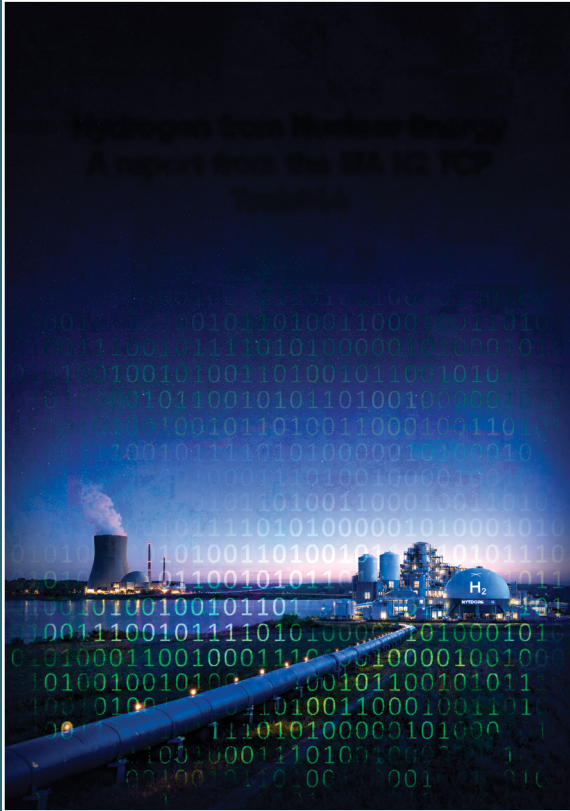


# Hydrogen from Nuclear Energy

## A report from the IEA H<sub>2</sub> TCP

### Task #44





## Comments on the cover page

- *This picture has been Generated by AI, then adjusted by a graphic designer.*
- *The nuclear reactor is in the background because the importance is the final product, the Hydrogen production.*
- *The filter is made of data-bits, showing that these concepts are still under study and development.*
- *All needs are represented: nuclear reactor, electric network, pipe network, hydrogen production plant & storage, and water (for cooling or for H<sub>2</sub> production with electrolysis).*
- *The picture is done in a uniform colour, because hydrogen has no link with colours.*
- *The picture is represented at night because the nuclear hydrogen production concept is planned to run 24h time.*
- *The dawn breaks, a signal of the potential for this technology.*

# Table of contents

|                                                                                                                                                                                        |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Foreword .....                                                                                                                                                                         | 7   |
| Executive summary .....                                                                                                                                                                | 9   |
| Preamble .....                                                                                                                                                                         | 11  |
| 1 Introduction & Task #44 management .....                                                                                                                                             | 11  |
| 1.1 Background and rationale .....                                                                                                                                                     | 11  |
| 1.2 Task #44 - Description & Management .....                                                                                                                                          | 12  |
| 1.3 Task #44 (HyNE) Objectives .....                                                                                                                                                   | 13  |
| 2 The need of low carbon hydrogen .....                                                                                                                                                | 16  |
| 3 Hydrogen from nuclear energy: a technological solution for large scale hydrogen production .....                                                                                     | 21  |
| 3.1 Background and history .....                                                                                                                                                       | 21  |
| 3.1.1 A succinct presentation of the civil nuclear reactor history .....                                                                                                               | 22  |
| 3.1.2 A succinct history of the hydrogen production and connection with the nuclear field .....                                                                                        | 26  |
| 3.2 Hydrogen production & nuclear reactor in a nutshell .....                                                                                                                          | 33  |
| 4 Hydrogen from nuclear energy: the existing cases and the most promising cases .....                                                                                                  | 37  |
| 4.1 Real case situation .....                                                                                                                                                          | 37  |
| 4.2 The project case preselected for modelling in recent European projects .....                                                                                                       | 42  |
| 4.3 The whole cogeneration cases and those pre-selected cases by Task #44 .....                                                                                                        | 43  |
| 5 Hydrogen from Nuclear Energy: viability of the system .....                                                                                                                          | 46  |
| 5.1 TRL approach .....                                                                                                                                                                 | 46  |
| 5.2 A global system analysis .....                                                                                                                                                     | 49  |
| 5.3 Safety approach .....                                                                                                                                                              | 54  |
| 5.4 Regulation approach .....                                                                                                                                                          | 63  |
| 5.5 Business case approach .....                                                                                                                                                       | 66  |
| 6 The Synthesis of the case study approach .....                                                                                                                                       | 76  |
| 7 Recommendations & future needs for a hydrogen production deployment .....                                                                                                            | 78  |
| 7.1 The main breakthroughs .....                                                                                                                                                       | 80  |
| 7.2 The technical recommendations .....                                                                                                                                                | 83  |
| 7.3 Strategic recommendations .....                                                                                                                                                    | 85  |
| 7.4 A prospective analysis .....                                                                                                                                                       | 89  |
| 8 HyNE: perspectives for a future IEA/H <sub>2</sub> TCP Contribution .....                                                                                                            | 91  |
| 9 Some last remarks .....                                                                                                                                                              | 95  |
| 10 Contributor's list and Task #44 members .....                                                                                                                                       | 96  |
| 11 List of acronyms .....                                                                                                                                                              | 98  |
| Acknowledgements .....                                                                                                                                                                 | 100 |
| Annex 1: Field-testing hydrogen production .....                                                                                                                                       | 101 |
| Annex 2: Comparing hydrogen by emissions intensity rather than colours .....                                                                                                           | 106 |
| Annex 3: Funding of hydrogen produced with nuclear energy projects .....                                                                                                               | 109 |
| Annex 4: The Euratom TANDEM project to pave the way of nuclear SMR integration into hybrid energy systems contributing to net-zero emissions: The two district heating scenarios ..... | 112 |
| Annex 5: The six Generation IV Systems .....                                                                                                                                           | 118 |
| Annex 6: "H <sub>2-be</sub> or H <sub>not-2-be</sub> " – Decarbonation of industrial uses in Europe .....                                                                              | 121 |
| Annex 7: The HyNE prospective analysis .....                                                                                                                                           | 124 |
| Annex 8: e-reputation all along the Task #44 duration .....                                                                                                                            | 127 |

## List of Inserts

|                                                                                                                                               |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------|----|
| Insert 1: SISYPHE Study: European trends for demand of low carbon hydrogen .....                                                              | 20 |
| Insert 2: HTSE coupled with a VHTR, why is it not the unique solution? .....                                                                  | 35 |
| Insert 3: Current status of high temperature gas-cooled reactor development and its usages on hydrogen production in Japan .....              | 40 |
| Insert 4: The Technology Readiness Level approach .....                                                                                       | 48 |
| Insert 5: The HTGR/H <sub>2</sub> production case - A GIF-OECD joint study .....                                                              | 52 |
| Insert 6: Hazards related to hydrogen production, handling and storage .....                                                                  | 61 |
| Insert 7: EU Codes & Standards, Regulations and Guidelines .....                                                                              | 64 |
| Insert 8: INL FORCE Tool Suite and DOVE: Optimizing Integrated Energy Systems .....                                                           | 69 |
| Insert 9: UK Bay Hydrogen Hub – Nuclear-Enabled Hydrogen to Decarbonise Industry and Beyond .....                                             | 72 |
| Insert 10: Low-carbon hydrogen production, the example carried out by an international chemical supplier company .....                        | 74 |
| Insert 11: The creative SWOT & PESTEL analysis .....                                                                                          | 81 |
| Insert 12: MARVEL a new microreactor developed by INL (Microreactor Application Research Validation and Evaluation program) .....             | 84 |
| Insert 13: The production of hydrogen with nuclear energy – A future position using prospective analysis by postulated future scenarios ..... | 89 |
| Insert 14: The Task #44 timeline (2023 – mid 2026) .....                                                                                      | 93 |

## List of Figures

|                                                                                                                                                                               |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1: Task #44 breakdown structure .....                                                                                                                                  | 14 |
| Figure 2: The Task #44 major objective as expressed when created .....                                                                                                        | 14 |
| Figure 3: The Task #44 representation by type of organization and by country .....                                                                                            | 15 |
| Figure 4: The Global hydrogen review summary program [Source the Global Hydrogen Review 2025] .....                                                                           | 17 |
| Figure 5: The different hydrogen policy approach in several countries [Source the Global Hydrogen Review 2025] .....                                                          | 18 |
| Figure 6: Global Energy demand [Source the 2025 IEA Energy Outlook] .....                                                                                                     | 19 |
| Figure 7: European Energy sectors .....                                                                                                                                       | 20 |
| Figure 8: The Proposed SISYPHE scenario on Hydrogen needs (2025-2040) .....                                                                                                   | 20 |
| Figure 9: The sum of world nuclear power capacity from its early beginning .....                                                                                              | 23 |
| Figure 10: The civil nuclear reactor generation from GEN I to GEN IV .....                                                                                                    | 23 |
| Figure 11: The six selected GEN IV concepts .....                                                                                                                             | 24 |
| Figure 12: The SMR technico-economic approach to compete with large nuclear reactors .....                                                                                    | 25 |
| Figure 13: Simplified flowsheet of the I-S thermochemical cycle [Source CEA pres.] .....                                                                                      | 27 |
| Figure 14: Simplified flowsheet of the Cu-Cl hybrid thermochemical cycle [Source R. El Emam pres.] .....                                                                      | 28 |
| Figure 15: Simplified flowsheet of the Sulphur hybrid process [Source Clefs CEA – N°50/51 2004-2005] .....                                                                    | 29 |
| Figure 16: The different routes of electrolysis [Source CEA, P. Serre Combe pres.] .....                                                                                      | 30 |
| Figure 17: Electrical efficiency of different electrolyser technologies [Source IEA Ref 22] .....                                                                             | 30 |
| Figure 18: Thermochemical table of water dissociation .....                                                                                                                   | 31 |
| Figure 19: A simplified flow diagram of the HTSE running with low temperature inputs and heat recovery systems. RNR means Sodium Fast Reactor in French .....                 | 32 |
| Figure 20: The TOPSOE HTSE image starting from a single planar HTSE cell up to the design of a Gigafactory .....                                                              | 33 |
| Figure 21: A simplified flow diagram of the coupling between a nuclear reactor heat source and the HTSE unit .....                                                            | 34 |
| Figure 22: The advantage of using heat in electrochemical processes rather than solely electricity, minimizing the LCOH <sub>2</sub> [Source J.F. Dhedin (EDF) pres.] .....   | 34 |
| Figure 23: The initial presentation of the VHTR from GIF (until 2024). The VHTR nuclear reactor is already shown to be coupled with an H <sub>2</sub> production plant) ..... | 35 |

|                                                                                                                                                                                                                                                                                   |    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 24: The flow diagram coupling a PWR with a HT [Source S. Bragg Sitton pres., Jan 2022]                                                                                                                                                                                     | 36 |
| Figure 25: 2025 world map of the existing and on-going project of hydrogen from nuclear energy [Source: Jonny Hawes, UKNNL printed in <a href="https://www.edfenergy.com/about/nuclear/hydrogen-handbook">https://www.edfenergy.com/about/nuclear/hydrogen-handbook</a> ]         | 38 |
| Figure 26: List of existing and short-term projects. Figure updated from                                                                                                                                                                                                          | 38 |
| Figure 27: HTTR description and major achievements [Source H. Noguchi pres.]                                                                                                                                                                                                      | 40 |
| Figure 28: Concept view of the SMR production facility coupled with the HTTR [Source H. Noguchi pres.]                                                                                                                                                                            | 40 |
| Figure 29: Flow diagram of the whole coupling system [Source H. Noguchi pres.]                                                                                                                                                                                                    | 41 |
| Figure 30: Logos of the three European project                                                                                                                                                                                                                                    | 42 |
| Figure 31: The TRL scale proposed by IEA                                                                                                                                                                                                                                          | 48 |
| Figure 32: The TRL and IRL scale                                                                                                                                                                                                                                                  | 48 |
| Figure 33: The holistic Advanced Nuclear Energy pathway by sector [Source INL pres.]                                                                                                                                                                                              | 49 |
| Figure 34: The INL Pilot plant demonstration: DETAIL [Source INL pres.]                                                                                                                                                                                                           | 51 |
| Figure 35: The cover page of the corresponding GIF document                                                                                                                                                                                                                       | 52 |
| Figure 36: Table of LCOH <sub>2</sub> according to several scenarios                                                                                                                                                                                                              | 53 |
| Figure 37: H <sub>2</sub> risk in Nuclear Power Plant [Source N. Chaumeix pres.]                                                                                                                                                                                                  | 55 |
| Figure 38: Hypothetical layout of a reactor site with typical Nuclear Island (NI) / Balance of Nuclear Island (BNI) and Conventional Island Balance of Plant (CI-BOP) buildings, including HES (on-site) and Electrolysis Facility (on-site and off-site) for hydrogen production | 57 |
| Figure 39: Potential design strategies to reduce risk from electrolysis facility to the reactor and nuclear island                                                                                                                                                                | 59 |
| Figure 40: Potential Co-generation Arrangement for HyNE                                                                                                                                                                                                                           | 60 |
| Figure 41: H <sub>2</sub> Event tree diagram [Source Z. Liang pres.]                                                                                                                                                                                                              | 62 |
| Figure 42: Optimization results of architectures for the energy hub case with the PERSEE tool: left= size of the HES components; right= total CO <sub>2</sub> emissions                                                                                                           | 68 |
| Figure 43: Optimization results of architectures for the energy hub case with PERSEE tool: left: LCOE; right: LCOH <sub>2</sub>                                                                                                                                                   | 68 |
| Figure 44: The FORCE architecture                                                                                                                                                                                                                                                 | 69 |
| Figure 45: Dispatch over one 120-hour segment showing how the system balances solar generation, nuclear power, and natural gas to meet demand                                                                                                                                     | 70 |
| Figure 46: Hydrogen Profitability: Transition hydrogen sales price (in \$/kg-H <sub>2</sub> ) sensitivity for NPP uprate in one U.S. Day-Ahead (DA) market                                                                                                                        | 71 |
| Figure 47: Schematic of co-location of a nuclear power station with a high-temperature solid oxide electrolyser                                                                                                                                                                   | 72 |
| Figure 48: Schematic of co-location of a nuclear power station with a high-temperature solid oxide electrolyser                                                                                                                                                                   | 73 |
| Figure 49: The asphalt production site (Heidelberg Materials, Criggion in North Wales)                                                                                                                                                                                            | 73 |
| Figure 50: Air Liquide Industrial Model                                                                                                                                                                                                                                           | 74 |
| Figure 51: Air Liquide Bécancour hydrogen factory and Normand'Hy low-carbon hydrogen network                                                                                                                                                                                      | 75 |
| Figure 52: The ranking of the several cases analysis                                                                                                                                                                                                                              | 77 |
| Figure 53: A graph representing what is known as "The valley of death"                                                                                                                                                                                                            | 79 |
| Figure 54: Bad news and good news related to Hydrogen                                                                                                                                                                                                                             | 80 |
| Figure 55: The HyNE creative SWOT analysis                                                                                                                                                                                                                                        | 81 |
| Figure 56: The HyNE PESTEL analysis                                                                                                                                                                                                                                               | 82 |
| Figure 57: The worldwide situation of research nuclear reactor [Extracted from data Source IAEA open database, 2026]                                                                                                                                                              | 83 |
| Figure 58: Artistic view of the MARVEL reactor [Source INL Brochure]                                                                                                                                                                                                              | 84 |
| Figure 59: The IDNES team approach (CEA) moving from H <sub>2</sub> production to e-fuel on-line production                                                                                                                                                                       | 86 |
| Figure 60: The chemical e-factory proposed by newcleo [Source newcleo pres.]                                                                                                                                                                                                      | 87 |
| Figure 61: Spatial and material requirement by energy source [source Damien Ernst from LinkedIn]                                                                                                                                                                                  | 88 |
| Figure 62: Crossing two axes to define 4 future scenarios                                                                                                                                                                                                                         | 89 |
| Figure 63: Four sectors = 4 worlds with 4 given titles                                                                                                                                                                                                                            | 90 |

|                                                                                                                                                                                                               |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 64: Synthesis of the prospective analysis for HyNE in four different world scenarios .....                                                                                                             | 90  |
| Figure 65: The Task #44 roadmap 2023 to mid-2024 .....                                                                                                                                                        | 93  |
| Figure 66: The Task #44 roadmap mid-2024 to mid-2025 .....                                                                                                                                                    | 94  |
| Figure 67: The Task #44 roadmap mid-2025 to Task end .....                                                                                                                                                    | 94  |
| Figure 68: The Task #44 team in front of the Jupiter 1000 building (France) .....                                                                                                                             | 101 |
| Figure 69: Task #44 members observing an HTSE stack module tested at INL (USA) .....                                                                                                                          | 102 |
| Figure 70: Task #44 members with WalterTosto members during the Codes & Standards workshop (Italy) .....                                                                                                      | 102 |
| Figure 71: Task members visiting Hysetco & Hyliko start-up companies (France) .....                                                                                                                           | 103 |
| Figure 72: Task #44 members visiting Enbridge solutions on hydrogen production & blending station .....                                                                                                       | 103 |
| Figure 73: Visit of Hone facilities fueling H <sub>2</sub> reservoirs in trucks to provide solution of low-carbon electricity on remote area for movie projects .....                                         | 104 |
| Figure 74: The ENEA & newcleo lead facility fleet erected at Brasimone (Italy) & an artist mock-up of the PRECURSOR facility (scale 1) [©Agnese Bedini/DSL Studio/newcleo] .....                              | 105 |
| Figure 75: Indirect costs of electricity production .....                                                                                                                                                     | 110 |
| Figure 76: Full system electricity cost in function of % Variable Renewable Energy (VRE) versus nuclear and in function of carbon emission constraint .....                                                   | 110 |
| Figure 77: Illustration of industrial hydrogen demand concentration in industry plants and hubs .....                                                                                                         | 110 |
| Figure 78: Energy market needs in EU .....                                                                                                                                                                    | 113 |
| Figure 79: Stepwise approach for the development of HES at local scale .....                                                                                                                                  | 114 |
| Figure 80: Conceptual layout of the hybrid energy systems configured by TANDEM: on the left, District Heating Configuration; on the right, Energy Hub Configuration (business-as-usual energy scenario) ..... | 114 |
| Figure 81: Gas Fast Reactor .....                                                                                                                                                                             | 118 |
| Figure 82: Lead Fast Reactor .....                                                                                                                                                                            | 118 |
| Figure 83: Molten Salt Reactor .....                                                                                                                                                                          | 119 |
| Figure 84: SuperCritical Water Reactor .....                                                                                                                                                                  | 119 |
| Figure 85: Sodium Fast Reactor .....                                                                                                                                                                          | 120 |
| Figure 86: Very High Temperature Reactor .....                                                                                                                                                                | 120 |
| Figure 87: Germany scenario's sectoral electricity consumption with green-hydrogen based of industrial .....                                                                                                  | 122 |
| Figure 88: Germany scenario's sectoral electricity consumption with direct electrification of industrial .....                                                                                                | 122 |
| Figure 89: Hydrogen vs Direct Electrification .....                                                                                                                                                           | 122 |
| Figure 90: Synthesis of the prospective analysis for HyNE in four different world scenarios .....                                                                                                             | 124 |
| Figure 91: Traffic since January 2023 on the ieahydrogen.org domain (Y axis is read in hundred) .....                                                                                                         | 127 |
| Figure 92: Search trends for the search terms "nuclear hydrogen" (in blue) and "hydrogen from nuclear energy" (in red) from February 2023 to present (Y axis is read in hundred) .....                        | 128 |
| Figure 93: Number of LinkedIn posts from January 2023 to December 2025 (Y axis is read in hundred) .....                                                                                                      | 128 |

## List of Tables

|                                                                                                          |     |
|----------------------------------------------------------------------------------------------------------|-----|
| Table 1: The matrix of solutions to produce hydrogen with nuclear energy and the preselected cases ..... | 43  |
| Table 2: The numbering of the preselected cases and the justification .....                              | 44  |
| Table 3: The TRL evaluation of the matrix of solutions .....                                             | 47  |
| Table 4: The matrix of solutions to produce hydrogen with nuclear energy and the preselected cases ..... | 124 |

# Foreword



**By Paul Lucchese,**  
**Chair of IEA Hydrogen TCP**

The IEA Hydrogen Technology Collaboration Program (TCP) was established during the first oil crisis in the 1970's. At that time, the focus was on seeking alternative energy sources to oil and gas for reasons of sovereignty and to mitigate the leverage held by Middle Eastern countries. The creation of the International Energy Agency in 1974 was a response from OECD countries to address the pressures exerted by the Middle East (specifically OPEC) and to enhance energy security. Climate change was not yet a topic of discussion.

Hydrogen was seen as a potential solution for industry and transportation to reduce dependency on oil imports. Given that renewable energy sources were neither available nor competitive during that period, nuclear energy became the preferred route for producing decarbonised hydrogen. The Hydrogen TCP has included nuclear energy in its core mission from the outset. Thus, the first initial tasks (Tasks #01, #02, #03, and others from 1977 to 1990) focused on hydrogen production from nuclear energy, particularly through the study of thermochemical cycles as well as end-use and system analysis.

High-Temperature Reactor (HTR) technology was preferred but, unfortunately, after the energy crises of the 1990's, oil and fossil fuels became more competitive, rendering hydrogen production from nuclear sources too expensive compared to fossil fuel options.

In the years that followed, Task #25 (2005-2009) centred on high-temperature processes for hydrogen production, combining two decarbonized energy supply options: Concentrated Solar Power (CSP) and nuclear reactors. This innovative approach aligned with IEA policy, emphasizing the necessity of utilizing all decarbonized technologies to achieve net-zero emissions (NZE) by 2050.

Beginning in the 2000's, climate change became the primary driver for developing new hydrogen production processes. However, by the 2020's, significant changes occurred in a relatively short time due to the COVID-19 crisis, the Ukraine war, and new geopolitical tensions. Despite these challenges, the focus on decarbonization remained, following the Paris Agreement, while energy independence and economic viability emerged as additional new drivers, aiming to create jobs in developed countries.

It is crucial to note that a substantial portion of renewable technology (including photovoltaic (PV), batteries, electric vehicles, and wind turbines) is manufactured predominantly in Asia, resulting in technological dependency and challenges related to critical materials.

