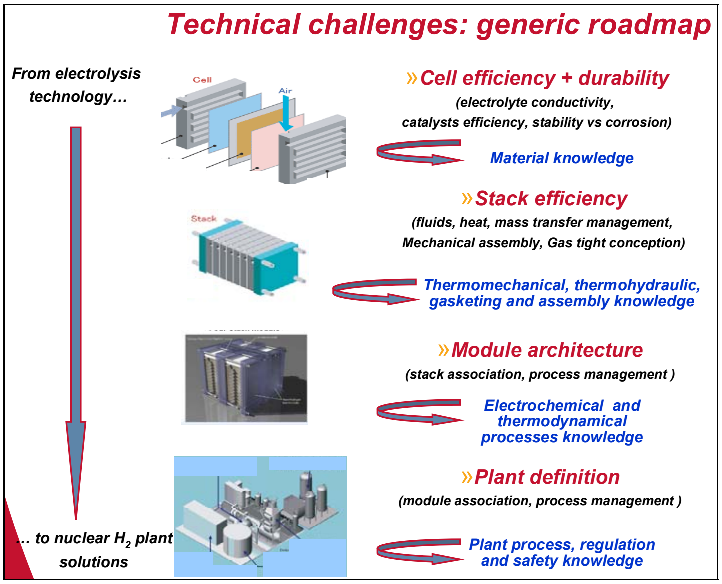
To improve the intrinsic economics of nuclear electrolysis, in the long term, hydrogen production by high-temperature electrolysis coupled with high-temperature nuclear reactors is an attractive alternative option. Today, high-temperature electrolysis is at an early stage of development, see Figure 5. Size

Figure 5: Development roadmap of different electrolysis technologies



scales of high-temperature electrolyser prototype are in the range of tens of square centimetres, and test runs are in the range of a thousand hours. An AREVA R&D programme is currently under way to develop high-temperature electrolysers, see Figure 6. This programme encompasses and covers all aspects of the electrolysers, from cell materials to system integration and massive hydrogen plant cost assessment.

Figure 6: AREVA roadmap for high-temperature electrolysis



However, in such a high-temperature option, even if the HTE development is a success, a critical issue will remain providing heat at around 900°C, which would require heavy reactor developments for a rather limited market, thus leading to development, engineering and licensing cost amortisation.

Systems should thus be designed to provide heat using reasonably ambitious high-temperature reactors so that technology is available in due time compared to climate change timings. Such an option can be offered with a 600°C HTR which would provide 550°C heat to steam, combined with electrolysers' outlet gases heat regeneration, the completion of energy requirements to reach 900°C being provided by electric heating, as summarised in Figure 7. Rough numbers for the energy balance of such a layout is given in the following table for a 600 MWth nuclear reactor, see Table 1.

Figure 7: Schematic view of good efficiency system delivering steam at 950°C using a 600°C HTR reactor

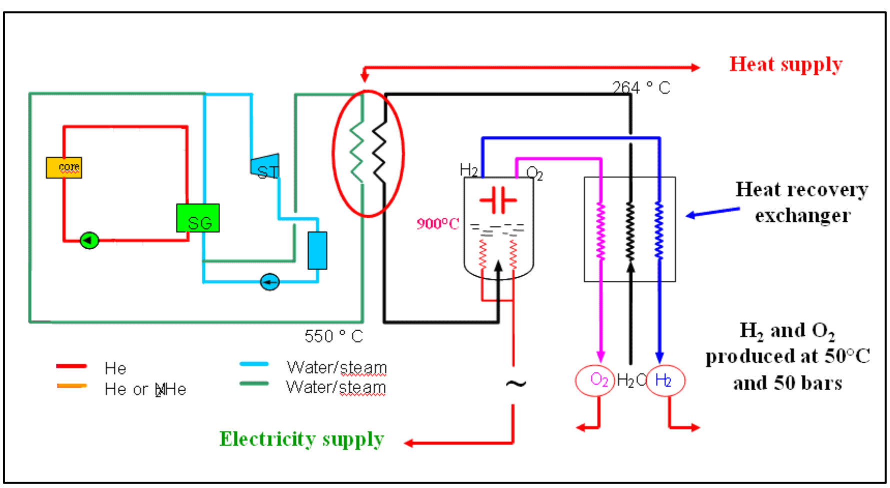


Table 1: Energy balance of Figure 7 heating system, 600 MWth nuclear reactor case

Regeneration	~ 41 MWth
Steam transport loop	~ 17 MWth
Electricity to heat the steam to 900°C	~15 MWe
Electrolysis itself (at 3.1 kWe/m^3)	~ 240 MWe

Such a solution is obviously less efficient than the one including a VHTR since it only provides 1.9 kg H_2/s instead of 2.1 kg H_2/s in the VHTR case (DOE, 2006), but the difference is not that important. Anyhow, it is small enough to make it possible for the cost of hydrogen in this "heat + electricity" option to turn out to be competitive as less stringent requirements will be put on the reactor and other systems such as:

- less advanced materials for high-temperature management involved;
- less fuel challenges;
- no 900°C heat to be carried on at least a few hundred meters, no advanced heat carrier like helium or molten salt;
- no lifetime issues with heat exchangers at both ends operating in the 950-900°C range, under substantial pressure differential.

Conclusion

Technological elements for transition to nuclear-hydrogen sustained oil processes are ready. However further developments are required for these free CO_2 hydrogen production assisted sustainable fuel production processes: demonstration of integration, overall H_2 plant design, etc. Either based on alkaline water electrolysis, or on high-temperature electrolysis, although these challenges remain significant challenges they are addressable in a limited time frame to enable mid-term industrial deployment.

Even if the economics of the nuclear hydrogen production are already rather good, they can be improved in the long term by consuming electricity during off-peak periods and developing high-temperature electrolysis. In order to keep most of the R&D efforts focused on electrolysis challenges, it is suggested that 900°C heat generation systems are based on relatively simple designs for the high-temperature reactors, meaning reactors not over 600°C.

Synthetic fuels will enable reconciling the necessity of reducing, in the short term, the issues of transportation and deployment of the alternative motorisations of vehicles. They will thus give time to the car industry to ensure the transition towards the electrical vehicle, which is, by far, more energy efficient than the thermal vehicle running on synfuels.

The hurdles to be passed for a major evolution of fuels and transport, by use of nuclear energy and electrolytic hydrogen are quite important. Among those, are the new interfaces between the petroleum industry and the power industry, which have very different time lines and mental sets. As the positive potential of this solution is proven, it is now of major importance to exchange with the oil industry and progressively identifying economic opportunities for first applications or demonstrations of clean synfuel production.

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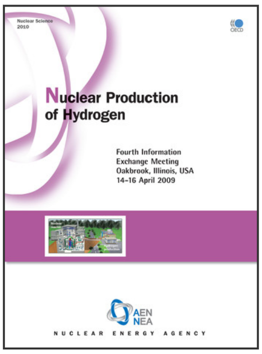

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