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THE PRODUCTION OF CLEAN AND LOW-COST HYDROGEN THROUGH NUCLEAR POWER PLANTS

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1. Introduction

The energy sector is by far the main culprit in growing greenhouse gas emissions, with a strong dependence based on fossil fuels of approximately 80%, accounting for around 75% of global emissions. The IPCC - Intergovernmental Panel on Climate Change in its report (2021) [19] made strong recommendations to keep the global warming limit below the average temperature rise of 1.5ºC and to ban fossil fuels, indicating the mass electrification of energy uses and the replacement of fossil sources with hydrogen. [19,18].

Supported by the IPCC report (2021), the Conferences of the Parties - COP 26 (2021), COP 27 (2022) and COP 28 (2023), set stricter targets for zero carbon emissions by 2050, known as “Net Zero Emissions" (NZE). Clean hydrogen, produced from low-carbon sources, has been appointed as the protagonist and main energy vector in the quest to eliminate fossil energy sources and thus achieve the targets set to curb global warming.

However, renewable sources such as wind and photovoltaics, considered by the IPCC to be the main drivers in the race for scale up the production of low-carbon hydrogen, are already facing technical barriers which will have economic consequences and additional costs, as well as issues related to land use, performance issues under climate extremes, among others, which could difficult to gain the scale required to meet either Mondial electricity demands increase and the electricity demands to make the hydrogen as a global scale fuel. In light of this possible mismatch, nuclear power plants are emerging - which are in a new cycle of development - and are capable of not only producing clean electricity, but also thermal energy, making it possible to produce clean hydrogen in a synergistic way, without or with low carbon emissions, throughout numerous routes, electrochemical, thermochemical, and even a combination of both, reducing the dependence of electricity, with high efficiency, high reliability, on scale and lower-cost.

2. Methodology

The present study was based on research from relevant sources presented in the scientific literature related to the power generation industry, climate change, energy transition and decarbonization, especially to the production of clean hydrogen, without carbon or low carbon emissions, from nuclear power plants, also known as hybrid nuclear power plants. Based on the analysis of this information, the aim was to point out the qualitative and quantitative advantages and opportunities that the production of hydrogen from nuclear energy brings compared to other low-carbon energy sources. Besides, it will also highlight the technological maturity level and the costs posed by the production of hydrogen from nuclear energy. Therefore, in the results section, important insights will be provided for the world's energy sector, and especially Brazil's, regarding the production of clean hydrogen through this considerable energy source.

3. Results and Discussion

The world's hydrogen production and consumption is around 90 MtH_2/year (2020), according to the IEA, and it is almost entirely covered by the thermochemical route, using fossil fuels and their derivatives as the raw material for obtaining hydrogen. Only about 0.03% of the world's hydrogen demand, which corresponds to around 27ktH_2, comes from electrochemical production via the alkaline electrolysis of water, using electricity to break down the water molecule to obtain hydrogen.

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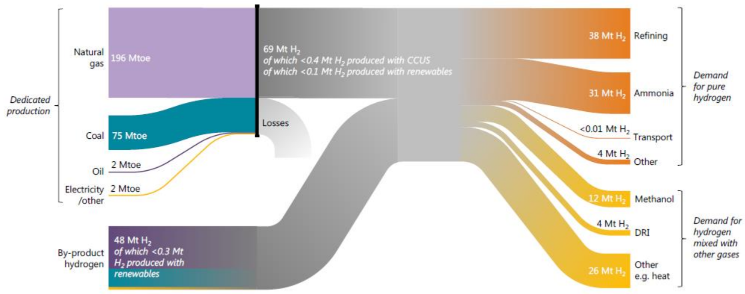

Image 1- Main sources and uses of hydrogen in the world today [15].

The path to zero emissions by 2050 (NZE), according to the IPCC report (2021), requires a substantial expansion of the use of low-carbon hydrogen in existing applications and a significant growth in its use, replacing fossil fuels mainly in heavy industry, road transport, maritime transport and aviation. The IEA's projections in this scenario indicate that low-carbon hydrogen is expected to increase almost sixfold, reaching an annual consumption of 530 MtH_2 by 2050. In SYSTEMIQ's report [7], the consumption forecast is expected to increase to 1,001 MtH_2, or 728 MtH2 if energy efficiency measures are implemented. The full paper shows the hydrogen consumption by each economic sector and the reliability of the projections based on technological maturity, the cost to replace fossil fuel with hydrogen and other challenges to be faced.

The projections of global electricity consumption, according to the IEA, in the NZE scenario, following the routes outlined by the IPCC report (2021), indicate an increase from the current 23 PWh to around 61 PWh. This growth will largely be the result of the use of electricity to produce hydrogen for energy purposes, which corresponds to an increase of around 12 PWh, plus 9 PWh due to the electrification of mobility as a whole.

And many countries, in the race to decarbonize their energy matrixes and achieve NZE, are also moving towards nuclear power. Nowadays, there are around 53 nuclear power plant projects underway, and around 35 countries are either carrying out programs to build new plants or extend the useful life of their plants. At COP 28, 25 countries publicly expressed their preference for nuclear energy and believe that by tripling the global current installed capacity to around 1,200 GW is the way to achieve the goals of banning fossil fuels by 2050.