Hydrogen produced from nuclear energy aligns perfectly with three objectives: decarbonization, enhanced energy autonomy, and job creation. While hydrogen from nuclear energy may not be the optimal solution when considering each criterion individually, a holistic analysis reveals that it can play an important role in developed countries. Moreover, nuclear energy does not rely on significant quantities of critical materials compared to renewables and requires less land area.

Additionally, nuclear energy is experiencing a resurgence globally, playing a significant role in IEA's Net Zero Emission scenario. This includes considerable innovation efforts, such as the development of Small Modular Reactors (SMRs) and extending the traditional applications of nuclear energy beyond electricity generation to include heat and hydrogen production.

The launching of a new task on this topic in 2022/2023 is well-aligned with the expectations of governments, industry, and the research community.

The main idea behind the creation of the task was to analyse and check the relevance of nuclear energy for hydrogen production: where and when nuclear energy could be a competitive and interesting option, for which applications, what are the main competitors, what are the main bottlenecks, what are the research priorities, without any « a priori » or ideological bias but just a fact-based analysis.

This task was a success story from different points of view:

- It gathered more than 50 experts coming from industries, governmental bodies, national research laboratories and institutes, engineering companies, energy and chemical producing companies, hydrogen and nuclear experts, start-up companies and Non-Governmental Organizations. Gathering this diversified panel of experts was a positive sign of the interest in this subject.
- This coordinated approach of Task #44 ensures the work was complementary and work together with other Nuclear International organizations (IAEA, OECD/NEA, Generation IV International Forum) rather than being duplicative. This approach has led to yearly joint workshops at the initiative of Task #44 in three major countries in Hydrogen from nuclear: USA, France and Canada. These joint workshops were always organized in the third week of January and are starting to become a “coordinated ritual around this subject”.
- The Task #44 management approach was immediately oriented towards the use of innovative tools, in its monitoring and in its way to report the progress of work. Some of these tools presented in the following report have already been adopted by other Tasks: project management through a shared platform, creative SWOT analysis, PESTEL and prospective analysis, e-reputation study, smart use of AI LLM for graphs images.

This report reflects what Task #44 has achieved during these last 3 years.



Task #44: Hydrogen from Nuclear Energy

HyNE 2023-2026



Hydrogen TCP

# Executive summary

This report is the output of the collective work and exchange of experts gathered around the IEA H<sub>2</sub> TCP Task #44 (2023-2026). It provides a comprehensive analysis and review of hydrogen production from nuclear energy, tackling all its aspects: technological, economic, safety, regulatory and strategic.

The report is composed of nine chapters, each of them can be read independently and a brief summary is proposed for all, favouring a quick understanding and overview of the complex subject.

The background and rationale of the analysis of the nuclear reactor in cogeneration with hydrogen production system is presented in [Chapter 1](#). It recalls that the global energy system is transitioning towards new paradigms focusing on energy sovereignty, resistance to the versatility of the supply chain and adaptability to stronger weather conditions. In addition, its race to decarbonization is marked with an ambitious target of net zero emissions by 2050 for a large number of countries. All these objectives are creating uncertainties that require exploring multiple, combined decarbonized energy scenarios beyond the massive use of natural gas, coal and fossil fuels. The cogeneration of hydrogen produced from the combination of nuclear heat and electricity is proposing a solution that can fulfil some of the requirements. It is the reason why the IEA H<sub>2</sub> TCP decided to create a Task named “HyNE” (Hydrogen from Nuclear Energy, Task #44) to provide a holistic view of this solution. This subject is not new; it has been already treated by several Tasks in the 80's (Task #01 and #02) and in the 2000's (Task #25). But since that time the context has significantly changed which justifies new uncertainties and at the same time an increasing demand of all kind of energies worldwide.

Even considering this increasing energy demand, [Chapter 2](#) shows that the hydrogen production projections are not ramping up as expected, even more so, low-carbon hydrogen production. In this difficult context where more than 95% of global hydrogen production is done by the steam methane reforming process, it remains difficult to forecast when the need

of low-carbon hydrogen will significantly increase, pulled by the end-users and the market. Some analysts are seeing this growing demand in the 2030's which will provide this technology with a window of opportunity to increase its maturity to become a viable all-in product when the market requires it. Nuclear energy has already made a transformation to produce not only low-carbon electricity but a large portfolio of usages such as heat supply, desalinization application and potentially low-carbon hydrogen.

The next chapter ([Chapter 3](#)) is recalling the basics of this system taken individually. Firstly, a succinct history of the civil nuclear reactor development is presented moving from the Generation I type of reactor to the actual Generation III reactors and the promising Generation IV nuclear systems, particularly from hydrogen production with high temperature processes. It is also explained how the approach of Small Modular Reactor / Advance Modular Reactor is revolutionising the nuclear approach in many countries transitioning from an economy of “scaling up” (producing larger power reactors) to an economy of scale (producing multiple SMR replicated in several regions or countries).

Following this, the description of low-carbon hydrogen production processes is presented. Among all hydrogen production techniques, the hottest favour cogeneration with nuclear reactors that use high temperature steam or very high temperature coolant (helium, lead, sodium, molten salt) that can be used to dissociate the water molecule with higher yields compared to low temperature processes such as alkaline or Proton Exchange Membrane electrolysis.

Thus, the High Temperature Steam Electrolysis and the thermochemical or hybrid cycles are well suited to nuclear systems, which will provide its low-carbon electricity and part of its steam (or heat) to increase the global efficiency.

Producing low-carbon hydrogen from nuclear energy is not a dream. It already exists as demonstration on some existing nuclear reactors, and is currently under

development to propose this solution for the near future. The [Chapter 4](#) presents the status of this nuclear hydrogen production existing today. It is principally made with standard alkaline electrolysis and for their on-site hydrogen consumption. The large variety of the two systems (nuclear reactors and hydrogen production) and their great adaptability allow a large number of combinations to produce low-carbon hydrogen. In total, eleven study cases have been pre-selected by the experts from the total wide range of potential combinations (96 in total). They are considered as the most promising cases.

Experts' proposals presented in [Chapter 5](#) give an evaluation of the viability of the whole HyNE system thanks to several tools such as the TRL approach, the safety assessment, the codes & standards, some techno-economic studies provided by different European and international projects, a holistic R&D approach coming from several national laboratories, and an input coming from the end-user requirement. This exhaustive analysis allows an assessment of the viability of the nuclear hydrogen production process and to evaluate the time to market and efforts required to fulfil this objective.

In a logical link with the previous two chapters, [Chapter 6](#) evaluates and ranks the eleven pre-selected cases. The ranking is done upon the TRL of the whole system, an evaluation of the time to deployment and the optimization of the given solution. The most mature cases (i.e., alkaline electrolysis with existing reactors) do not lead to the most promising optimized solutions. The most promising ones are found by coupling High Temperature Steam Electrolysers with a dedicated Small Modular Reactor (water cooled) or with a dedicated Advance Modular Reactor (helium, lead or sodium cooled).

Even if significant efforts are deployed by national laboratories to make this nuclear hydrogen production progress, experts are identifying this technology in a valley of death situation. This is a typical situation when proposing a disruptive solution. The objective is therefore to investigate the current situation and to

propose solutions to mitigate it. In [Chapter 7](#), Task #44 experts propose several recommendations to get out of this valley of death as quickly as possible. They analyse the HyNE solution by a PESTEL and creative SWOT analysis. Recommendations are towards two directions: i) Increase the number of real demonstrations by using existing experimental nuclear reactors and by creating new microreactor (0.1 to max 10MWth) fully dedicated to these needs (i.e., like the MARVEL reactor proposed as test rig in the USA); ii) seek high potential future markets by producing hydrogen not as an energy vector but as the first step to production of high value molecules.

By making a prospective analysis study, Task #44 experts have investigated several potential scenarios where the HyNE solutions may be well positioned among the global energy market and worldwide competition. These scenarios of hypothetical futures are created from a methodology proposed by the strategic corps of army. They are particularly well suited to these current conditions where uncertainties and geopolitical tensions around the future energy paradigm are becoming more and more meaningful.

The last chapters ([Chapter 8](#) and [Chapter 9](#)) are summarizing the roadmap of this Task #44 and main events allowing to visit the hydrogen production during the several workshops organized. As expressed at its creation, the objective was to make a fair analysis and check the relevance of nuclear energy for hydrogen production without any « *a priori* » or ideological bias, but just a fact-based analysis. [We](#)<sup>1</sup> believe that this document meets these conditions. We tried to propose innovative methods and approaches to provide an original point of view on this complex subject.

Several hurdles and bottlenecks have been identified. Nevertheless, HyNE is a promising technological solution that can be proposed as a key area for continued activities within the IEA.

<sup>1</sup>: All Task #44 expert members are listed in [Chapter 10](#).

# Preamble

*This report has been integrally written with 0% of LLM Artificial Intelligence, but thanks to 100% of human and collective intelligence. AI LLM was used only for the cover page.*

## CHAPTER 1

# Introduction & Task #44 management

## §1 - KEY TAKE AWAYS

- i. *The global energy system is transitioning towards new energy systems driven by geopolitics and its move to decarbonization with an ambitious target of net zero emissions by 2050. This creates uncertainties that require exploring multiple, combined decarbonized energy scenarios beyond the massive use of fossil fuels.*
- ii. *Hydrogen can play a role as an energy vector for decarbonization, energy storage, and hard-to-abate sectors, even if electricity and heat remain central pillars of the future energy system.*
- iii. *Nuclear energy has strong potential beyond electricity generation, providing reliable low-carbon power and high-temperature heat for large-scale hydrogen and synthetic fuel production.*
- iv. *Energy security, sovereignty, and industrial competitiveness have become important (urgent) drivers, making it necessary to reassess nuclear-hydrogen solutions under new technical, economic, and regulatory conditions.*
- v. *The IEA H<sub>2</sub> TCP Task #44 (named HyNE for Hydrogen from Nuclear Energy) has been set up to deliver a neutral, industry-focused framework to evaluate, guide, and accelerate viable hydrogen production techniques from nuclear energy for policymakers and business developers.*

## 1.1 Background and rationale

The energy world is changing and is fast moving towards an uncertain new energy paradigm which is no longer based on massive crude oil and coal consumption: we need to pave the way towards the decarbonization of all energies and industrial process according to new scenarios accelerating energy transitions and sovereignty.

In this global energy trade, we are in a particular transition phase where i) we cannot exactly forecast what the future energy scenarios will be, ii) we cannot trust the old patterns, and we need to investigate multiple scenarios, and iii) the global transition to net zero emissions in line with COP28 outcomes is a tough challenge. Therefore, it is crucial to investigate all solutions, fitting global or specific (local) needs.

In this coming new energy system, the future model could be preferentially centered on two primary energy vectors: electricity and heat. But the challenge is not focused only on energy producers, it must also concern the energy end-users: industrial hubs, heavy industries, transportation...

In this context, hydrogen is hailed as a promising energy vector in storage, energy regulator, and within the chemical industry as a based chemical product to decarbonize the industry (i.e., fabrication of synthetic fuel and/or ammonia). Moreover, nuclear energy could provide a key position in this energy mix because it has the potentiality to supply future energy needs in particular due to its high energy density.

Thus, the future of nuclear energy cannot be identified only as an electricity supplier. Its portfolio will significantly increase and must include for the future several energetic services, including hydrogen production, synthetic fuels and high-value chemical products (e-fuel, SAF (Sustainable Aviation Fuel) & SMF (Sustainable Maritime Fuel), ammonia, urea...). In addition to decarbonization, there is an increasingly urgent need for energy security (diversification of energy sources) worldwide, with a need for countries to regain energy sovereignty. This leads to new socio-economic challenges such as technology leadership, high skilled job, energy network and distribution.

All these points have been confirmed during the 2026 IEA Ministerial Meeting on Feb. 2026<sup>2</sup>. In the frame of Energy Security, the summit *“recognised the importance of multilateral cooperation and that global energy systems face heightened and more complex risks, driven by geopolitics, supply chain vulnerabilities, extreme weather events and cyber security. Many Ministers recognised that accelerating energy transitions offers opportunities to diversify energy sources, lower energy costs and enhance system resilience. They also stressed the need to scale up investments in a diverse range of energy sources and technologies to enhance resilience, affordability, sustainability and security”*.

In this context the IEA H<sub>2</sub> TCP Board raised the necessity to get a dedicated task on that subject because the context and transition to new secured energy scenario and energy transition to net zero emission has considerably changed. Nuclear energy has to be taken into account as a large-scale energy supply, and it appears necessary to re-evaluate its potentialities using electricity production and/or coupling its heat sources with some hydrogen production processes<sup>3</sup>. The techno-economic situation has also changed and conclusions provided in the past have to be reconsidered under a new energy paradigm, new global and environmental context, and new constraints too (regulation, low carbon hydrogen...). The role of this task will be to help and advise decision makers and at the same time to act as an aggregator of information and facilitator to reduce the time to market for some relevant solutions, coupling nuclear energy and hydrogen production process.

## 1.2 Task #44 - Description & Management

This Task aims to identify and provide analysis on the development of Hydrogen production from Nuclear Energy. The acronym **HyNE** (Hydrogen from Nuclear Energy) will be often used for the continuation of this document.

---

<sup>2</sup>: <https://www.iea.org/news/2026-iea-ministerial-chair-s-summary>

<sup>3</sup>: 2026 IEA Ministerial Chair's Summary has resumed its position regarding nuclear energy as follow: *“Many Ministers noted the renewed interest in nuclear energy as a secure, low-emissions and dispatchable source to meet growing energy demand, considering full lifecycle aspects and nuclear safety. They underscored the need for a reliable, long-term vision to foster bankability of new projects, including small modular reactors, accompanied by market-appropriate incentives and clear government guidance to mobilise public and private investment, noting in particular the importance of designing incentives and policy frameworks suited to national electricity market characteristics. They also highlighted supply chain resilience, skill development of the workforce, cooperation among like-minded countries as key enablers of deployment and to achieve economies of scale and innovation. In this context, a significant number of Member countries encouraged the IEA Secretariat to strengthen its analytical and advisory work on nuclear energy within an all-fuels, all-technologies approach, including monitoring market and policy developments, and supporting diversified supply chains and investment dialogue.”*

This Task served as a platform and framework for sharing and contributing information on the different possibilities of hydrogen production from nuclear energy by:

- identifying the on-going and planned activities in this subject,
- providing a holistic analysis of the situation, context and constraints to identify all conditions to fulfil for this technology to be deployed.

This Task is not defined to promote nuclear energy but to identify in what situation and according to which conditions, nuclear energy could be one of the solutions for the large-scale production of hydrogen.

## 1.3 Task #44 (HyNE) Objectives

The objectives of this Task are multiple and listed below:

- Get an overview of the technical and economic analysis and survey on the key points to develop a competitive hydrogen production from nuclear energy in different contexts.
  - Identify barriers and hurdles to the progress of hydrogen from nuclear energy systems.
  - Identify R&D needs, demonstrations and recent progress.
  - Provide global analysis on the implementation of a nuclear system in a regional ecosystem (including the nuclear reactor, the hydrogen production process, storage, transport, and distribution as well as its final utilization, especially for heat and/or hydrogen consuming industries).
- Deliver general guidelines and recommendations to both business developers and policymakers.
  - Comprehensive analysis, tools, guidelines to inform and facilitate decision processes (investment decisions, policy measures...) and to propose also recommendations to allow current and future hydrogen deployment coming from nuclear energy.
  - Develop nuclear energy for hydrogen production as a key energy carrier for a sustainable and smart energy system.
  - The collected data and results would enable this task to deliver to policy makers, industrials, licensing authorities and investors, and more generally to IEA member states, advice to assess which nuclear systems are best suited and in which context.

The Definition of Task structure has included six subtasks in its early definition phase. The interaction between all the Subtask are described in the following figure represented by the green and violet arrows.

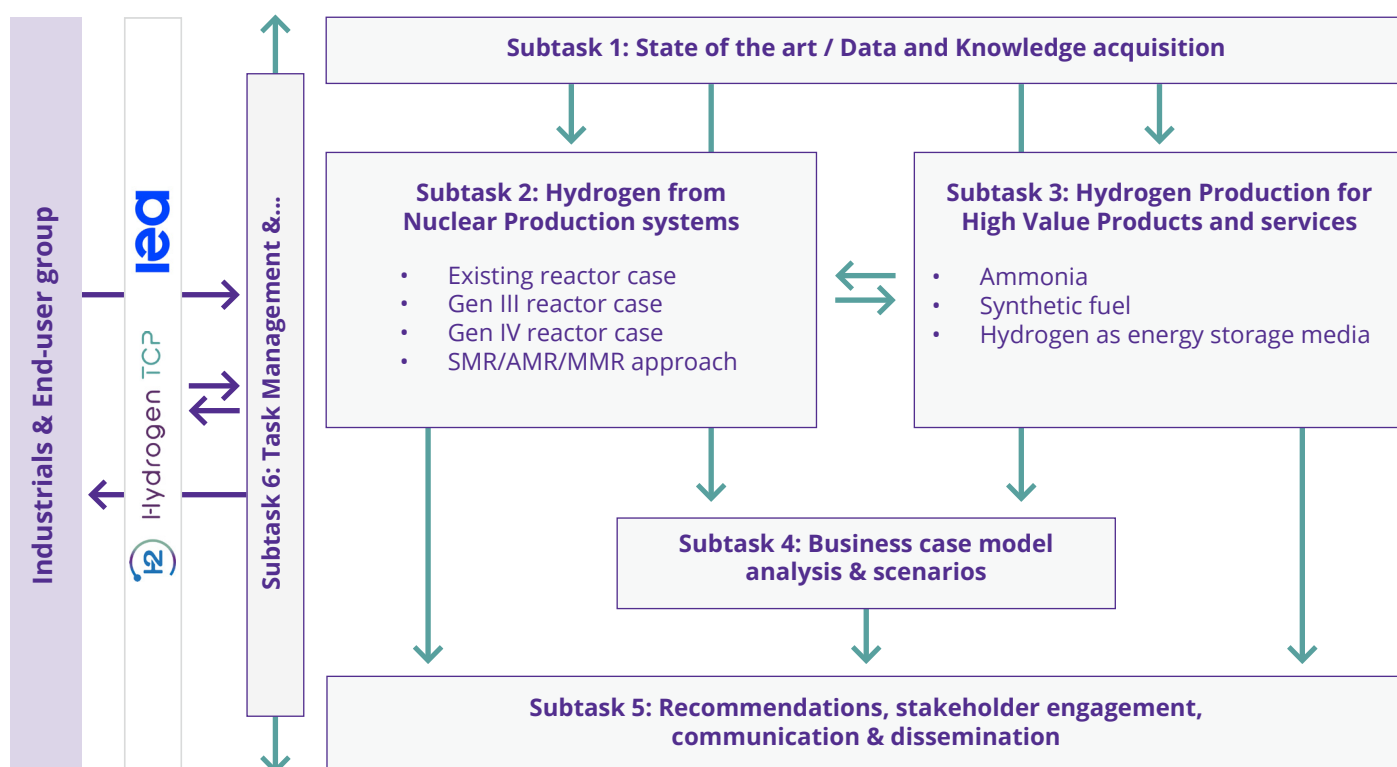


Figure 1: Task #44 breakdown structure

The Task ran from Feb. 2023 until April 2026, and its internal organization was integrated without formal subtasks, partly due to the absence of identified sub-task leaders. But an identical level of expertise was covered in all boxes. HyNE Task worked with a group of around 50 experts managing regular virtual monthly meetings and yearly in-person meetings where we took the opportunity to visit the hydrogen facilities on-site (see Annex 1). Task #44 members were primarily focused on industrial deployment rather than academic research, addressing both technical and economic aspects, looking for solutions already at relatively high Technology Readiness Levels. In a nutshell the major objectives of the HyNE Task are synthesized in the following Figure.

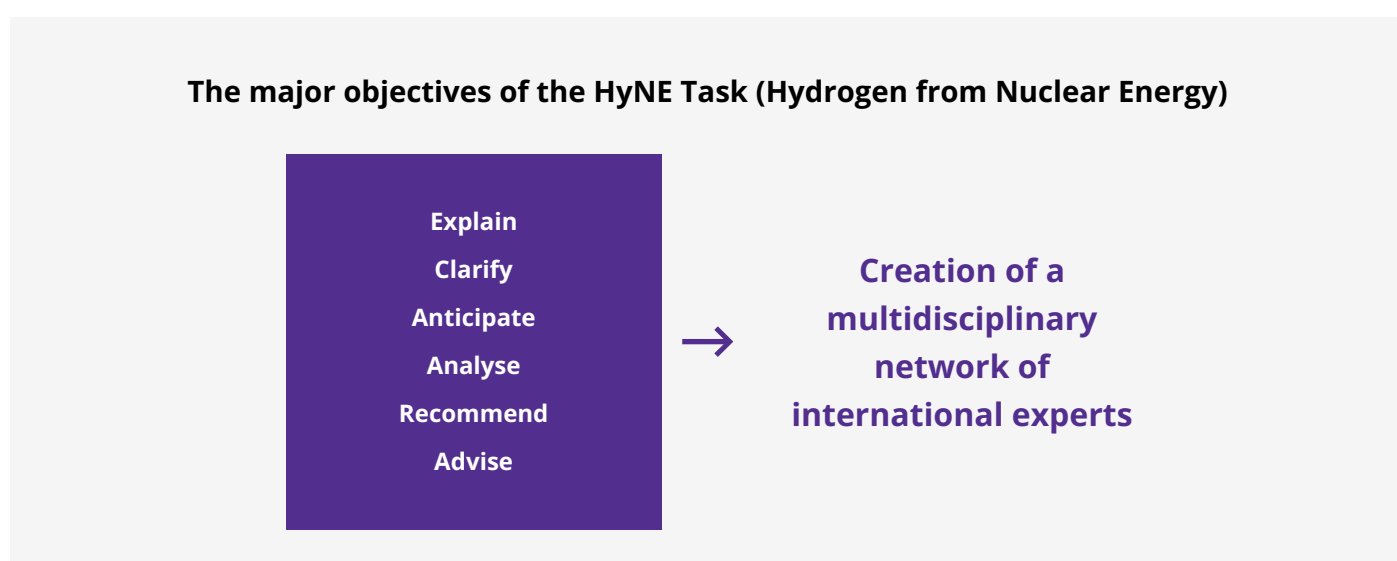


Figure 2: The Task #44 major objective as expressed when created

## HyNE COMPANY DISTRIBUTION



## HyNE MEMBER DISTRIBUTION BY COUNTRY

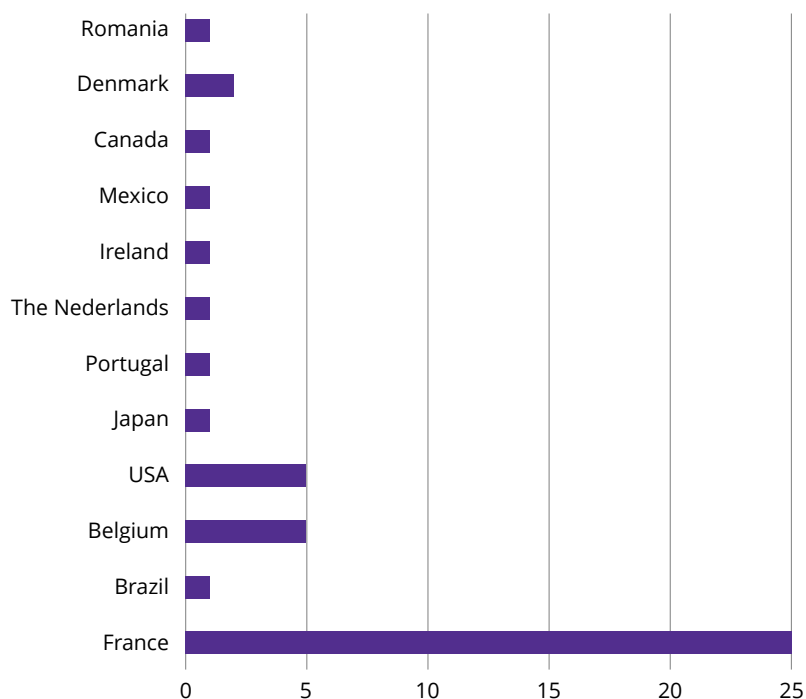


Figure 3: The Task #44 representation by type of organization and by country

The following chapters present the results and input data of 3 years coming from all members who generously provided their expertise, data, open results and short notes written collectively to take important positions (see Annex 1 to 7).

## CHAPTER 2

# The need of low carbon hydrogen

## §2 - KEY TAKE AWAYS

- i. *The increasing demand of low carbon hydrogen is not ramping up as projected.*
- ii. *The growing demand for hydrogen is more likely to be seen in the 2030's. This delay can be seen as an opportunity to increase in maturity the low-carbon hydrogen solutions.*
- iii. *It is important to overcome a "Wait and see" position, to anticipate the potential fast and rising future demand in hydrogen. This allocated time can serve to increase the technological readiness of the systems, and to be technically mature when a larger demand will come from industrials and end-users.*
- iv. *Nuclear energy has already anticipated this trend where new nuclear projects are not only proposing delivering electricity but a larger portfolio of energy sources for non-electric usages: heat (for industry or for desalinisation systems), steam supply, hydrogen as an energy vector, or hydrogen for the production of ammonia or e-fuels molecules (H<sub>2</sub> as value chain).*
- v. *Thus, the hydrogen sector has to be recontextualised in a "thirsty" energy situation where the global needs for energy in all aspects are fast growing in various sectors.*

In its 2025 IEA Global Hydrogen Review report<sup>4</sup>, IEA depicts an uneven situation and prediction for the future of the hydrogen sector and moreover for the position of low-carbon hydrogen production. Indeed, the global hydrogen demand increased to almost 100 million tonnes (Mt) in 2024, up 2% from 2023 and in line with overall energy demand growth. But this growth is far less than the expected projection provided in the 2020's.

This hydrogen sector is still being dominated by the use of fossil fuels. Low-carbon hydrogen production grew by 10% in 2024 and is on track to reach 1 Mt in 2025, but it still accounts for less than 1% of global production.

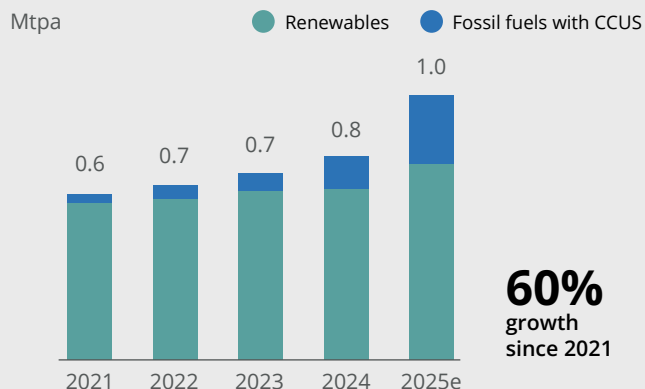
This observation is global and several enquiries are confirming locally (nation, continent) this matter of fact (*See Insert 1 the dedicated SISYPHE study*). The uptake of low-carbon hydrogen is not yet meeting the ambitions set in recent years being held back by high costs, uncertain demand and regulatory environments, and consequently slow infrastructure development. Despite this situation, some figures and indicators are showing that - even if some statistic predictions were far too ambitious – the sector of low carbon hydrogen production can reasonably ramp up by 2030.

<sup>4</sup>: 2025 IEA Global Hydrogen Review, <https://www.iea.org/reports/global-hydrogen-review-2025>

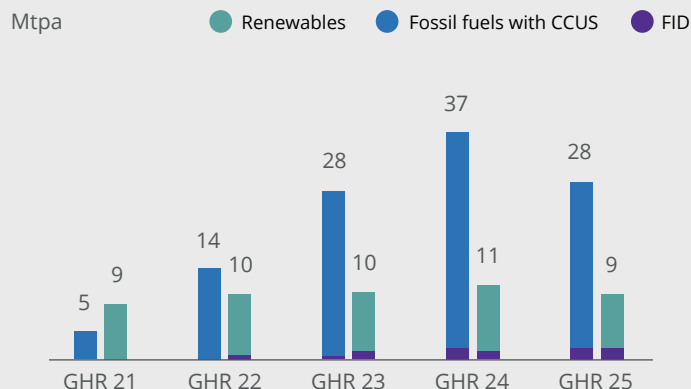
# The Global hydrogen review summary program [Source the Global Hydrogen Review 2025]

## PRODUCTION

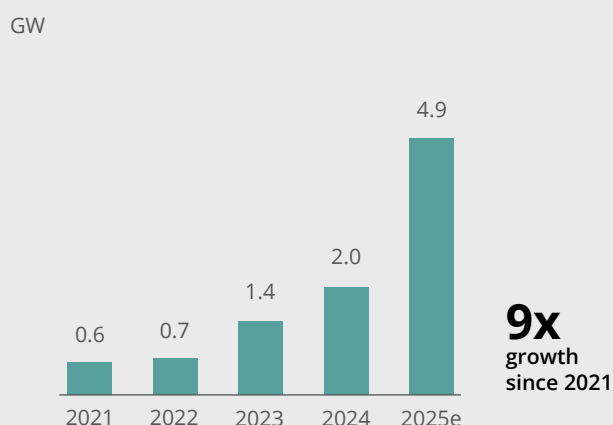
### Low-emissions hydrogen



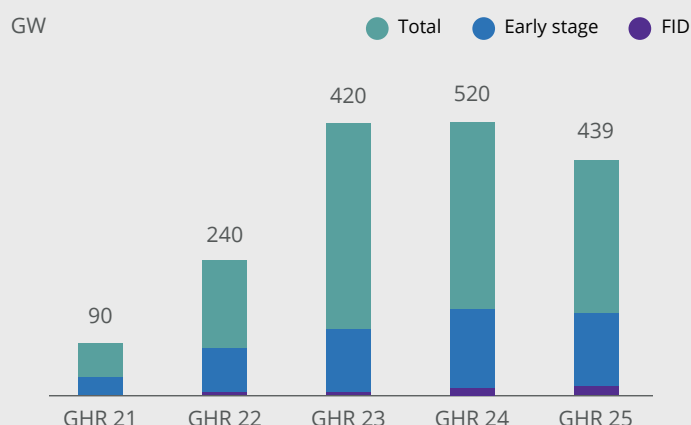
### Low-emissions hydrogen production from announced projects by 2030



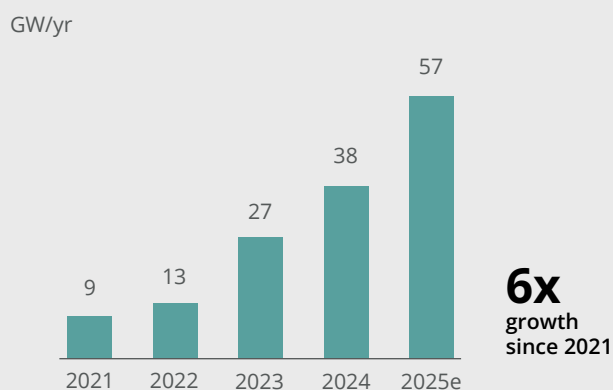
### Electrolyser installed capacity



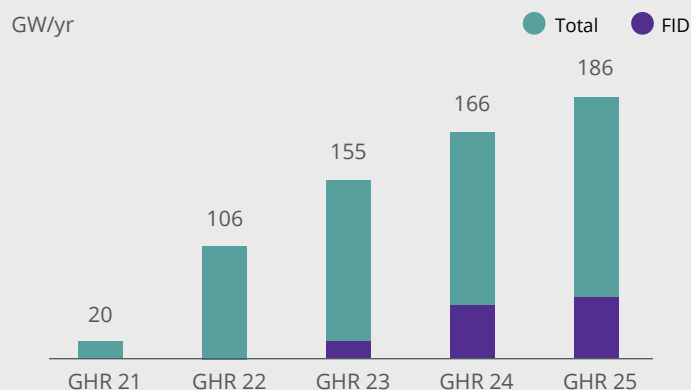
### Announced electrolyser projects by 2030



### Electrolyser manufacturing capacity



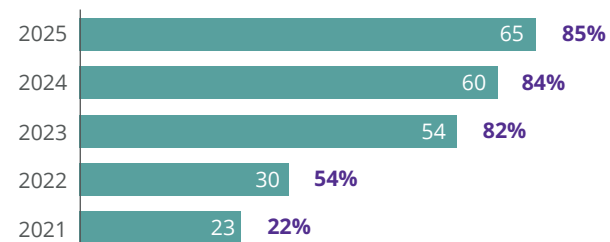
### Announced electrolyser manufacturing capacity by 2030



## POLICIES

Share of energy-related CO<sub>2</sub> emissions

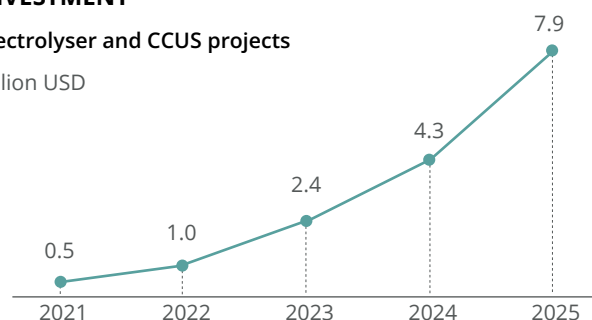
### Number of hydrogen strategies



## INVESTMENT

### Electrolyser and CCUS projects

Billion USD



Note: 2025e = Estimated based on announced projects. FID = Final Investment Decision.

Figure 4: The Global hydrogen review summary program [Source the Global Hydrogen Review 2025]

The cost gap between low carbon hydrogen and unabated fossil-based hydrogen production remains a key barrier for project development but – according to the 2025 IEA Global Hydrogen Review – the gap is expected to narrow by 2030. Several actions are favouring this future positive trend. A pragmatic country policy approach remains necessary to support the dynamic of low-carbon hydrogen projects and developments. These different country actions are all going toward the same target to favour the hydrogen sector serving as a financing support and providing confidence to future investors. They are a relay to address the cost gap until the low carbon hydrogen economy can be self-sustained by the end-user demand. They serve to reduce the investment risk and lower the cost of capital during this uncertain transition phase<sup>5</sup>.

At this period of time, it is essential to avoid a “wait and see” situation but on the contrary to take benefit of this transition time to investigate all technology solutions that could meet the future demand. Indeed, when this demand grows, the demand for mature, low cost and easy to implement solutions will be the new key parameter and the main driving force. If the hydrogen market is driven by industrials and end-users, it is necessary to already prepare solutions to answer to their future requirements and meet the customers future demands.

### Comparison of hydrogen policy approaches adopted across selected hydrogen markets

| Category              |  European Union |  United states |  China |  Japan |  India |
|-----------------------|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| <b>Targets</b>        | 2030: 40 GW of domestic electrolyser capacity                                                    | -                                                                                               | 2025: 100-200 kt green hydrogen production                                              | 2030: 3 Mtpa of hydrogen consumption                                                      | 2030: 5 Mtpa green hydrogen production                                                    |
| <b>Supply</b>         | European H <sub>2</sub> Bank<br>IPCEI<br>Innovation Fund                                         | Inflation Reduction Act<br>(45V, 45Q, 45Z, 48C)                                                 | Provincial subsidies;<br>roll-out through SOEs                                          | CfD scheme                                                                                | Financial support for electrolysis, ammonia, manufacturing                                |
| <b>Infrastructure</b> | H <sub>2</sub> and gas markets decarbonisation<br>IPCEI; AFIR; CEF                               | Support for hydrogen refuelling stations                                                        | Support for new hydrogen pipelines                                                      | Clusters support scheme; CAPEX subsidy for storage                                        | Hydrogen Valley Innovation Clusters                                                       |
| <b>Demand</b>         | RED; ReFuel Aviation; FuelEU Maritime; CISAF; IPCEI                                              | Loan guarantees, tax credits, ZEV mandates                                                      | Implementation plan for industry; FCEV tax exemptions/ subsidies                        | Hub support; tax credits for industry; FCEV subsidies                                     | Guaranteed offtake through SECI                                                           |
| <b>Certification</b>  | Delegated Acts for renewable and low-carbon hydrogen                                             | Clean Hydrogen Production Standard (CHPS)                                                       | Clean and Low-Carbon Hydrogen Energy Evaluation Standards                               | Hydrogen Society Promotion Act                                                            | Green Hydrogen Standard                                                                   |
| <b>R&amp;D</b>        | Clean Hydrogen Partnership                                                                       | Offices of Energy Efficiency, Renewable Energy, FECM                                            | Demo programmes across the entire value chain                                           | Green Innovation Fund                                                                     | R&D scheme of National Green Hydrogen Mission                                             |

IEA. CC BY 4.0.

Notes: AFIR = Alternative Fuels Infrastructure Regulation; CEF = Connecting Europe Facility; CfD = Contract for difference; CISAF = Clean Industrial State Aid Framework; FCEV = Fuel cell electric vehicle; FECM = Fossil Energy and Carbon Management; IPCEI = Important Projects of Common European Interest; RED = Renewable Energy Directive; SECI = Solar Energy Corporation of India; SOE = State-owned enterprise; ZEV = Zero Emission Vehicles.

Figure 5: The different hydrogen policy approach in several countries [Source the Global Hydrogen Review 2025]

<sup>5</sup>: In innovation sectors this situation is known as “Valley of death”. – See § 7 of this document.

The hydrogen sector has to be recontextualised in the energy situation where the need is fast growing<sup>6</sup> (see Figure 6), and predictions remain increasing. Thus, if we consider this megatrend and extrapolate weak signals relative to low carbon hydrogen production, it is important to grab the opportunity of this dedicated period of time until the 2030's to raise the technology maturity of all hydrogen production systems, being technologically operational when then growing and pressing demand on hydrogen will come.

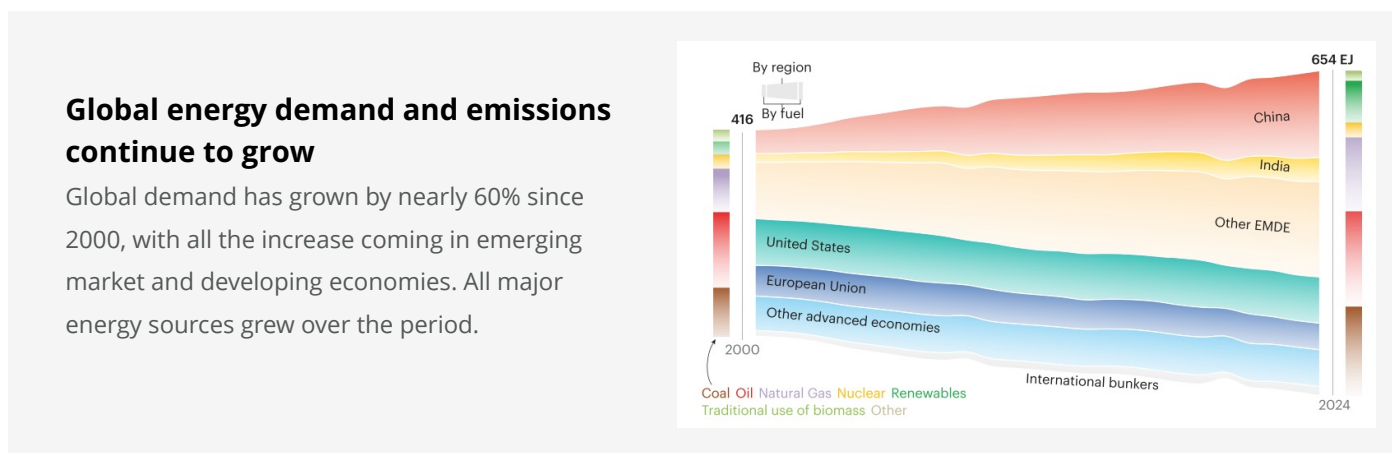


Figure 6: Global Energy demand [Source the 2025 IEA Energy Outlook]

In this future potential scenario seen as an opportunity for the production of low-carbon hydrogen, nuclear energy can play a key role. “Nuclear hydrogen production” is defined as the production of hydrogen using nuclear energy in the form of nuclear based electricity, or in most frequent situations with a combination of electricity, steam, and heat produced within the nuclear island. The advantage of using nuclear energy – apart from its low carbon emissions – is its power density<sup>7</sup>, its ability to produce continuously several “energy sources” (electricity, steam and/or heat) at stable costs and with high load factors (90% or more for operational Pressurized Water commercial reactors). Thus, we find renewable and nuclear energy to be good complementary systems which can be used to address the entire growing low-carbon energy demand.

On this specific situation where electrification of many applications is becoming one of the main answers to cope with climate change and abate CO<sub>2</sub> emissions<sup>8</sup>, a large number of nuclear projects are now proposing not only to produce electricity (as it was still the reference until the end of the 1990’ – 2000’s) but a portfolio of energy services with a flexible ability to dedicate one part of the steam produced for non-electric usages: heat (for industry or for desalinisation systems), steam supply, hydrogen as energy vector, or hydrogen for ammonia or e-fuels molecules production (H<sub>2</sub> as value chain). One main drawback of nuclear energy implementation is its time to deployment. The time required for a nuclear reactor to be built is estimated to range between 8 and 10 years.

Thus, the delay in the increased low-carbon hydrogen demand can also be seen as an opportunity for the nuclear field to raise its maturity level of designing nuclear reactors to operate in a cogeneration mode. The solutions of producing hydrogen with nuclear energy have to be available and technologically mature when the time to market arrives.

<sup>6</sup>: As expressed in the 2025 IEA Energy Outlook, page 17: “the world remains thirsty for energy”. <https://www.iea.org/reports/world-energy-outlook-2025>

<sup>7</sup>: The land area requirement is about 100-150 times less compared with solar PV units for a same units of electricity generated on an annual basis.

<sup>8</sup>: In the 2025 World Energy Outlook, IEA is titling “The Age of Electricity is here”, mentioning that “Electricity is at the heart of modern economies and electricity demand grows much faster than overall energy use in all scenarios.”

### Insert 1: SISYPHE Study: European trends for demand of low carbon hydrogen

## Insert 1: SISYPHE STUDY: EUROPEAN TRENDS FOR DEMAND OF LOW-CARBON HYDROGEN UNTIL 2040

The REPowerEU plan, launched by the European Commission in 2022, sets an ambitious consumption target of 20 million tons per year of renewable hydrogen by 2030 in the EU, with 10 million tons to be produced in Europe. By way of comparison, 9 million tons of hydrogen (mostly of fossil origin) are consumed in Europe today, mainly by the refining and chemical industries. Through the SISYPHE study, the CEA has tried to evaluate the trends of demand for low-carbon hydrogen in Europe up to 2040.

CEA's SISYPHE study<sup>9</sup> shows a significant gap between the European target and the projected demand for low-carbon hydrogen in Europe by 2040. This projection is based on projects actually underway and on the forecasts of some 70 European industrials or stakeholders questioned about their potential hydrogen needs. The study evaluates the demand for electrolytic hydrogen at 2.5 million tons in 2030 and 9 million tons in 2040. This shows a high risk of not achieving the targets set at European level, even if the uncertainties underlying the projections are numerous. The study highlights very different trends among potential hydrogen-consuming sectors. As things stand, steel industry and air transport are likely to have the largest demand for electrolytic hydrogen over the 2030-2040 period.

To date, few of the industrialists surveyed have a precise vision of what their hydrogen consumption will be over the decade 2030-2040. For this reason, the SISYPHE study is based on a quantitative framework reflecting the current trends as revealed by the interviews. The trajectory of demand for electrolytic hydrogen has been defined on the basis of the following assumptions:

- A flat demand for fuel in maritime and air transport, as well as for hydrogen in the chemical sector
- A compliance with European regulations imposed on the air transport, shipping and chemical sectors (excluding ammonia);
- The inclusion of projects undertaken today in the steel, ammonia production and refining sectors;
- A very gradual development of road mobility, mainly driven by the deployment of light commercial vehicle fleets.

This trajectory therefore **reflects the trends of the projects underway and the regulations set for 2023**. It does not prejudice any new regulations that may arise.