The IEA points out that nuclear power from 1971 to 2020 has already avoided the emission of 65GtCO_2.

The production of hydrogen in nuclear power plants is already a very successful reality. An example of this is the Angra Complex nuclear power plant in Brazil, which for 26 years has been producing a biocide - sodium hypochlorite (NaClO) - to eliminate the fouling organisms that adhere to the tubes of the pumping system and the steam turbine condenser (the plant's tertiary cooling circuit). The full paper shows the reactions and data relating to the process of producing the biocide that has clean hydrogen as a byproduct.

The complete work shows the nuclear reactor technologies, some already in commercial use and others under development, and their main features that allow greater synergy with the hydrogen production routes.

3.1 Technological Routes for Hydrogen Production through Nuclear Power Plants

Nuclear power plants have a significant synergy for the production of clean hydrogen, especially those using Generation IV reactors, due to a series of characteristics already mentioned, making hydrogen production an economically attractive option.

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3.1.1 Electrolysis of water to produce hydrogen

The processes of low-temperature electrolysis (LTE), which takes place either in an alkaline environment, known as Alkaline Electrolysis, or in a polymer membrane electrolyte, known as Proton Exchange Membrane Electrolysis (PEM) usually occurs in the temperature range of 40- 90◦C.

However, Solid Oxide Electrolysis (SOEC), also called High-temperature Electrolysis (HTE), works with steam and operates close to the output temperatures of nuclear reactors, with temperatures between 700 and 1000 ◦C, and lower electricity consumption comparable to low-temperature electrolysis.

For both temperature regime processes, nuclear power plants offer competitive energy costs. Further details are given in the full paper for both low and high-temperature electrolysis.

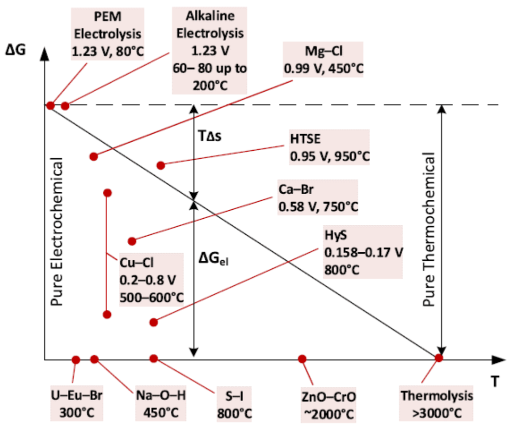
3.1.2 Cycles of Thermochemical Breakdown of the Water Molecule

The thermochemical cycles can be pure, in which only thermochemical reactions take place, or hybrid, which combines electrochemical and thermochemical reactions. In the full paper there will be more details of the processes, their reactions and characteristics, graphs and tables for a better understanding of each of the hydrogen production routes.

This work will detail the following pure or hybrid thermochemical cycles.

- Sulfur-Iodine Cycle (S-I)
- Calcium-Bromine Cycle (Ca-Br)
- Hybrid Sulfur or Westinghouse Cycle
- Hybrid Copper-Chlorine Cycle (Cu-Cl)

In the provided chart below shows a summary of the different methods of hydrogen production that we have discussed in this work, along with some other cycles for illustrative purposes. The figures are theoretical values even for temperature and voltage, without considering the losses inherent in the processes.



3.2.3 Technological Maturity and Costs of Hydrogen Production Routes

In order to produce clean hydrogen to meet the goals of decarbonizing the global energy matrix, we will not only need abundant water resources but also electricity and heat. Nuclear power plants have a promising role to play in meeting the world's hydrogen demands if they indeed happens.

In this work we will see that there is a major technological challenge which will require considerable resources in investment, research and development (R&D) for the hydrogen market to come true, firstly, to have demand for what is projected in terms of hydrogen use and consumption, (in the full paper Table

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1 shows part of these challenges), and secondly, the sources of energy to guarantee the supply of hydrogen to meet the demands if they do materialize, and the nuclear energy sources have shown better conditions to meet this great challenge.

This chapter presents hydrogen production costs through the various routes using nuclear energy and it compares them with other energy sources.

4. Conclusions

In order to increase the share of low-carbon energy sources, promoting clean and sustainable energy in the global energy matrix, replacing fossil fuels and sustaining the increase in consumption, especially hydrogen, as we have seen in this study nuclear energy will play a key role as a vector that will drive the low-carbon and low-cost economy.

Some of the technologies for producing hydrogen using nuclear power plants as a source of energy have been analyzed in this study, there will be need significant investments in research and development and joint efforts by research centers, industries, governments and societies to face the enormous challenges that the energy transition imposes on us. Furthermore, there will be a need to unlock and promote the use of hydrogen through carbon offsetting mechanisms, encouraging the replacement of fossil sources by hydrogen.

The nuclear energy source has proven to be robust and less vulnerable to adverse effects from the climate, electrical market, and others. Historically, its operation has been with a high load factor and sufficiently reliable to ensure energy security to meet electricity demands for the market, combined with new modular reactor technologies that are emerging and that will be closer to load centers, industries and industrial hubs, with greater modulation capacity in the face of variations in thermal and electrical demand and which will a play a significant role in the production of clean, low-cost hydrogen in a more sustainable world.

5. Acknowledges

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6. References

The article presents 38 bibliographical references that will be shown in the complete work.

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