Figure 7: European Energy sectors

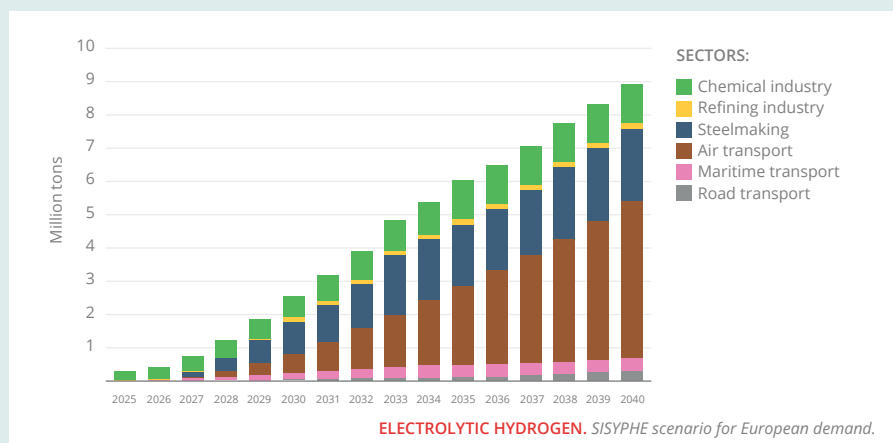


Figure 8: The Proposed SISYPHE scenario on Hydrogen needs (2025-2040)

<sup>9</sup>: <https://www.cea.fr/english/Documents/scientific-and-economic-publications/sisyphe-study-european-trends-for-demand-low-carbon-hydrogen-until-2040.pdf>

## CHAPTER 3

# Hydrogen from nuclear energy: a technological solution for large scale hydrogen production

## §3 - KEY TAKE AWAYS

- i. *The nuclear energy sector has evolved towards several phases, from GEN I to GEN IV types. Today the trend is to diversify the usage of nuclear reactor systems, designed more closely in connection with the end-users needs.*
- ii. *The design of Small Modular Reactors (SMRs) and/or Generation IV type nuclear reactors is considering more than simply just electricity production. Nuclear systems are now investigating a larger portfolio of non-electric and cogeneration usages.*
- iii. *All cogeneration solutions with nuclear reactor can lead to hydrogen production, but this Task has focused on investigating high temperature solutions (High Temperature Steam Electrolysis and Thermochemical cycles) to take advantage of the heat (or superheated steam) directly produced by nuclear reactors and increase its global yield.*
- iv. *To produce hydrogen with a nuclear reactor in a cogeneration mode two major principles are carried out:*
  - *Use of thermochemical cycles that have been developed in the 1980's, that are now focused on the Iodine Sulphur process (I-S) and the Copper Chlorine hybrid process (Cu-Cl),*
  - *Use of High Temperature Steam Electrolysis (HTSE) developed since the 1990's with Solid Oxide Fuel Cells that can operate in reverse mode as an electrolyser.*
- v. *The thermochemical cycles require high temperature output from the nuclear reactor (500°C for the Cu-Cl hybrid process and 800°C for the I-S process). The HTSE can operate with a larger range of temperature output allowing coupling with lower temperature operating nuclear reactors and hence compatibility with the Pressurized Water Reactor (PWR). In this specific case, the additional heat input to boost input steam (at 250-350°C) to reach 700°C in the HTSE can be done by heat recovery from the gas exhaust and by increasing the cell current density.*

## 3.1 Background and history

Co-generation is a means of using a source of energy, in this case energy from a nuclear reactor, to efficiently produce power and thermal energy. Since a great deal of the heat energy is lost to the environment in a power plant<sup>10</sup>, making use of wasted energy for other useful outputs like the production of hydrogen and direct heating would be advantageous to plant economics and energy system flexibility. The aspiration of using a nuclear reactor as the energy source to enable hydrogen production in a co-generation arrangement provides great opportunities to decarbonise energy systems and improve energy efficiencies.

<sup>10</sup>: The global thermal efficiency of a nuclear plant producing 100% electricity output is about from 33 to 42% maximum. But the mean yearly load factor is between 70 to 80%. In electrical engineering the load factor is defined as the average load divided by the peak load in a specified time period. It is a measure of the utilization rate, or efficiency of electrical energy usage; a high load factor indicates that load is using the electric system more efficiently.

The combination of using nuclear power (electricity and heat) to produce large quantities of hydrogen is not a new concept. It came from the 1970's in the particular international context of the oil energy crisis. With time, the geopolitical and energetical world situation has largely evolved. Nevertheless, it appears important in the current context to recall briefly the background and history of civil nuclear reactors, hydrogen production processes and the idea of their coupling for cogeneration purposes. This chapter referring back to "history from the first ages" is produced to better understand today's Task #44 work orientations.

### 3.1.1 A succinct presentation of the civil nuclear reactor history

The development of nuclear reactors for commercial electricity production started just after World War 2. After several demonstration systems in the 50's and 60's, the first nuclear reactors developed for electricity production were produced in the 60's with several nuclear reactor concepts using different kind of coolants (helium, water or liquid metal<sup>11</sup>). This period is denominated by GEN I & II nuclear reactors. The commercial nuclear reactor fleet expanded rapidly during the 80's with a significant increase at the end of the 80's. This could be explained by the maturity level attained to develop large power commercial reactors, most of them as water cooled technologies, either in pressurized water or boiling water configurations.

This inflection point can also be understood in some countries - typically in France - as an answer from the mid 70's oil crisis with a certain delay corresponding to the nuclear reactor construction time<sup>12</sup>.

At this time the nuclear reactors built were designed to produce electricity despite the non-electric applications of nuclear heat that were also envisaged and tested in some cases at low power scale<sup>13</sup>. The nuclear reactors built during the 70's and 80's decades are known as GEN II reactors. The transition from GEN II to GEN III reactors was motivated by enhanced safety features and larger power requirements. The power of reactors plants increased with time from 600 MWe up to 1600 MWe for the last versions in Europe. It is usual to find several nuclear reactors at the same nuclear site. Thus, site installed capacities can reach up to 8000 MWe (Kashiwazaki Kariwa in Japan, Niigata prefecture). This evolution is a response to an economy of scaling-up and concentration of nuclear infrastructures in a unique nuclear island.

The GEN III nuclear reactors built from the 90's have to adhere to the requirements of new safety assessments taking into account the knowledge gained by accumulating hundreds of years of nuclear power plant monitoring worldwide and also considering a better approach to severe accident scenarios<sup>14</sup> (such as core melting). These so-called GEN III nuclear reactor designs are a scaling up evolution of the previous designs using – for most of them – water as coolant (boiling or pressurized).

---

<sup>11</sup>: EBR-1, the first nuclear reactor to produce electricity using nuclear energy at INEL (USA) was sodium-potassium eutectic (NaK) cooled! 20th Dec. 1951, four 200-watt light bulbs were lit up for the first time by electricity generated by nuclear power.

<sup>12</sup>: The history of nuclear power in France, by Virginie Lefèvre, <https://www.sirenergies.com/en/article/history-of-nuclear-power-in-france>

<sup>13</sup>: The use of nuclear energy for district heating, Peter Margen, Progress in nuclear energy, Volume 2, Issue 1, 1978, Pages 1-28.

<sup>14</sup>: Design Extension Condition (DEC) according to the IAEA terminology.

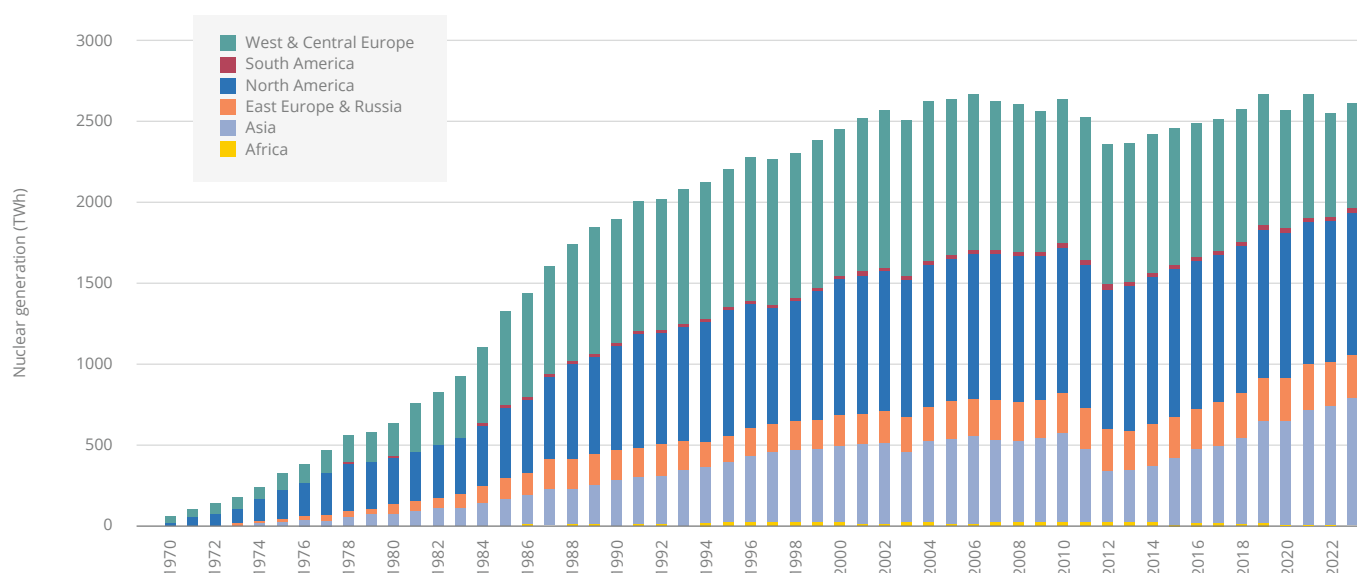


Figure 9: The sum of world nuclear power capacity from its early beginning<sup>15</sup>

The GEN IV reactors are concepts selected by the GIF international organisation (GIF for Generation IV International Forum) in 2000. The six GIF systems are all disruptive systems compared to GEN III concepts.

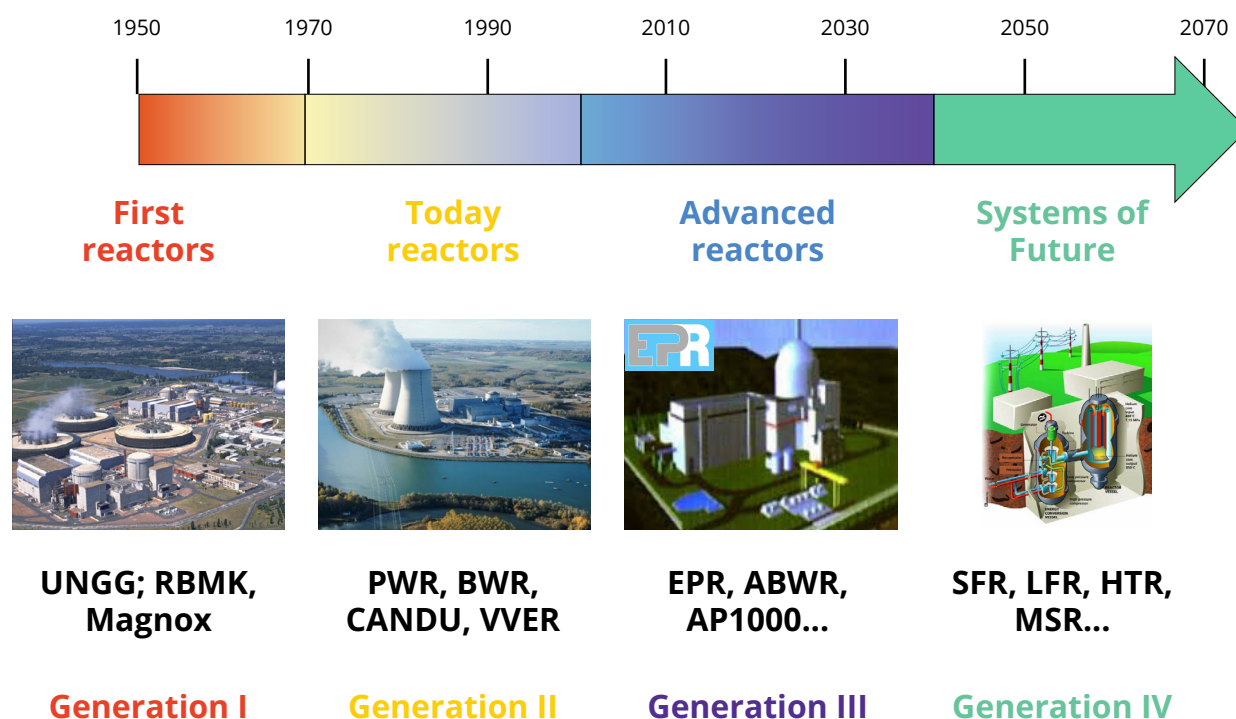


Figure 10: The civil nuclear reactor generation from GEN I to GEN IV<sup>16</sup>

<sup>15</sup>: Source: World Nuclear Association and IAEA PRIS, <https://world-nuclear-news.org/articles/record-breaking-year-for-nuclear-electricity-generation>

<sup>16</sup>: Note that the SFR and HTR are actually enter into the deployment stage in several countries.

Among the six selected systems (Lead Fast Reactor, Sodium Fast Reactor, Molten Salt Reactor, Very High Temperature Reactor, Gas Fast Reactor and Super Critical Water Reactor<sup>17</sup>), the first five are operating with a high temperature coolant - equal to or over 500°C - which offers the following advantages:

- Increase the thermodynamic cycle efficiency,
- Think about non electric applications and cogeneration solutions,
- Use optimally the nuclear fuel, thanks to fast neutrons flux to allow a positive breeder ratio and a closed fuel cycle system.

From these six systems, the VHTR (T° output > 800°C, potentially up to 1000°C) was specifically selected at the start for its non-electric application capability and its ability to produce hydrogen. This nuclear type was initially conceived not uniquely for electricity generation, but first of all for large scale hydrogen production. Later, all other GEN IV nuclear systems with high temperature coolant output were also considered as potentially being able to produce hydrogen with a high yield. During this period of time (2000's – present day), two hydrogen production concepts were considered to be heated coupled with a nuclear reactor: Thermochemical Cycles and High Temperature Steam electrolysis.

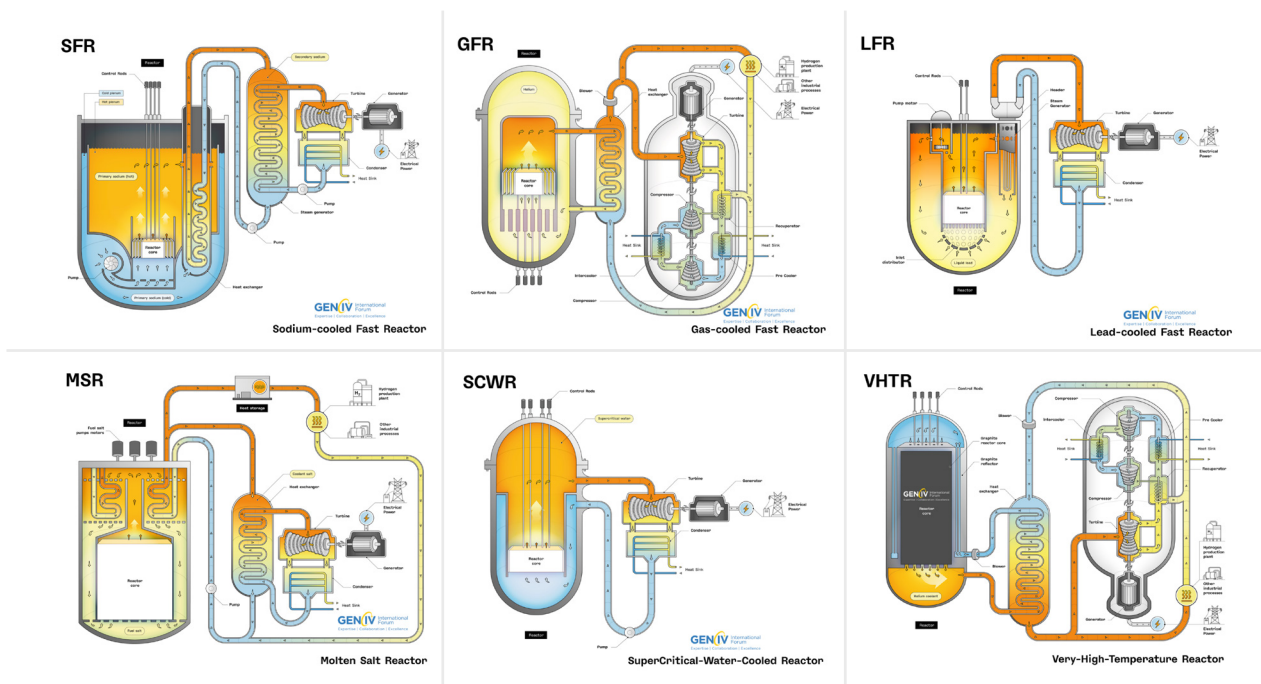


Figure 11: The six selected GEN IV concepts<sup>18 19</sup>

In the 2010's, a new phase of nuclear reactor concepts arose: the SMR (Small Modular Reactor). SMRs are not strictly driven by new technologies but principally by new techno-economic approaches. We are switching from an economy of “scaling up”<sup>20</sup> to an economy of scale. We consider an economy of “scaling-up” when a nuclear company saves

<sup>17</sup>: LFR=Lead Fast Reactor; SFR=Sodium Fast Reactor; MSR= Molten Salt Reactor, VHTR=Very High Temperature Reactor, GFR=Gas Fast Reactor, SCWR=Super-Critical Water Reactor.

<sup>18</sup>: Source: <https://www.gen-4.org/generation-iv-criteria-and-technologies>

<sup>19</sup>: See in Annex 5 a larger view of the six GENERATION IV Systems

<sup>20</sup>: This terminology is proposed by the Task #44 experts.

money due to an increase of the unit reactor power. This trend has been followed at the beginning of the nuclear ages moving step by step from demo reactors (150-350 MWe) up to power reactor (1000 – 1200 MWe per unit). An economy of scale is when a nuclear company intends <sup>21</sup> to save money due to an increase in its level of production of an identical standardized product (gain on the learning factor<sup>22</sup>). The SMR approach was initially developed by the USA. These SMR concepts were motivated by proposing to reduce the construction time and decreasing the Levelized Cost of Energy produced by a nuclear reactor, hard pushing on three pillars at the same time<sup>23</sup>:

- Manufacturing & factory build of all Components & Systems, the modularity aspects must be largely adopted. It will shorten the construction time.
- Provide a standardisation of the concept which allows a unique safety authorization for a whole fleet of identical SMRs types worldwide and favour series production.
- Search for design simplification gained by the reduced power (small core power is more favourable to safety case demonstrations and passive safety).

Furthermore, the reduced power of these nuclear reactors (to 50 - 500 MWe) shall allow more flexibility: new market opportunities in some local isolated areas, industrial hubs, non-electric application to provide a wide range of energy services beyond the electricity production (including district heating, hydrogen, high value molecules), and also non-terrestrial applications (maritime system, floating barge platform, icebreaker ship, space systems). In addition, their higher flexibility offers the opportunity to investigate a greater combination with other low carbon energy sources (renewables).

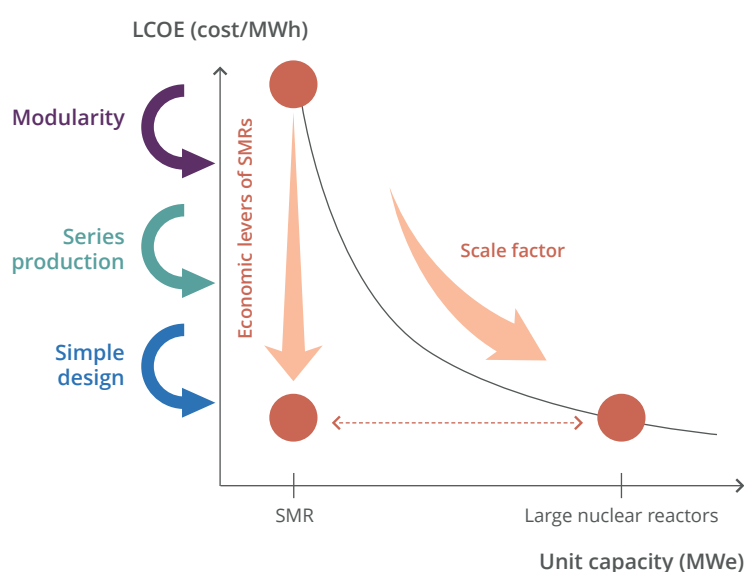


Figure 12: The SMR technico-economic approach to compete with large nuclear reactors

There are now more than 100 SMRs concepts investigated, which can be in two families: the SMR (Small Modular Reactor) is today a Water-Cooled Small Modular Reactor, while the AMR (Advanced Modular Reactor) is gathering all SMR types which are not water cooled (either with helium gas, liquid metal or molten salts). Thus, the actual typology of nuclear reactors is considering large scale (over 1000 MWe) commercial water-cooled reactor in operation (GEN II or III), recently built or being built (GEN III); primarily under design (SMR & AMR). It is worth noting that the SMR or AMR approach has also implicated new actors on the nuclear market. While large power reactors are considered as a commercial product supported by historical nuclear engineering companies; SMRs and AMRs have also seen the creation of numerous start-up companies associated with a combination of public, private and investors funds.

<sup>21</sup>: The verb intend is set on purpose because it has not been yet industrially demonstrated.

<sup>22</sup>: The learning factor refers to the efficiency gain achieved through duplication or replication of modules at a certain learning rate, leading to a reduction in unit costs and increased profitability as smaller modules becomes more attractive. *This definition is based on Computer Aided Chemical Engineering, 2019.*

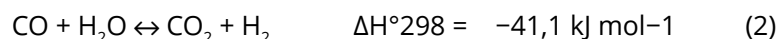
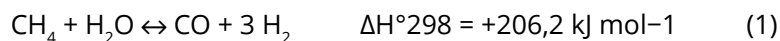
<sup>23</sup>: Rachael E. Josephs et al., "Regulation of Small Modular Reactors (SMRs): Innovative Strategies and Economic Insights", Eng. 2025, 6, 61, <https://doi.org/10.3390/eng6040061>.

Therefore, the recent nuclear ecosystem is becoming more and more complex. An overall view of this current and fast evolving situation is provided by: the OECD SMR Dashboard<sup>24</sup> and the IAEA Platform on Small Modular Reactors and their applications<sup>25</sup>.

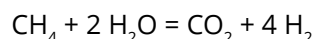
This new approach has largely reorganised the nuclear industry and economy approaches. The cohabitation is between “historical” nuclear engineering companies and start-ups from the USA in the 2010's and expanded to all countries using or developing nuclear energy. The financing of this nuclear ecosystem is becoming more diversified, linked with an expanded market sector where the future nuclear reactor will not have only to produce electricity but propose a wide variety of services. Water desalinisation, district heating, low carbon heat for industry, hydrogen production, synthetic fuel and ammonia production, grid flexibility, long distance autonomy (air, space, maritime), better adaptation to renewables intermittency, local energetic autonomy of isolated areas...: all these applications are now in the potential portfolio of future nuclear reactors which offer moreover the major asset of producing low carbon energy (along with hydro, solar and wind energies). Thus, the future nuclear reactors development – especially SMRs and AMRs – are driven by both the technology and the usage of the energy produced, in service of a future decarbonized society and industry. To illustrate it, in 2009 the IEA used the term of “nuclear renaissance” in its World Energy Outlook book<sup>26</sup>.

### 3.1.2 A succinct history of the hydrogen production and connection with the nuclear field

Today about 95% of the hydrogen produced worldwide is done by Steam Methane Reformation. This solution is not aligned with the future decarbonization goals since it emits CO<sub>2</sub> during the methane dissociation process. The CO<sub>2</sub> emission is in fact produced by two steps: the chemical dissociation itself and the heating required to allow the chemical decomposition. The first chemical reaction operates at 600°C with the presence of a nickel catalyst. The second reaction operates at 200°C.



The overall chemical equation is therefore:



It is considered that today, every kilogram of hydrogen produced results in approximately 7 kg of CO<sub>2</sub> emission, 78% from the stoichiometric ratio of the chemical reaction, and 22% from carbonized energy input<sup>27</sup>. Moreover, the requirement of methane imports to produce hydrogen is a signal of economical dependency. It is subject to significant uncertainties in the actual geopolitical context.

For this reason, other means of hydrogen production have been investigated especially during the several world energy crises. In this context, high temperature hydrogen production systems found their origin in the 70's by coupling the

<sup>24</sup>: [https://www.oecd-neia.org/jcms/pl\\_73678/nea-small-modular-reactor-smr-dashboard](https://www.oecd-neia.org/jcms/pl_73678/nea-small-modular-reactor-smr-dashboard)

<sup>25</sup>: <https://nucleus.iaea.org/sites/smr/SitePages/SMR-Databases.aspx>

<sup>26</sup>: IEA, World Energy Outlook, p160, § Chapter 3.

<sup>27</sup>: I. Dincer et al., Comprehensive Energy Systems, Volume 3, 2018, pages 470-520 – Chap. 3.11 Chemical Energy Production.

water splitting approach with solar energy. Concentrated solar energy systems can reach very high temperature output (over 1000°C) where the opportunity to increase the water dissociation yield due to this temperature range was seen. In the 70's-80's all means of energetic systems were investigated to fight against the oil crisis. Basically, two families of technologies compatible with nuclear reactor were developed: thermochemical cycles and high temperature steam electrolysis. These two HT (high temperature) H<sub>2</sub> production systems were investigated to try to find an alternative that was a technically and economically viable alternative to the Steam Methane Reforming process.

It is interesting to note that within the IEA H<sub>2</sub> TCP framework, the two first tasks were specifically dedicated to this subject:

- Task #01: Thermochemical production (1977 – 1988).
- Task #02: High Temperature Reactors (1977 – 1979).

At the same time, other IEA H<sub>2</sub> TCP Task were dealing with hydrogen production in general. Later, Task #25 (2007-2011) "High Temperature Production of Hydrogen" specifically dealt with the coupling of HT H<sub>2</sub> production processes with nuclear or concentrated solar sources. Therefore, the subject of coupling nuclear reactor with HT H<sub>2</sub> production process is not new. It has regained a large part of interest these recent years with the objective to decarbonize energy and with the new solutions brought by SMR & AMR<sup>28</sup> (see § 3.1.1).

## Principles of the thermochemical cycles

Thermochemical cycles allow the decomposition of water through a series of chemical reactions at temperatures compatible with a HT nuclear or solar energy source. All reactants are recycled within the cycle. This solution appears attractive since, in theory, it avoids the need for an electrical intermediary and therefore theoretically allows higher yields than the electrolytic process. More than 360 thermochemical cycles have been proposed since the 1970's (some of which were evaluated in Task #01!) to compete with electrolysis or Steam Methane Reforming.

The most worldwide studied and experimented cycle is the Iodine-Sulfur process described below.

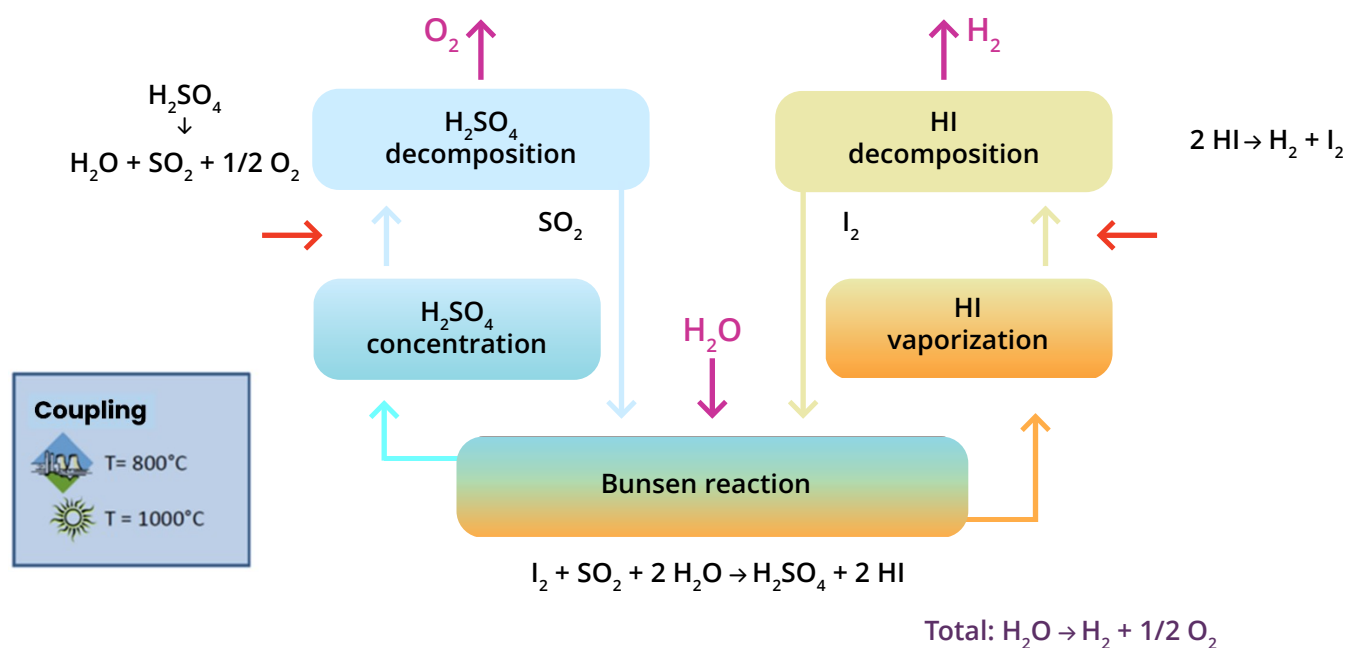


Figure 13: Simplified flowsheet of the I-S thermochemical cycle [Source CEA pres.]

<sup>28</sup>: SMRs with an 's' means SMR and AMR concepts.

The sulfur decomposition requires temperatures above 850°C and the iodine hydride dissociation operates at 400°C. Both require an input of heat which can be provided by nuclear (or solar). Due to the very HT demand, this cycle is only compatible with high temperature gas cooled nuclear reactors (known as HTR or VHTR, which are helium cooled). This process has been and is still studied by JAEA (Japan).

The other most known thermochemical cycle are the Copper-chlorine cycle and the sulfur hybrid cycle. They are both considered as a hybrid process because they employ both thermochemical and electrolysis steps.

**The Copper-chlorine cycle** is composed of 3 to 5 steps (depending the particular Cu-Cl version). Its maximum operating temperature is below 500°C (significantly lower than the I-S cycle) which allows its compatibility with other GEN IV type reactors such as SFR, MSR, LFR or GFR. The energy efficiency is close to that of the I-S cycle but is very sensitive to energy recovery between the different temperature levels of the process. One of the cycle steps includes electrolysis (justifying the term of hybrid); and one step is dealing with solid material fluxes which are never easy to handle in continuous chemical processes. This hybrid process has been extensively studied by ANL in the USA and AECL in Canada.

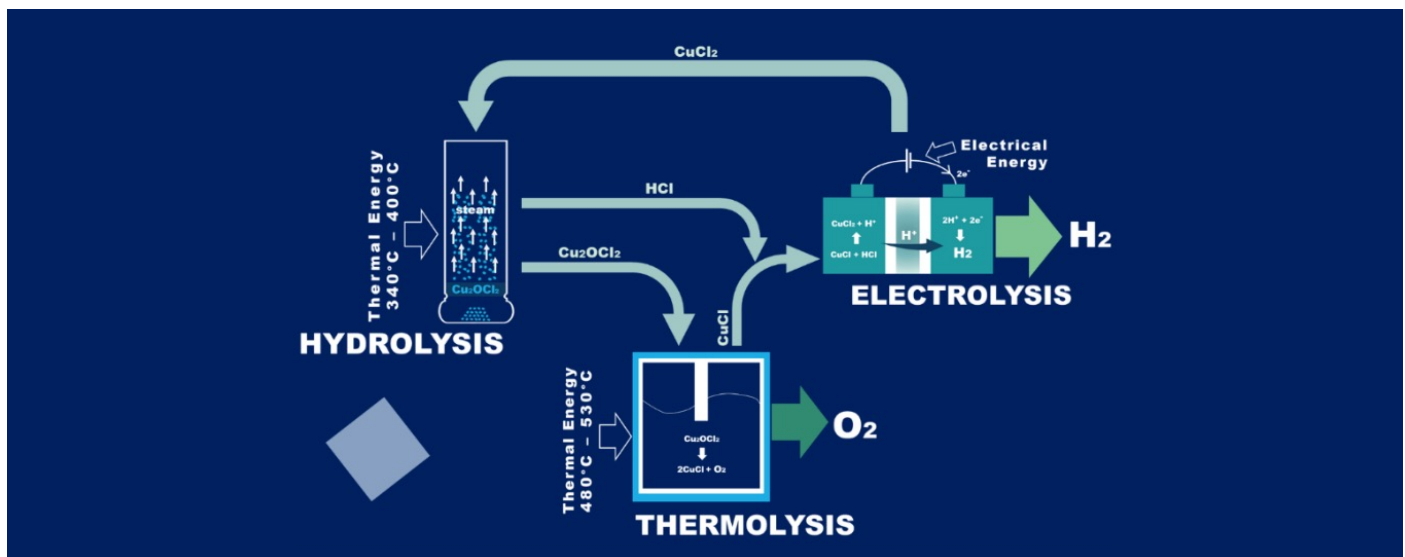
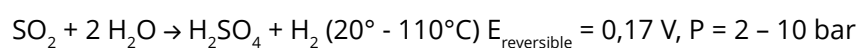
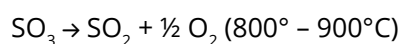
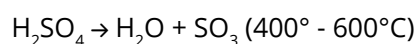


Figure 14: Simplified flowsheet of the Cu-Cl hybrid thermochemical cycle [Source R. El Emam pres.]

The sulphur hybrid process (also previously known as the Westinghouse process) may be seen as a variant of the iodine sulphur process where the iodine chemical reactions are substituted by sulphur dioxide electrolysis:



This cycle has the advantage of requiring only one intermediate element, sulphur, which moreover is abundant. Possible issues linked to chemical composition drift in the mass flows are thus limited, by contrast with cycles involving several elements. Resulting recirculation mass flow, furthermore, are decidedly smaller. On the other

hand, it does require electric energy for part of the cycle, which restricts efficiency. Electrolysis is carried out in a strong acid medium, potentially leading to corrosion issues. Moreover, this would require several compartments, to restrict parasitic sulphur and H<sub>2</sub>S production at the cathode.

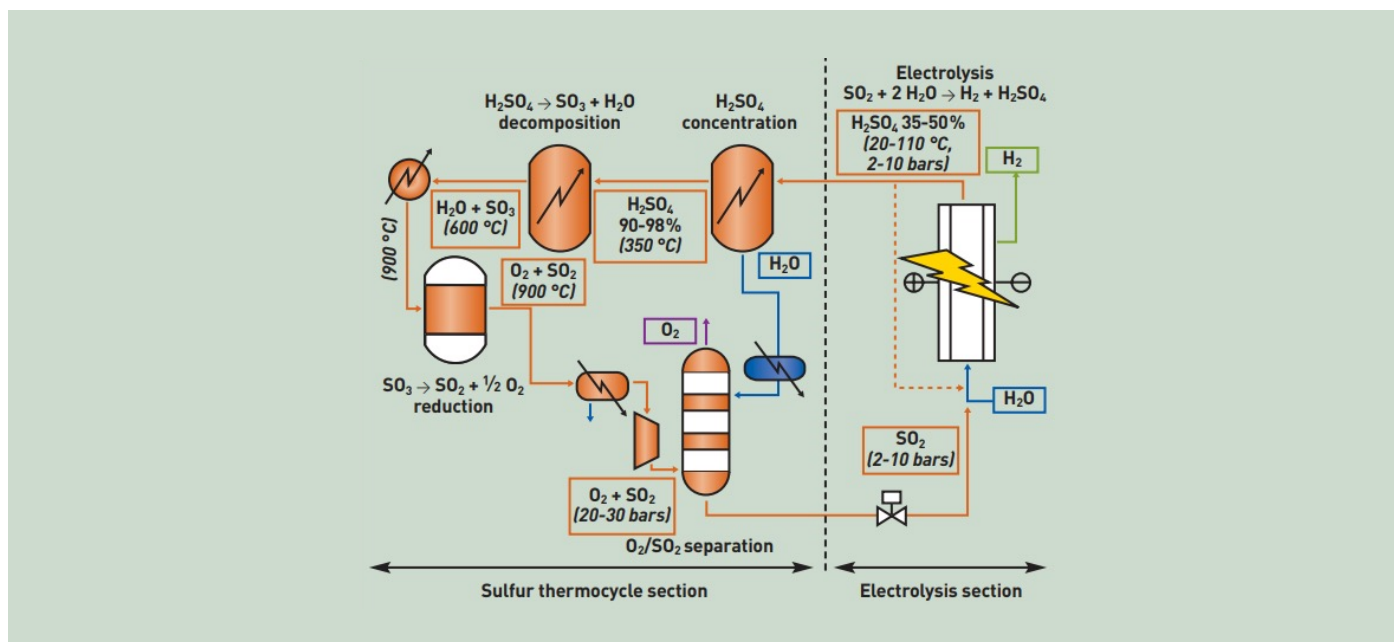


Figure 15: Simplified flowsheet of the Sulphur hybrid process [Source Clefs CEA – N°50/51 2004-2005]

Major efforts were spent investigating these thermochemical cycles first in the 80's, and then in the beginning of the 2000's. In practice, several constraints arise, including economic, chemical, HT material resistance to corrosion and thermodynamic issues. Bench scale demonstration plants have been achieved for both the I-S and the Cu-Cl cycles<sup>29</sup>. It confirms that these two cycles have reached a maturity level of "Proof of Concept" (TRL 4-5). The scaling up to industrial or semi-industrial process has not been achieved yet. For the Hybrid sulphur process according to a literature review we can assess that the cycle is at the same maturity level as the two others. Since there was no expert on this cycle in the Task #44 group members, it will not be evaluated in this document.

## A succinct history of the High Temperature Steam Electrolysis

The dissociation of water by pure electrolysis techniques is a well-known and old process. Three main techniques exist, which can be grouped according to the operating temperature and the water state: liquid or steam.

<sup>29</sup>: R. El Emam et al., Chap 19. – Hydrogen production pathways for Generation IV reactors, of Handbook of Generation IV Nuclear Reactors, Woodhead Publishing Series in Energy, 2023, Pages 665-680.

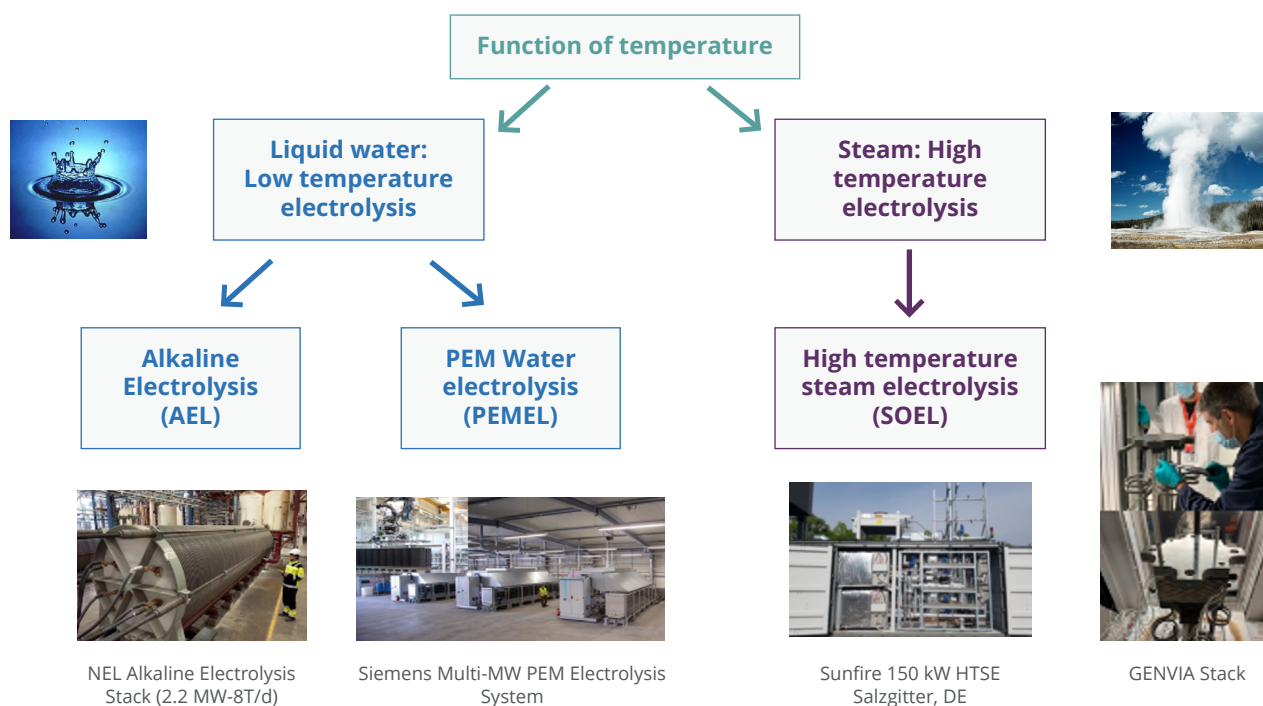


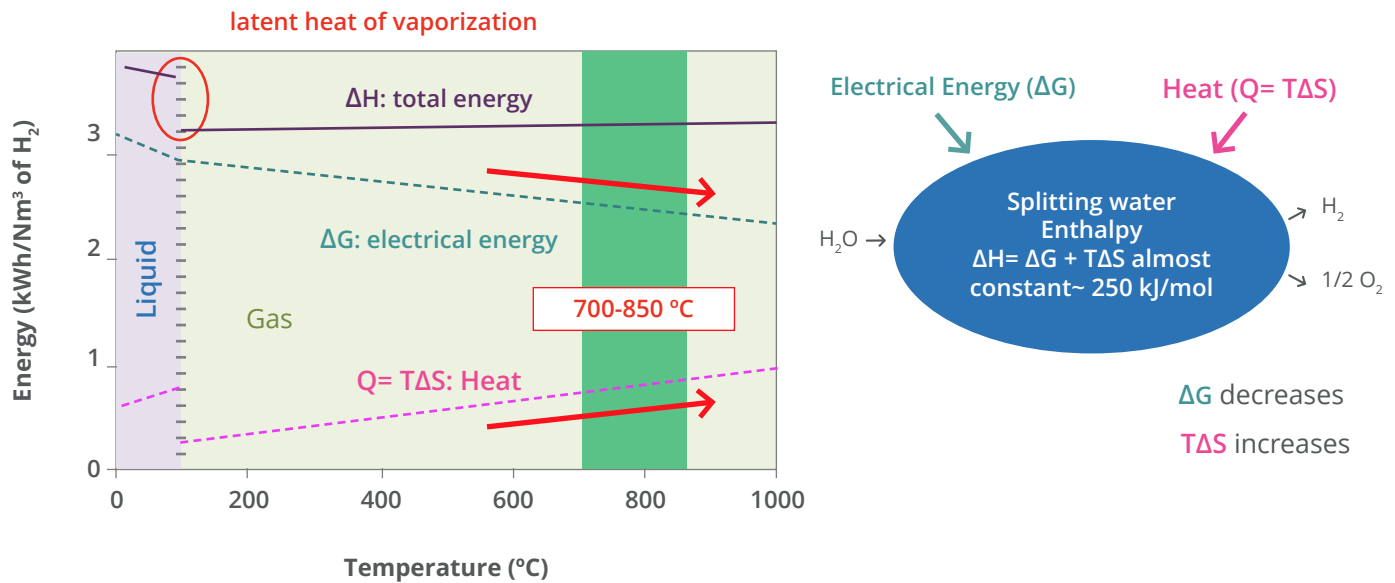
Figure 16: The different routes of electrolysis [Source CEA, P. Serre Combe pres.]

Because electricity is not a primary energy and is expensive to produce, the principle carried out by the Solid Oxide Electrolysis technology is to use steam, possibly at its highest temperature, to reduce the electrical energy demand ( $\Delta G$ ) and favouring the heat sources to reach the Enthalpy of dissociation of water (see Fig. 16 and 17). Its net efficiency is estimated to reach a greater value than liquid water electrolysis technologies<sup>30</sup>.

|                                     | Alkaline electrolyser |       |           | PEM electrolyser |       |           | SOEC electrolyser |       |           |
|-------------------------------------|-----------------------|-------|-----------|------------------|-------|-----------|-------------------|-------|-----------|
|                                     | Today                 | 2030  | Long term | Today            | 2030  | Long term | Today             | 2030  | Long term |
| <b>Electrical efficiency (%LHV)</b> | 63-70                 | 65-71 | 70-80     | 56-60            | 63-68 | 67-74     | 74-81             | 77-84 | 77-90     |
| <b>CAPEX (USD/kW<sub>e</sub>)</b>   | 500                   | 400   | 200       | 1 100            | 650   | 200       | 2 800             | 800   | 500       |
|                                     | -                     | -     | -         | -                | -     | -         | -                 | -     | -         |
|                                     | 1400                  | 850   | 700       | 1 800            | 1 500 | 900       | 5 600             | 2 800 | 1 000     |

Figure 17: Electrical efficiency of different electrolyser technologies [Source IEA Ref 22].

<sup>30</sup>: IEA Publication, "The Future of hydrogen", June 19 page 45.



Source: Chase NIST-JANAF Thermochemical Tables (1998) Monograph 9, 1325

Figure 18: Thermochemical table of water dissociation<sup>31</sup>

Increasing the temperature will decrease the electricity demand thanks to thermodynamics, and also improve electrochemical kinetics. From Fig. 18, we see that the enthalpy  $\Delta H$ , representing the total energy demand to dissociate one mole of water, increases much less rapidly than the product of entropy and temperature  $T\Delta S$ , representing the thermal energy supplied.  $\Delta H$  is the sum of  $T\Delta S$  and of the free energy  $\Delta G$  ( $\Delta H = T\Delta S + \Delta G$ ).  $\Delta G$  represents the electrical energy demand. The electric potential difference to be applied to the electrolyser is proportional to  $\Delta G$  ( $E = \Delta G/2F$ ), where  $F$  is the Faraday number.  $\Delta G$ , and therefore the electrical energy required, decreases with increasing temperature.

But materials limitations and reduced cell lifetime occurs at higher temperatures. In Fig. 17 we can see that using steam instead of liquid water provides a significant discontinuity in the total energy demand. Then heat ( $T\Delta S$ ) increases with a positive linear gradient with temperature. Operating in a range of 700 - 850 °C is defined today as optimum taking into consideration the energetical balance and also cell performances and lifetime.

Thus, this temperature can be reached in two possible ways:

- The system utilises a HT heat source coming, for instance, from a high temperature nuclear reactor, or
- The system utilises steam (or superheated steam) which will be heated to the desired temperatures by an increased current density of the electrolyser cell.

The use of a solid ceramic electrolyte operating without critical materials for the SOEC (Solid Oxide Electrolysis Cell) is an important challenge for the maturity of this technology. Moreover, this technology can also run reversibly (as SOFC = Solid Oxide Fuel Cell), opening the door to future storage applications. Thus, there are many advantages of this technology and as a result, it has received a growing interest the last decade.

<sup>31</sup>: Source: Chase NIST JANAF, Thermochemical Tables (1998) Monograph 9, 1325.

The first significant studies on High Temperature Steam Electrolysis started in Germany by Doenitz<sup>32</sup> (1975-1990), in Japan by Hino<sup>33</sup> (1990-2000's), in the USA<sup>34</sup> (2000's), and in France by Le Naour<sup>35</sup> & Mougin<sup>36</sup> (2000's). At that time the objective was to couple this HTSE technology with a HT heat source (800-900°C) coming either from concentrated solar or HT nuclear reactor. Since the 2010's, the trend is much more in favour of coupling this technology with all kinds of nuclear reactors. Pressurized Water Reactors are of particular interest because whilst they produce a lower temperature output (superheated pressurized steam at 240-280°C), their level of maturity will allow a sooner deployment ([see Insert 2 at the end of this §](#)). The energetic step from this lower temperature up to 700°C HTSE operating temperature (at its optimum operating condition) will be provided by two heat inputs: the amperometric power density that will overheat the system by the Joule effect and the heat recovery from the hot product output by a heat exchanger (Fig. 19).

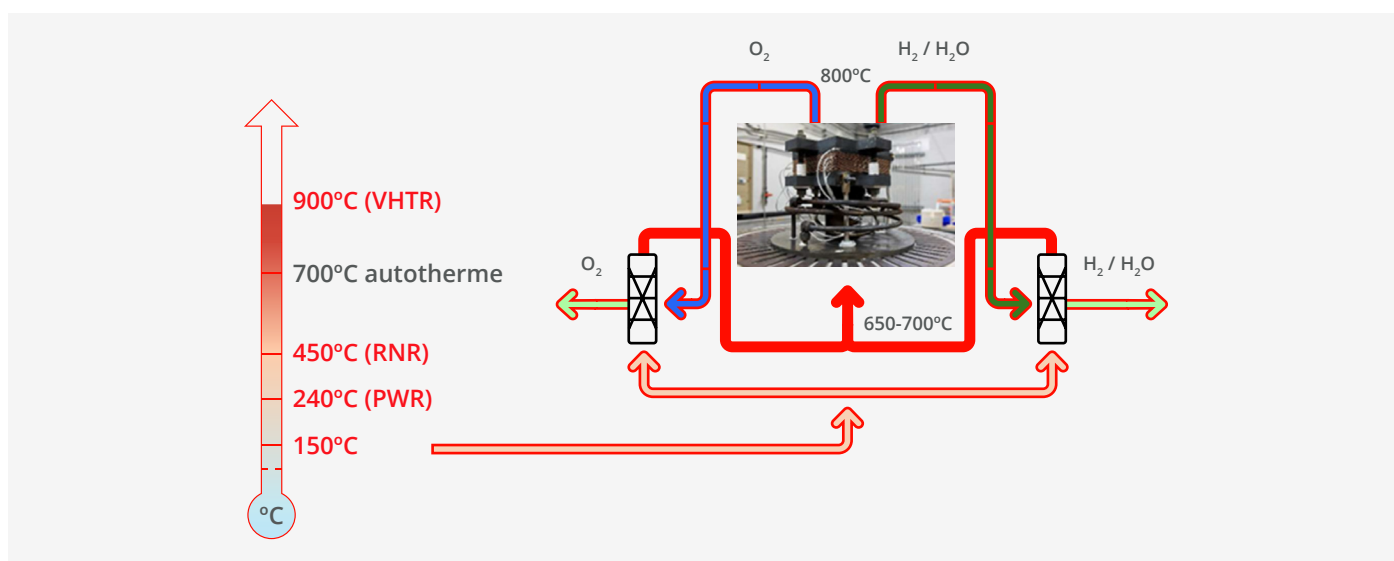


Figure 19: A simplified flow diagram of the HTSE running with low temperature inputs and heat recovery systems. RNR means Sodium Fast Reactor in French.

HTSE is an electrochemistry process realized with electrochemical cells. It is a surface electrochemical process (principally planar) that needs to adapt this technology to comply to industrial constraints (Balance of Plant, Operating systems, Monitoring). Therefore, an important effort is also carried out to integrate SOEC performances, to its optimal arrangement in stacks, modules (or core) and units (or section).

<sup>32</sup>: W. Doenitz et al., "Hydrogen production by high temperature electrolysis of water vapor", IJHE, Volume 5, Issue 1, 1980.

<sup>33</sup>: R. Hino et al., "R&D on hydrogen production by high-temperature electrolysis of steam", Nuclear Engineering & Design, Volume 233, Issue 1-3, Oct 2004.

<sup>34</sup>: K. Randolph et al 2021, « An Overview of the U.S. Department of Energy's Consortia Focused on Enabling Low-Cost Hydrogen Production Via Water Splitting Technologies », *Meet. Abstr.* MA2021-02 1330.

<sup>35</sup>: Le Naour, François "Nuclear Production of Hydrogen." Proceedings of Third Information Exchange Meeting. Oarai, Japan, 5-7 October 2005. NEA Report No. 6122.

<sup>36</sup>: J. Mougin et al., « High Temperature Steam Electrolysis stack with enhanced performance and durability », *Energy Procedia* 29, 2012.

## Scalable Hydrogen Production: from NANO to GIGA

### TOPSOE WORKS WITH SOEC ELECTROLYSIS AT ALL SCALES

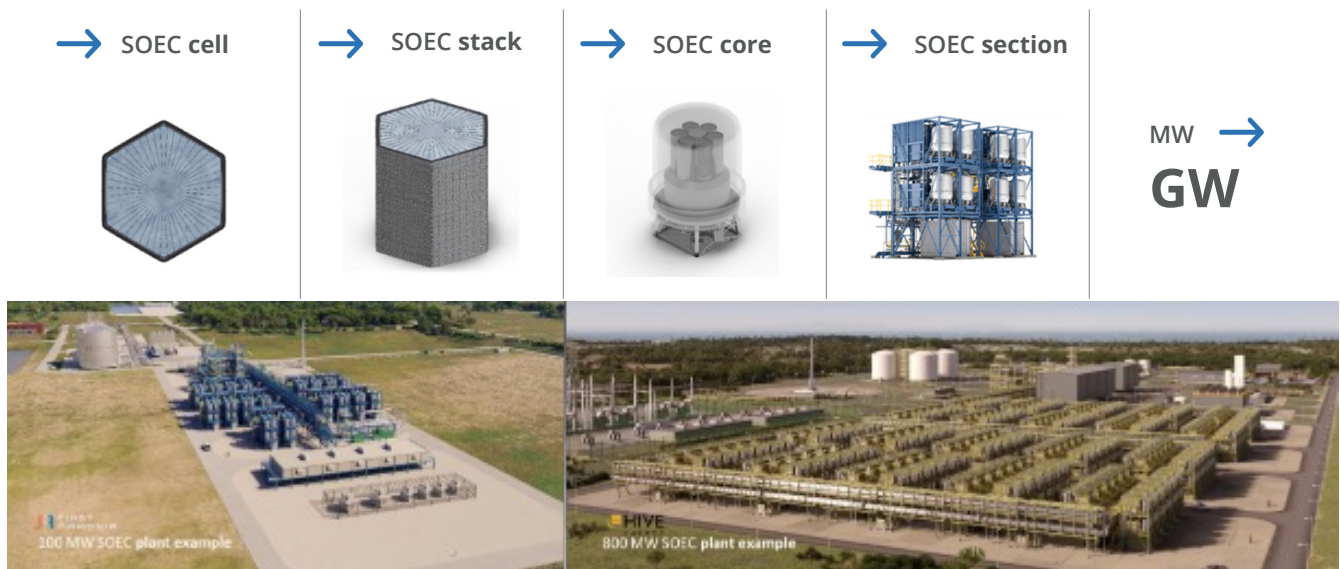


Figure 20: The TOPSOE HTSE image starting from a single planar HTSE cell up to the design of a Gigafactory

## 3.2 Hydrogen production & nuclear reactor in a nutshell

The concept of using heat from nuclear power plants for optimally producing low carbon hydrogen has been envisaged for a long time. There is a wide range of combinations between the different nuclear reactor types (considering the different coolants and various operating temperatures), the reactor power (Large Power or Small Modular Reactor), and the hydrogen production process (thermochemical with different range of temperatures, and high temperature electrochemical that can comply with a larger range of inlet water temperature). This large number of solutions can be considered as an asset; however, it also adds complexity which can make it difficult to effectively explain and communicate this more widely.

An additional level of complexity must not be forgotten in this system: the thermal coupling system between the nuclear plant and the heat transfer loop to carry steam on the hydrogen production plant. This thermal integration coupling is also the subject of many studies examining the design, thermodynamic optimization and evaluation of system impacts (fast transients, start-up and shutdown, safety assessment and demonstration...). It requires a more thorough analysis than simple heat transport.

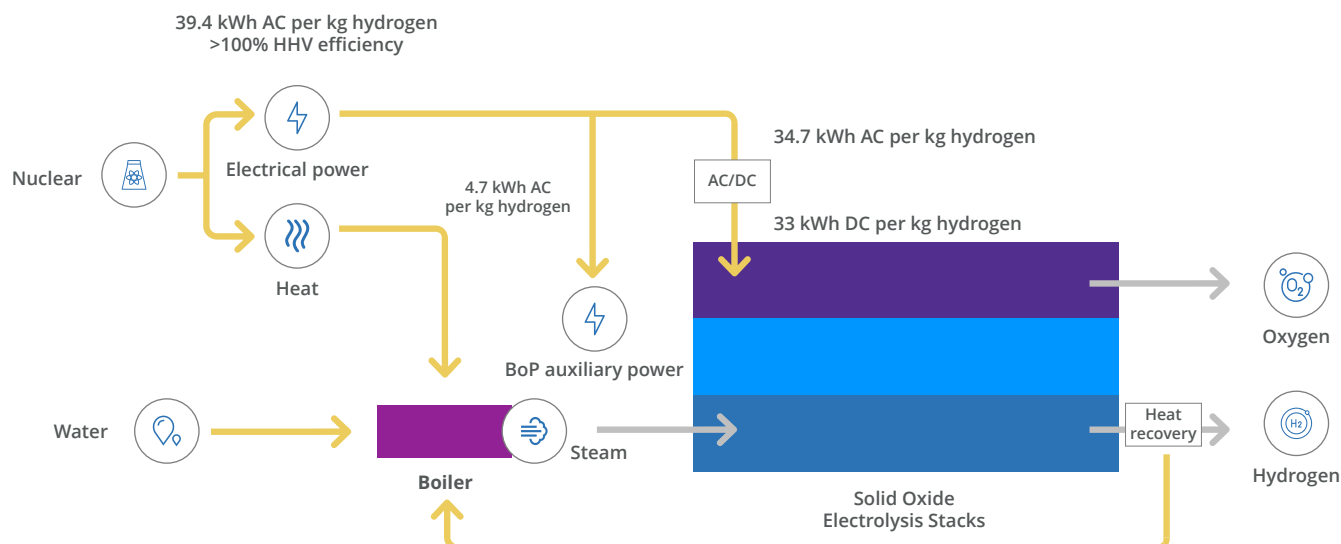


Figure 21: A simplified flow diagram of the coupling between a nuclear reactor heat source and the HTSE unit<sup>37</sup>

Thermochemical and HTSE hydrogen production methods were developed in parallel, but their approach is fundamentally different. While all thermochemical processes are requiring a high temperature source, the high temperature electrolysis process gets more flexibility to adjust the steam inlet temperature. The first family is based on thermochemical approach (sometimes hybrid), the second way is a pure electrochemical approach.

The common point is that to gain efficiency and the best use of all nuclear power assets, the hot hydrogen production process will be preferably selected. As said by an expert in the 2000's during Task #25: "All processes are leading to hydrogen but the nuclear community will select the hottest"<sup>38</sup>.

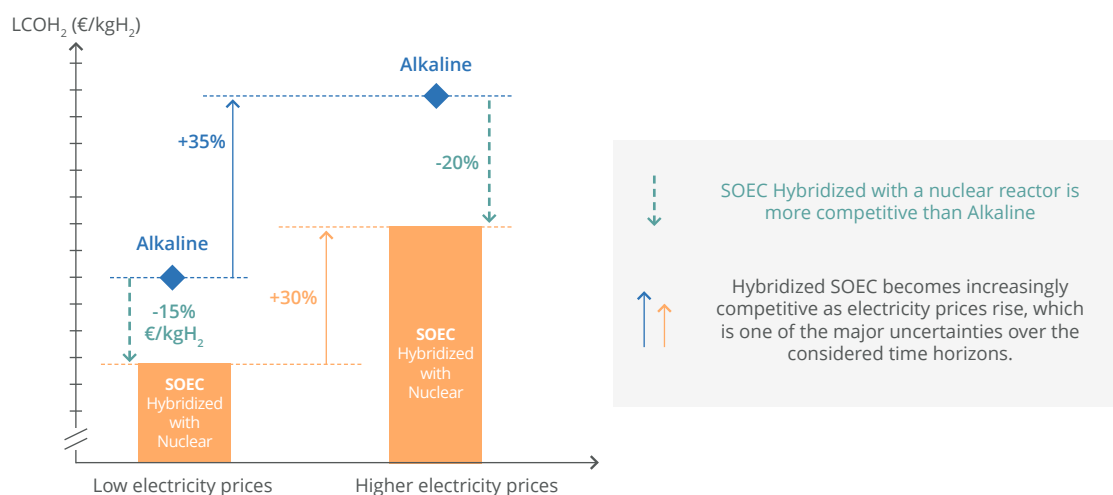


Figure 22: The advantage of using heat in electrochemical processes rather than solely electricity, minimizing the LCOH<sub>2</sub> [Source J.F. Dhedin (EDF) pres.]

<sup>37</sup>: <https://www.fuelcellenergy.com/blog/low-cost-hydrogen-production-from-nuclear-energy>

<sup>38</sup>: François Le Naour

## Insert 2: HTSE coupled with a VHTR, why is it not the unique solution?

### Insert 2: HTSE coupled with a VHTR, why is it not the unique solution?<sup>39</sup>

To answer to this question, we have to refer a little bit to past studies and to the history of hydrogen and nuclear production. Initially there were two known ways to produce hydrogen without emitting CO<sub>2</sub>:

- From Thermochemical Cycles (TC). The genesis is estimated to be in the 60's and there is a patent in 1978 named "Process for the thermochemical production of hydrogen" from General Atomic Company. This patent proves the link in the 70's between TC and nuclear energy.
- From electrolysis. The splitting of water by electrolysis was first experienced in 1789 by van Troostwijk and Deiman. It is estimated that around 1900, over 400 industrial alkaline water electrolyzers were in operation worldwide. Over the course of the 20<sup>th</sup> century, the more cost-effective production of hydrogen by steam reforming of methane replaced water electrolysis. End of the 20<sup>th</sup> century, the process was only used in niche applications (high purity H<sub>2</sub>). Later, and pushed by Germany, Dornier Company carried out the HOT-ELLY project in the mid-1980s, developing the first HTSE prototypes. New interest in water electrolysis was stimulated in the 1990s as hydrogen was regarded as a green energy carrier from renewable energy sources.

In 2000's the Generation IV International Forum (GIF) was created. They selected six GEN IV nuclear systems and among them one principally dedicated to hydrogen production: the Very High Temperature Reactor (VHTR). In its communicative approach GIF early presented schematic pictures of its 6 selected systems. The VHTR system was always shown with its usages: the hydrogen production plant.

*20 years later this popular image is still the same and largely reproduced in lots of Intl papers for GEN IV reactors*

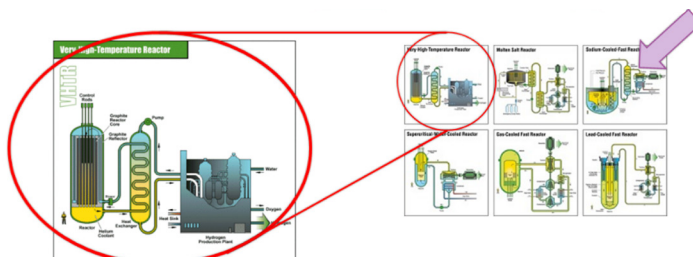


Figure 23: The initial presentation of the VHTR from GIF (until 2024). The VHTR nuclear reactor is already shown to be coupled with an H<sub>2</sub> production plant.

Many scientific organisations followed this trend and studied the coupling of high temperature reactors (at least over 700°C) and hydrogen production systems, either thermochemical (because this level of temperature is necessary to fulfil the I-S needs) or with high temperature steam electrolysis. It became a sort of scientific "belief" from the 90's until the 00's that only high temperature reactors can produce hydrogen in a cogeneration mode. As an example, the IAEA document named "Hydrogen production using nuclear energy" published in 2013<sup>40</sup> only considered VHTR coupled with hydrogen production processes because they were the current (and only) studies investigated worldwide at this time.

### What has changed these recent years, and especially since the 2010's?

It is always a challenge to "write the history" especially when this one is recent. But we can propose several assumptions to answer this question.

1. There is now a dynamic to realize low-carbon hydrogen for a decarbonized society at near term deployment (see COP28). Steam methane reforming is not the unique techno-economic case, there is also a need to investigate low-carbon hydrogen production processes.

<sup>39</sup>: G. Rodriguez, "Hydrogen high temperature process coupled with nuclear reactor. A tentative historical review initiated by the IEA / H<sub>2</sub> TCP TASK #44", IAEA TM on Advances in High Temperature Processes for Hydrogen Production with Nuclear Energy, Ref. No.: EVT2103544, Vienna, Austria, 5-8 September 2023.

<sup>40</sup>: IAEA Nuclear Energy Series, NO NP-T-4.2, 2013.

2. The demand for hydrogen is expected to be huge and in relatively short timescales (around 2030). At the same time the maturity level of VHTR concept (1000°C output) has not progressed as expected. Due to material challenges, development is focused on HTR designs (850-900°C output). In parallel the different thermochemical cycles investigated did not increase their maturity level as quickly as expected.
3. It was demonstrated that it is not « necessary » to couple SOEC with (V)HTR because what is really needed is the provision of steam. Then it is possible to adjust the SOEC power density to heat up the whole system, using the excess electrolyser heat or from the gas exhaust to reach the stack operating temperature (700°C). This showed that the concept of coupling a Pressurized Water Reactor with HTSE is feasible with a higher level of nuclear plant maturity (see Fig. 21). This is less feasible for thermochemical systems which need high temperatures (at least 500°C for hybrid process).
4. At the same time, the Small Modular Reactor approach brings a new perspective to define nuclear reactors with a large portfolio of non-electric applications, including large-scale hydrogen production. Thus, since 2015, numerous process flow diagrams propose the coupling of any SMR (including Gen III) with HTSE.

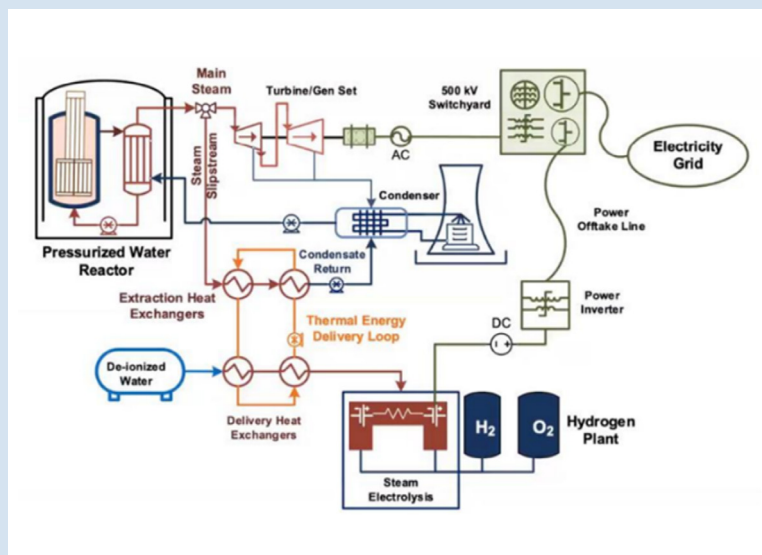


Figure 24: The flow diagram coupling a PWR with a HT

[Source S. Bragg Sitton pres., Jan 2022]

In this landscape, and according to its related document<sup>41</sup> we can extract the following phrase which explains the current design now investigated: *“In HTSE, for example, the steam and air sweep gas that have been heated with a nuclear heat source can be boosted to the electrolysis cell stack operating temperature (~700-800°C). In this case, the majority of the feed stream heating is accomplished with thermal energy provided by the nuclear heat source.”*

Thermodynamically speaking, nothing will be better than coupling an HTR (or a VHTR) with HTSE, but nothing is purely thermodynamic! Maturity levels of the different technologies, near term deployment, nuclear fuel management, safety assessment and techno-economic approach are also part of the final choice. Combining all these constraints lead to today's investigations – if we consider producing hydrogen with high temperature processes – additional solutions to coupling HTR with a hydrogen production factory can be found. The most interesting cases are presented in § 4.

<sup>41</sup>: S. Bragg Sitton et al., « Integrated Energy System: 2020 roadmap, Sept. 2020, INL EXT-20-57708 Rev 1.

## CHAPTER 4

# Hydrogen from nuclear energy: the existing cases and the most promising cases

## §4 - KEY TAKE AWAYS

- i. *The production of hydrogen on a nuclear site is already a reality and worldwide several demonstration cases are in operation or in a feasibility study stage. These are typically utilizing standard alkaline electrolysis and the hydrogen is for their on-site use.*
- ii. *Using an already built Nuclear Power Plant is not the optimum solution to implement a hydrogen production unit. Indeed, the project will encounter safety and administrative hurdles. The mix between the objectives of a commercial reactor and the commissioning approach of hydrogen unit implementation can stop a demonstration project. Administrative processes, licensing and safety impacts are easier to address in new projects and create challenges for retrofitting existing nuclear power plants with a hydrogen production unit.*
- iii. *To achieve a large-scale demonstration, the optimum is – as JAEA did with its HTTR – to use an engineering test nuclear reactor dedicated for testing and R&D.*
- iv. *Three recent European projects carried out in parallel with Task #44 (NPHYCO, GEMINI 4.0 and TANDEM) provided joint significant conclusions and recommendations that were followed by Task #44.*
- v. *The projection of future systems of hydrogen production coupled with nuclear reactors is leading to a 6x16 matrix (6 hydrogen production methods to cross with 16 nuclear reactor types). From this matrix, 16 cases were pre-selected. Five were identified as referenced scenarios, and the other 11 are the most promising solutions to consider. There is a justification for the selection of these 11 scenarios.*

## 4.1 Real case situation

In May 2025, IAEA produced a reference document on the hydrogen production with operating nuclear power plants<sup>42</sup>. Additionally, a study produced by UKNNL and EDF Energy Nuclear Generation Limited was completed in Nov 2025<sup>43</sup>. These documents identify a series of existing nuclear power plant already producing hydrogen or with a budgeted project to produce hydrogen on-site in the short term (between 1 and 5 years). The UKNNL/EDF Handbook is a thorough evaluation of the feasibility study to produce hydrogen on-site (adjacent to the nuclear power station) investigating opportunities for the future UK projects: Sizewell C, Hinkley Point C and potential future SMRs and AMRs projects.

<sup>42</sup>: <https://www.iaea.org/sites/default/files/hydrogen-production-with-operating-nuclear-power-plants.pdf>

<sup>43</sup>: Nuclear Enabled Hydrogen Handbook, <https://www.edfenergy.com/sites/default/files/2025-11/NEH%20Handbook%20-%20Public%20version%20-%20Final%20-%202025.pdf>

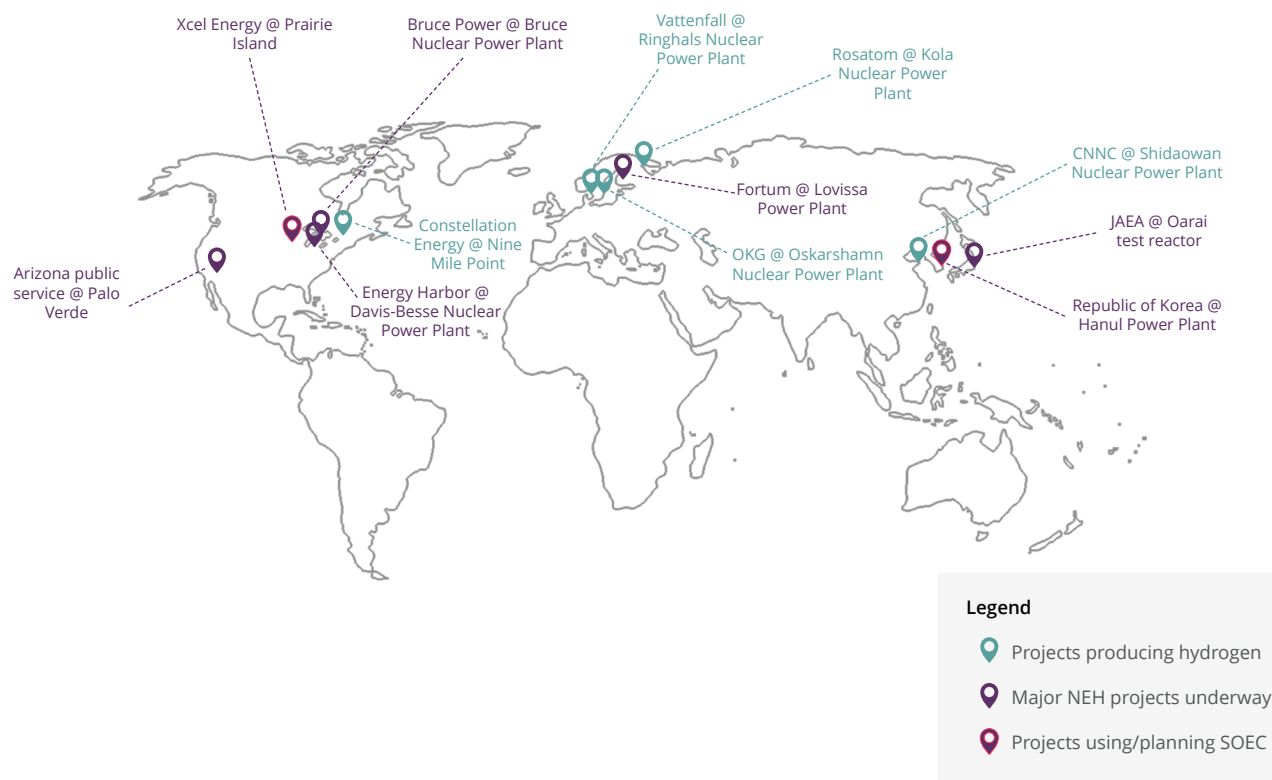


Figure 25: 2025 world map of the existing and on-going project of hydrogen from nuclear energy

[Source: Jonny Hawes, UKNNL printed in <https://www.edfenergy.com/about/nuclear/hydrogen-handbook>]

Considering only the already operating systems of them are only for a demonstration scale and not for large scale production. Typically, the hydrogen produced is used on the nuclear site (generator cooling or chemistry purposes).

| Country | Project         | Nuclear Tech. | Electrolyzer               | Production    | Status      |
|---------|-----------------|---------------|----------------------------|---------------|-------------|
| USA     | Nine Mile Point | BWR           | PEM (1.25 MW)              | 531 kg/day    | Operational |
| USA     | Davis-Besse     | PWR           | PEM (2 MW)                 | 1 t/day       | Planned     |
| USA     | Palo Verde      | PWR           | PEM (17 MW)                | Not specified | Planned     |
| USA     | Prairie Island  | PWR           | SOEC (0.24 – 1 MW)         | 130 kg/day    | Planned     |
| UK      | Heysham         | AGR           | LTE Alk. (1MW), PEM (1 MW) | 800 kg/day    | In planning |
| UK      | Sizewell C      | EPR           | HTE                        | 800 kg/day    | In planning |
| Canada  | Bruce           | PHWR          | PEM (5 MW)                 | Not specified | Pilot       |
| Russia  | Kola            | VVER          | LTE AEM (1 MW)             | Not specified | In planning |
| Sweden  | Ringhals        | PWR           | LTE (0.8 MW)               | 230 kg/day    | Operational |
| Sweden  | Oskarshamn      | BWR           | LTE Alk. (0.7 MW)          | 288 kg/day    | Operational |
| Japan   | HTTR            | HTR           | Not available              | Not available | In planning |
| China   | HTR-PM          | HTR           | Not available              | Not available | In planning |

Figure 26: List of existing and short-term projects. Figure updated from<sup>44 45</sup>

<sup>44</sup>: J. Linares et al., "Unlocking nuclear flexibility through hydrogen production", Energy Conversion and Management, Vol. 349, February 2026, 120934.

<sup>45</sup>: This Table is a snapshot from end 2025 that may change according to project decision. It is recommended to verify its relevance with time.

These developments are focussing on feasibility cases with hydrogen production modules from 0.2 to 1 MWe. None of them are intending to increase their hydrogen production capacity for a large market. It is worth noting that in its study EDF/UKNNL Handbook is evaluating a larger case study based on a 24MW Nuclear Enabled Hydrogen plant concept.

The challenge for these existing plants is to try to adapt to their already existing plant layout for a new hydrogen production facility. This will require a new safety analysis and a series of administrative procedures to incorporate the hydrogen production unit within the plant safety standards. In some specific cases it could necessitate a licence modification with a new public consultation. But at the same time these power plants have to fulfil their electricity production commitments. Therefore, this additional unit and its implementation cannot alter their electricity production (commercial & financial objectives). It is the reason why in all cases the funding to realize this demonstration is motivated by national program and public funds. Some of them did not go beyond the feasibility study due to administrative risks analysis. The risks of delay and electricity production loss during the unit implementation appears to be too high.

The purpose of these demonstration cases is to demonstrate the feasibility of the coupled system Nuclear Power Plant (NPP) and hydrogen production unit. It is a significant step on the nuclear hydrogen production but cannot be the basis of the final demonstration for several reasons:

- As explained, changing the NPP purpose during its operating phase is not optimal. The new licensing and new administrative needs may create at least the same level (and sometimes more!) of obstacles as the technical implementation. Consequently, administrative processes, licensing and safety impacts are easier to address for new build projects. In-depth safety assessment can then be implemented at the early design phase.
- In an existing NPP, the hydrogen is produced on site even if there is no industrial need at its vicinity. This is why this hydrogen is used on site (but the need is a rather low amount), otherwise there is a need to store it for a future transfer. Hydrogen storage could require new safety risk analysis and additional safety design constraints. It is one of the major reasons for the low power hydrogen production systems. For a new build NPP with a hydrogen production unit, the hydrogen consumer needs and locations will be better taken into account in the market specification.
- Mixing an industrial facility (TRL = 9 or more) with an experimental facility (TRL < = 6) is not the best approach to R&D. The two facilities do not require the same constraints and, in this context, at the end, the economical and industrial approach chosen may be detrimental to the experimental part<sup>46</sup>.
- One specific approach carried out in Japan by JAEA is more rational, as they are using a test NPP (HTTR at Oarai research centre) to demonstrate the feasibility of the heat coupling system with a steam methane reforming unit (see Insert 3). However, it is important to underline – and congratulate too - these significant milestones and demonstrations because they all may have encountered many hurdles to overcome, but they succeed achieving these demonstration units and make them operate. Despite all the difficulties of using an existing NPP, it is possible to say now - thanks to these demonstrations - that **“Low carbon hydrogen produced from NPPs is not an engineering dream, it already exists!”**.

<sup>46</sup>: In addition, as experienced in many hybrid facilities mixing production and R&D, the different fields do not have the same culture.

### Insert 3: Current status of high temperature gas-cooled reactor development and its usages on hydrogen production in Japan

#### Insert 3: Current status of high temperature gas-cooled reactor development and its use for hydrogen production in Japan<sup>47</sup>. The significant impact of the HTTR test.

Japan Atomic Energy Agency (JAEA) has been conducting R&Ds for HTGR technologies with a central focus on the use of a High Temperature Engineering Test Reactor (HTTR). HTTR reactor is an experimental reactor located at Oarai Nuclear Engineering Institute in support of the HTGR development. Based on the knowledge accumulated from the various HTTR tests conducted so far, JAEA obtained permission for changes to reactor installation in June 2020. Loss of forced cooling (LOFC) tests which simulate the situation where the reactor cannot be cooled and shutdown were carried out in March 2024<sup>48</sup>.

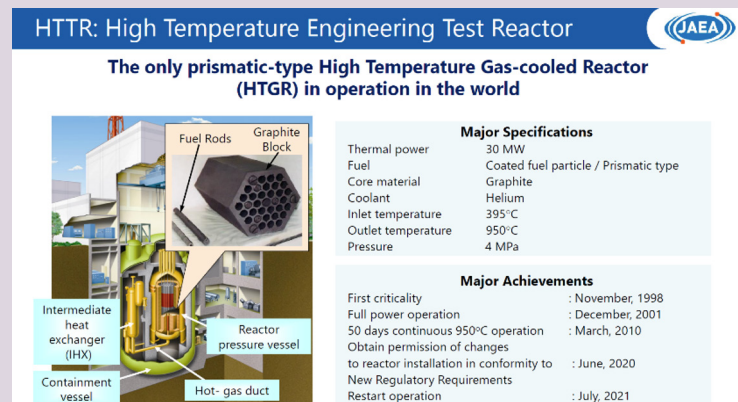


Figure 27: HTTR description and major achievements [Source H. Noguchi pres.]

JAEA initiated the HTTR heat application test plan from FY2022 to put a large-scale, low-cost, and carbon-free hydrogen production technology into practical use in the future and expected completion is FY2030, following the schedule. In this plan, the hydrogen production facility is coupled with the HTTR for the hydrogen production by a steam methane reforming method using high temperature heat supplied from the HTTR. The objectives are to establish a high safety coupling technology and to develop necessary equipment to connect the HTTR with the hydrogen production facility.

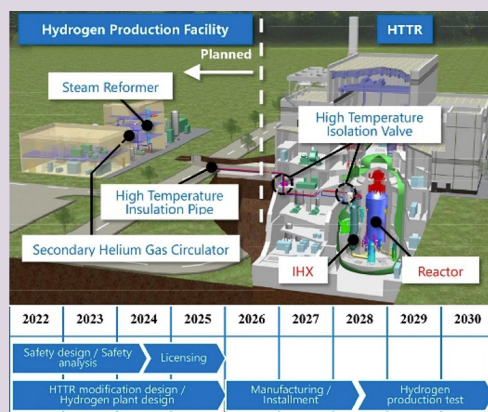


Figure 28: Concept view of the SMR production facility coupled with the HTTR [Source H. Noguchi pres.]

To utilize a portion of the nuclear heat extracted from the Intermediate Heat Exchanger (IHx) as a heat source for hydrogen production, modifications of HTTR are required. In this plan, secondary helium piping is attached to the head of IHx and penetrates the containment vessel and reactor building. High temperature secondary helium coolant is then transported from the IHx to a steam reformer through the secondary helium piping (see the flow diagram below). The hydrogen produced by the facility is expected to be more than 800 Nm<sup>3</sup>/h in rated operation.

The coupling of these two systems requires the development of the following coupling equipment:

- **High temperature isolation valve:** to prevent the leakage of fission products generated in the reactor core in case the heat transfer tube rupture of IHx occurs. The other role is to prevent the ingress of flammable gases contained in hydrogen production facility into the IHx in case of the rupture of reaction tube in the reformer.

<sup>47</sup>: K. Nagatsuka, H. Noguchi, S. Nagasumi, Y. Nomoto, A. Shimizu, H. Sato, T. Nishihara, N. Sakaba, "Current status of high temperature gas-cooled reactor development in Japan", Nuclear Engineering and Design, Vol. 425, 15/08/2024.

<sup>48</sup>: S. Nagasumi, et al., Demonstration of the inherent safety feature of HTGRs through the loss-of-forced-cooling test in the HTTR, Nuclear Engineering and Design, Vol. 446.

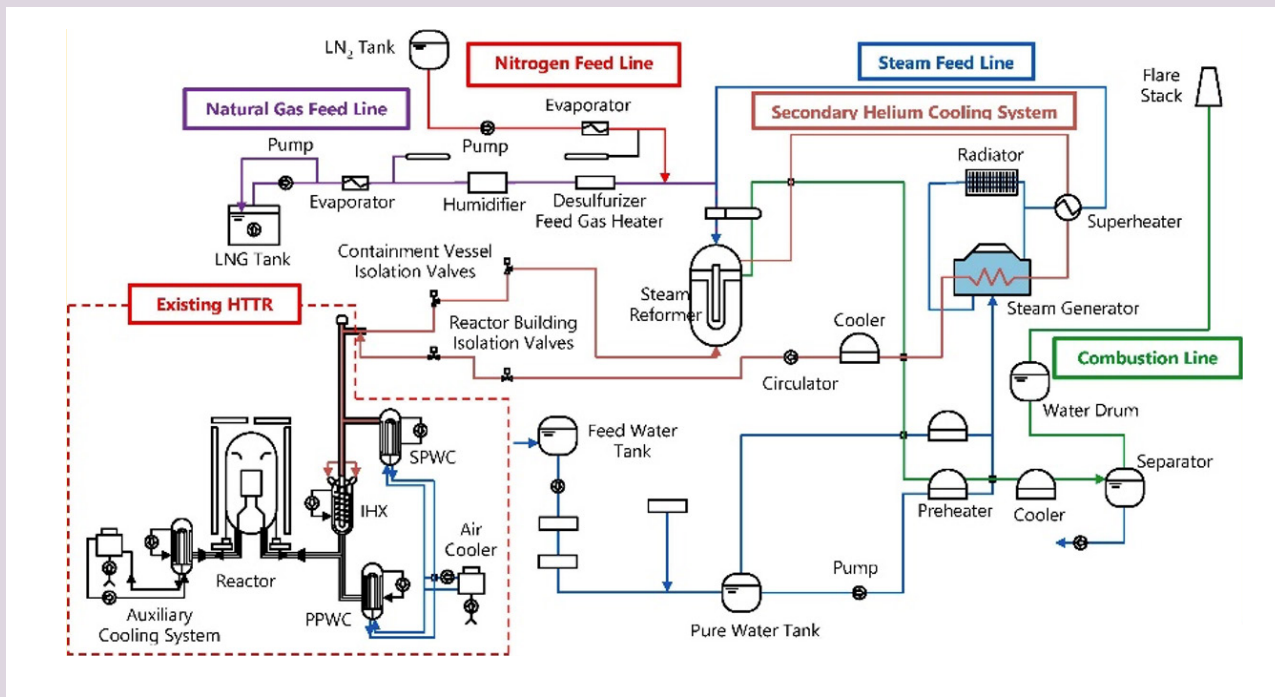


Figure 29: Flow diagram of the whole coupling system [Source H. Noguchi pres.]

- Secondary helium gas circulator: The secondary helium gas circulator transports the high temperature secondary helium gas from the IHX to the hydrogen production facility.
- High temperature insulation pipe: High temperature heat from the IHX is transported to the hydrogen production facility through a high temperature insulation pipe. The high temperature insulation pipe is a coaxial annular structure piping with a heat resistant alloy liner and a thermal insulation material inside the pressure tube.

According to this specific project and to the great expectations of the tests, it should be possible to:

- Demonstrate the real case of coupling a nuclear reactor to a hydrogen production process coupled mainly through the use of high temperature heat,
- Provide feedback of the conditions for an efficient coupling design (technically, administratively, licensing, safety approach),
- Provide an increased value of the TRL of the coupling system.

## 4.2 The project case preselected for modelling in recent European projects

In almost the same period of time and in parallel with operating the Task #44 project, three Euratom projects, GEMINI 4.0, NPHyCo and TANDEM, were carried out<sup>49</sup>. Their assessments were on low-carbon energy generation solutions (heat, electricity, hydrogen) provided by nuclear reactors in the general framework of nuclear co-generation.

- GEMINI 4.0 was evaluating the hydrogen systems coupled with a GEN IV type reactor (HTTR).
- NPHyCo case was the use of existing nuclear power plant (GEN 2 reactors – especially VVER),
- and TANDEM studied the integration of Small Modular Reactors (SMRs) of GEN 3 into Hybrid Energy Systems (HES) (see Annex 4).



Figure 30: Logos of the three European project

The main conclusions and outcomes of these three complementary projects are the following:

- *"Technical feasibility to realize nuclear / hydrogen cogeneration is confirmed. Several potential technical solutions were described by the projects. They confirmed that there is no showstopper to the production of low carbon nuclear hydrogen".* These results will serve as validation for the pre-selected Task #44 cases (see the next § 4.3).
- *"This cogeneration design is implying specific risks that need to be considered to ensure a safe operation and with regards to the impacts they may have to the coupled nuclear power. Hydrogen hazards at the vicinity of a NPP and study of hybridization transients coming from the interactions of the NPP with the Hybrid Energy System are the major outcomes of the safety gap analysis".* Task #44 conducted an equivalent gap analysis and held a workshop specifically dedicated to safety approach associated with the nuclear hydrogen production (see corresponding §5.4).
- *"On the techno-economical evaluation all three projects have performed their own evaluations. Current results all show that nuclear hydrogen may become competitive with hydrogen created from natural gas, or methane (without capturing the greenhouse gases emitted) when CO<sub>2</sub> emissions will be sufficiently taxed to support the energy transition. Today the financial viability of the system is not present and the estimated value of these systems are evaluating LCOH<sub>2</sub> in a range of 3 to 3.5 \$ / kg H<sub>2</sub>".* Task #44 did not conduct a specific techno-economic study but experts were involved in numerous studies reported in this document.
- Hydrogen transportation is an important aspect, storage and transport of hydrogen has a significant impact on the LCOH<sub>2</sub>. This point is in favour of the implementation of future Cogeneration Nuclear Plant at the vicinity of H<sub>2</sub> demand and consumption (Industrial Valleys). In a transition phase it appears more pragmatic and economically viable to transport low carbon electricity and produce the low carbon hydrogen on the customer site (with alkaline or PEM electrolyzers). Task #44 will provide its position on this global analysis (see corresponding §7).
- These three projects have also driven public awareness and acceptance studies. They have highlighted that public knowledge about use and production of hydrogen is rather low. Awareness about the opportunities and risks of cogeneration of hydrogen with nuclear power is even lower. Task #44 has conducted a different approach by setting an e-reputation study on the internet network at the start and at the end of this study to evaluate how these parameters have evolved in these last three years (2023 – 2025). (See Annex 8).

<sup>49</sup>: C. Serin, M. Glückler, M. Pasquet, C. Vaglio-Gaudard, "Outcomes of three Euratom projects on cogeneration of electricity, heat and hydrogen", EPJ Nuclear Sci. Technol. 11, 12 (2025).

## 4.3 The whole cogeneration cases and those pre-selected cases by Task #44

As previously explained the combination between the nuclear reactor systems with different hydrogen production processes can vary greatly. It leads to a large matrix of potential combinations:

- 16 systems of electricity with or without heat delivery: low carbon electricity from the grid, GEN II type reactor, GEN III type reactor in Small Modular Reactor or large power reactor, six GEN IV type systems in Advanced Modular Reactor or large power reactor<sup>50</sup>.
- Six systems of hydrogen production processes: alkaline, PEM, HTSE, thermochemical cycle, hybrid cycle and steam methane reforming. As explained previously the Sulfur hybrid process has not been evaluated because no expert of this cycle was in the Task #44 group members. Nevertheless, this process is requiring the same range of temperature as the I-S process. Main conclusions from the I-S process are therefore equivalent to the Hybrid sulphur cycle.

Coupling these two produces 96 different possibilities. Not all systems are relevant however, and the most relevant ones as selected by experts are presented in the following table.

Table 1: The matrix of solutions to produce hydrogen with nuclear energy and the preselected cases

|                                    | E- from the grid | GEN II            | GEN III |     | GEN IV   |     |     |     |     |     |     |     |     |     |      |     |
|------------------------------------|------------------|-------------------|---------|-----|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|
|                                    |                  |                   |         |     | HTR/VHTR |     | MSR |     | SFR |     | LFR |     | GFR |     | SCWR |     |
| H <sub>2</sub> Production process  |                  | LSR <sup>51</sup> | SMR     | LSR | AMR      | LSR | AMR | LSR | AMR | LSR | AMR | LSR | AMR | LSR | AMR  | LSR |
| Alkaline                           | ✓                | ✓                 |         | ✓   |          |     |     |     |     |     |     |     |     |     |      |     |
| PEM                                | ✓                | ✓                 |         |     |          |     |     |     |     |     |     |     |     |     |      |     |
| HTSE                               |                  | ✓                 | ✓       | ✓   | ✓        | ✓   |     |     | ✓   |     | ✓   |     |     |     |      |     |
| Thermochemical cycle I-S process   |                  |                   |         |     | ✓        |     |     |     |     |     |     |     |     |     |      |     |
| Thermochemical cycle Cu-Cl process |                  |                   |         |     |          |     |     |     | ✓   |     |     |     |     |     |      |     |
| Steam Methane Reforming            | ✓                |                   |         |     | ✓        |     |     |     |     |     |     |     |     |     |      |     |

### Colours definition

Blue = Reference case to compare with the different nuclear hydrogen production solutions

Green = Systems which already exist

Yellow = System envisaged, in progress or to be evaluated (considered as interesting)

<sup>50</sup>: Micro nuclear reactors were not considered in this matrix even if they are recognized to be able to play a key role in the validation roadmap of the system (see § 6 of this document).

<sup>51</sup>: LSR: Large Scale Reactor.

This matrix also highlights the most relevant coupling systems. The colours show if this solution already exists or not. For the evaluation, it was decided to perform the following down selection:

- All shaded grey cases are scenarios that are not evaluated because they do not make sense technically, the TRL is too low, or solutions are too far from deployment.
- Scenarios where the electricity is coming from the grid are not investigated. They served, if necessary, as reference scenarios.
- Gen II reactor scenarios are only kept with HTSE system.

In the end then eleven following scenarios are kept.

Table 2: The numbering of the preselected cases and the justification

|                                    | E- from the grid | GEN II | GEN III |        | GEN IV   |        |     |     |         |     |        |     |     |     |      |     |
|------------------------------------|------------------|--------|---------|--------|----------|--------|-----|-----|---------|-----|--------|-----|-----|-----|------|-----|
|                                    |                  |        |         |        | HTR/VHTR |        | MSR |     | SFR     |     | LFR    |     | GFR |     | SCWR |     |
| H <sub>2</sub> Production process  |                  | LSR    | SMR     | LSR    | AMR      | LSR    | AMR | LSR | AMR     | LSR | AMR    | LSR | AMR | LSR | AMR  | LSR |
| Alkaline                           | ✓                | ✓      |         | Case 1 |          |        |     |     |         |     |        |     |     |     |      |     |
| PEM                                | ✓                | ✓      |         |        |          |        |     |     |         |     |        |     |     |     |      |     |
| HTSE                               |                  | Case 2 | Case 3  | Case 4 | Case 5   | Case 6 |     |     | Case 7  |     | Case 8 |     |     |     |      |     |
| Thermochemical cycle I-S process   |                  |        |         |        | Case 9   |        |     |     |         |     |        |     |     |     |      |     |
| Thermochemical cycle Cu-Cl process |                  |        |         |        |          |        |     |     | Case 10 |     |        |     |     |     |      |     |
| Steam Methane Reforming            | ✓                |        |         |        | Case 11  |        |     |     |         |     |        |     |     |     |      |     |

| CASE SELECTED                         | JUSTIFICATION                                                                                             |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Case 1: GEN III PR + alkaline process | Process already used as demonstration in the USA.                                                         |
| Case 2: GEN II + HTSE process         | Process under investigation with GEN II utilities at INL (USA) and in the UK (Heysham reactor)            |
| Case 3: GEN III SMR + HTSE process    | System investigated in several projects worldwide.                                                        |
| Case 4: GEN III PR + HTSE process     | System considered as a continuation (scaling up) of the Case 3, if Case 3 is providing positive feedback. |

| CASE SELECTED                                    | JUSTIFICATION                                                                                                                                                                                                                                              |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Case 5: GEN IV HTR AMR + HTSE process            | System which is studied by several European projects (GEMINI).                                                                                                                                                                                             |
| Case 6: GEN IV HTR PR + HTSE process             | System considered as a continuation (scaling up) of the Case 5, if Case 5 is providing positive feedback. It is the specific subject of a joint case analysis carried out by the GIF NECA WG <sup>52</sup> ( <a href="#">see corresponding Insert 5</a> ). |
| Case 7: GEN IV SFR AMR + HTSE process            | Interesting system to investigate co-generation systems with an SFR.                                                                                                                                                                                       |
| Case 8: GEN IV LFR AMR + HTSE process            | Interesting system to investigate co-generation systems with an LFR. Project proposed by one of the Task #44 members (Newcleo company).                                                                                                                    |
| Case 9: GEN IV HTR AMR + thermochemical cycle    | The most coherent system to use a pure thermochemical cycle as hydrogen production process.                                                                                                                                                                |
| Case 10: GEN IV SFR AMR + thermochemical cycle   | The coherent system using a hybrid thermochemical cycle.                                                                                                                                                                                                   |
| Case 11: GEN IV HTRAMR + steam methane reforming | This system is tested by JAEA on their HTTR test reactor ( <a href="#">see corresponding Insert 3</a> ).                                                                                                                                                   |

<sup>52</sup>: GIF NECA WG: Generation IV / Non-Electric and Cogeneration Applications Working Group.

## CHAPTER 5

# Hydrogen from Nuclear Energy: viability of the system

## §5 - KEY TAKE AWAYS

- i. *The Technology Readiness Level (TRL) is a useful tool to quickly evaluate the maturity of a concept. In this specific case, it must be distinguished the TRL of the nuclear system, of the hydrogen production system and of the coupling system.*
- ii. *The holistic approach of developing hydrogen from nuclear provided by Idaho Nuclear Laboratory (INL, USA) gives an insight of the needs for this solution to progress and find future potential end-users. Complementary to this, the HTGR/H<sub>2</sub> production case carried out by GIF experts is paving the way for a future deployment solution.*
- iii. *The safety approach of this cogeneration system recommends the hydrogen production facility located outside the nuclear site licence boundary but within the security boundary. The harmonization of two safety approaches (nuclear and chemical) is a requirement, even if the most pragmatic solution consists in decoupling these two systems and incorporating a safety separation distance. Harmonization in Regulations, Codes & Standards has to be investigated.*
- iv. *The business case approach proposed by the TANDEM European funded project compares several scenarios and shows that SMRs coupled to a HTSE production facility can be a relevant option to decarbonize Hybrid Energy Systems.*
- v. *An example of a major company (Air Liquide) producing and using hydrogen is setting out its interest in nuclear to power H<sub>2</sub> production: i) It is a low carbon energy, ii) It can provide predictable cost of energy for long term, iii) It gets a high and reliable availability, iv) Its power density implies a small footprint.*

## 5.1 TRL approach

The 16 preselected cases (see previous chapter) are evaluated according to the IEA TRL scale (see [Insert 4](#)). The TRL values are necessary to describe the nuclear cogeneration systems. TRL#1 is set for the hydrogen production system, TRL#2 is set for the whole nuclear reactor system, and TRL#3 is set for the coupling system between the two systems (nuclear and H<sub>2</sub> production units). In some cases, there is no need to use the TRL#3: i.e., when only electricity is necessary (no heat required) and when electricity is taken from the grid. In those cases, TRL#3 is marked with an X.

Table 3: The TRL evaluation of the matrix of solutions<sup>53</sup>

|                                    | E- from the grid                  | GEN II                           | GEN III                          |                                  | GEN IV                           |                                  |     |     |                                    |     |                                    |     |     |     |      |     |
|------------------------------------|-----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|-----|-----|------------------------------------|-----|------------------------------------|-----|-----|-----|------|-----|
|                                    |                                   |                                  |                                  |                                  | HTR/VHTR                         |                                  | MSR |     | SFR                                |     | LFR                                |     | GFR |     | SCWR |     |
| H <sub>2</sub> Production process  |                                   | LSR <sup>51</sup>                | SMR                              | LSR                              | AMR                              | LSR                              | AMR | LSR | AMR                                | LSR | AMR                                | LSR | AMR | LSR | AMR  | LSR |
| Alkaline                           | TRL#1: 10<br>TRL#2: X<br>TRL#3: X | TRL#1: 9<br>TRL#2: 9<br>TRL#3: X |                                  | TRL#1: 9<br>TRL#2: 9<br>TRL#3: X |                                  |                                  |     |     |                                    |     |                                    |     |     |     |      |     |
| PEM                                | TRL#1: 9<br>TRL#2: X<br>TRL#3: X  | TRL#1: 9<br>TRL#2: 9<br>TRL#3: X |                                  |                                  |                                  |                                  |     |     |                                    |     |                                    |     |     |     |      |     |
| HTSE                               |                                   | TRL#1: 6<br>TRL#2: 9<br>TRL#3: 4 | TRL#1: 6<br>TRL#2: 6<br>TRL#3: 4 | TRL#1: 6<br>TRL#2: 9<br>TRL#3: 4 | TRL#1: 6<br>TRL#2: 7<br>TRL#3: 4 | TRL#1: 6<br>TRL#2: 5<br>TRL#3: 4 |     |     | TRL#1: 6<br>TRL#2: 6-7<br>TRL#3: 4 |     | TRL#1: 6<br>TRL#2: 4-5<br>TRL#3: 4 |     |     |     |      |     |
| Thermochemical cycle I-S process   |                                   |                                  |                                  |                                  | TRL#1: 4<br>TRL#2: 7<br>TRL#3: 4 |                                  |     |     |                                    |     |                                    |     |     |     |      |     |
| Thermochemical cycle Cu-Cl process |                                   |                                  |                                  |                                  |                                  |                                  |     |     | TRL#1: 4<br>TRL#2: 6-7<br>TRL#3: 4 |     |                                    |     |     |     |      |     |
| Steam Methane Reforming            | TRL#1: 11<br>TRL#2: X<br>TRL#3: X |                                  |                                  |                                  | TRL#1: 8<br>TRL#2: 7<br>TRL#3: 5 |                                  |     |     |                                    |     |                                    |     |     |     |      |     |

**TRL Level definition**TRL#1: TRL of the H<sub>2</sub> production process

TRL#2: TRL of the nuclear reactor system

TRL#3: TRL of the coupling system between the H<sub>2</sub> production process and the nuclear reactor**Colours definition**

Blue = Reference case to compare with the different nuclear hydrogen production solutions

Green = System already existing

Yellow = System envisaged, in progress or to be evaluated (considered as interesting)

The most mature systems are today given by those where the hydrogen production process is at low temperature with liquid water (alkaline or PEM electrolysis) and when the coupling with the nuclear reactor is really limited or even nil. However, in Task #44 the objective is also to describe the future achievements where potentials are promising in terms of yields and optimizing the use of primary energy (heat). This is the reason why, even if in most cases the high temperature processes currently have lower TRLs, their investigation remains important in the R&D field for future nuclear H<sub>2</sub> competitiveness.

The coupling system (when it is relevant) is always ranked at a rather low value. This illustrates today's lack of real case demonstration. With the exception of the HTR/steam methane reforming demonstration case (see insert 3 at the previous chapter), there are no "real case"<sup>54</sup> coupling system projects. In most cases each technology component is tested separately.

<sup>54</sup>: In that case we consider a "real case" when the heat is provided by a nuclear system and not simulated by an extra heat source.

### Insert 4: The Technology Readiness Level approach

#### Insert 4: The Technology Readiness Level approach<sup>55</sup>

Originally developed by the United States National Aeronautics and Space Administration (NASA) in the 1970s, the Technology Readiness Level scale provides a snapshot in time of the level of maturity of a given technology within a defined scale. It is now widely used by research institutions and technology developers around the world to set research priorities and design innovation support programmes.

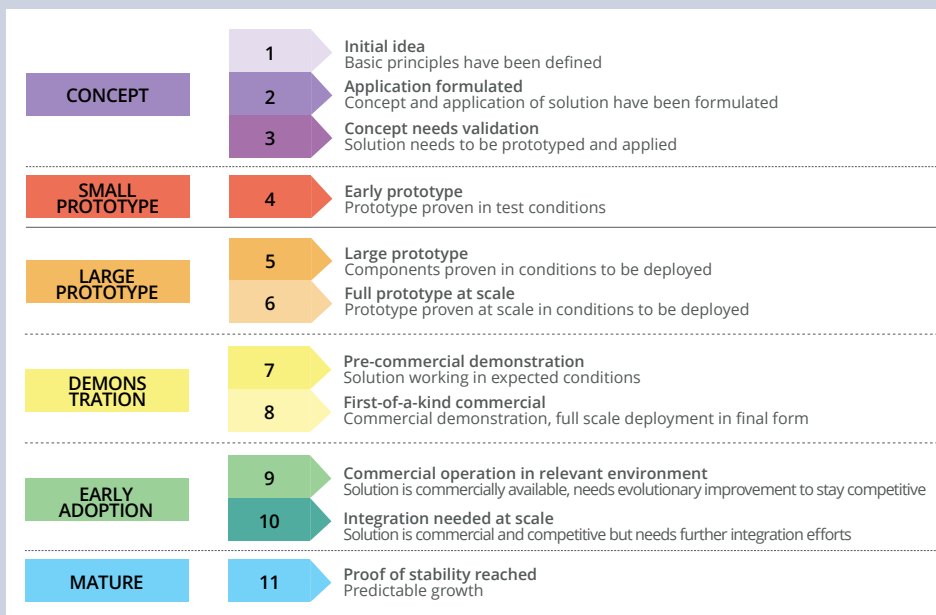


Figure 31: The TRL scale proposed by IEA

TABLE 1. INTEGRATION READINESS LEVEL (IRL) AND TECHNOLOGY READINESS LEVEL (TRL) LEVELS

| Level | TRL                                                                                  | IRL                                                                                                                                                                   |
|-------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1     | Basic principles observed and reported                                               | An interface between technologies has been identified with sufficient detail to allow characterization of the relationship                                            |
| 2     | Technology concept and/or application formulated                                     | There is some level of specificity to characterize the interaction between technologies through their interface                                                       |
| 3     | Analytical and experimental critical function and/or characteristic proof of concept | There is compatibility between technologies to orderly and efficiently integrate and interact                                                                         |
| 4     | Component and/or breadboard validation in laboratory environment                     | There is sufficient detail in the quality and assurance of the integration between technologies                                                                       |
| 5     | Component and/or breadboard validation in relevant environment                       | There is sufficient control between technologies necessary to establish, manage, and terminate the integration                                                        |
| 6     | System/subsystem model demonstration in relevant environment                         | The integrating technologies can accept, translate, and structure information for its intended application                                                            |
| 7     | System prototype demonstration in relevant environment                               | The integration of technologies has been verified and validated with sufficient detail to be actionable                                                               |
| 8     | Actual system completed and qualified through test and demonstration                 | Actual integration completed and mission-qualified through test and demonstration in the system environment                                                           |
| 9     | Integration is mission-proven through successful mission operations                  | Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle |

Figure 32: The TRL and IRL scale<sup>56</sup>

The scale, which in most applications range from 1 to 9, can be applied to any technology. However, arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. For this reason, the IEA has extended the TRL scale to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11).

This simple and straightforward approach is useful to evaluate global concepts. In some specific cases, it should be complemented by other scales to better describe the complexity of a whole system. It is possible for instance to

<sup>55</sup>: IEA (2020), Clean Energy Innovation, IEA, Paris <https://www.iea.org/reports/clean-energy-innovation>, License: CC BY 4.0.

<sup>56</sup>: C. Eder et al., "Beyond Integration, Readiness Level (IRL): A Multidimensional Framework to Facilitate the Integration of system of systems", DOI: <https://doi.org/10.22594/dau.16-766.24.03>.

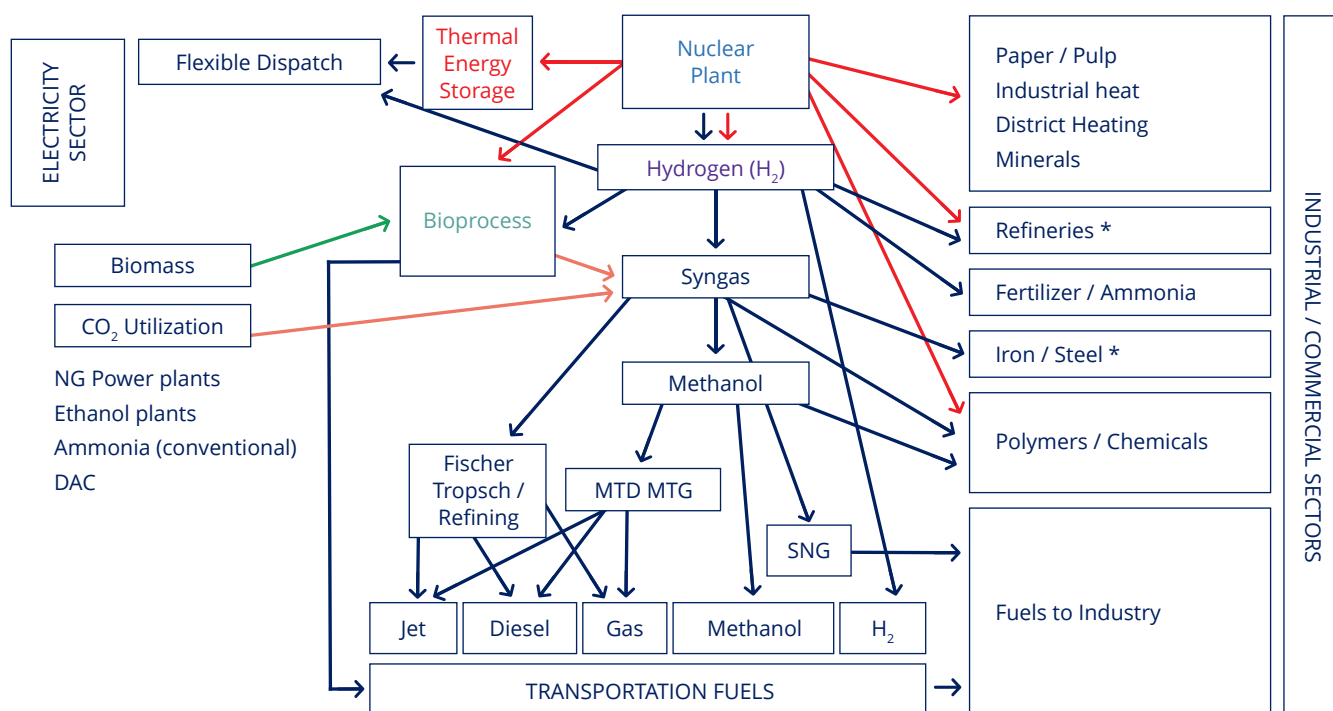
decompose the global TRL evaluation to sub-TRL evaluations according to the product breakdown system. In some other cases it can be used an IRL scale (Integration Readiness Level) to better assess the integration of one complete system into or associated to another one. The need to expand the use of IRL is becoming increasingly more relevant. e.g., in the U.S. Department of Defence (DoD) acquisition as program managers aim to develop and acquire weapon systems with ever increasing multiple capabilities and interfaces; and in space the integration of a satellite in a space launcher will need an IRL approach.

In a cogeneration nuclear system, the simplest approach was to define the three different TRL systems separately: the hydrogen production system, the nuclear reactor and the heat/electricity coupling system of the two. As the maturity increases a better evaluation of the coupling system with an IRL scale will be required.

## 5.2 A global system analysis<sup>57</sup>

As demonstrated in the previous chapter the matrix of possibilities is quite large and it is necessary to down-select the most promising couples for the proposed Integrated Energy Systems (IES). To explain the IES approach into the field of hydrogen nuclear cogeneration, it is proposed to lean on the USA DOE/INL approach completed with a GIF case study (see insert 5).

Describing the holistic Advanced Nuclear Energy pathway by sector illustrated by the following figure is the first step to provide a vision and start to answer the corresponding questions: How to achieve the vision? What will be the objectives & goals? What will be the needs in terms of study, test and modelling approaches to reach these goals?



\* significant additional electricity use not shown to simplify diagram

Figure 33: The holistic Advanced Nuclear Energy pathway by sector [Source INL pres.]

<sup>57</sup>: S. Gallier, "Hydrogen: The best shot for nuclear sustainability?", Nuclear News December 2021, pp 22-29.

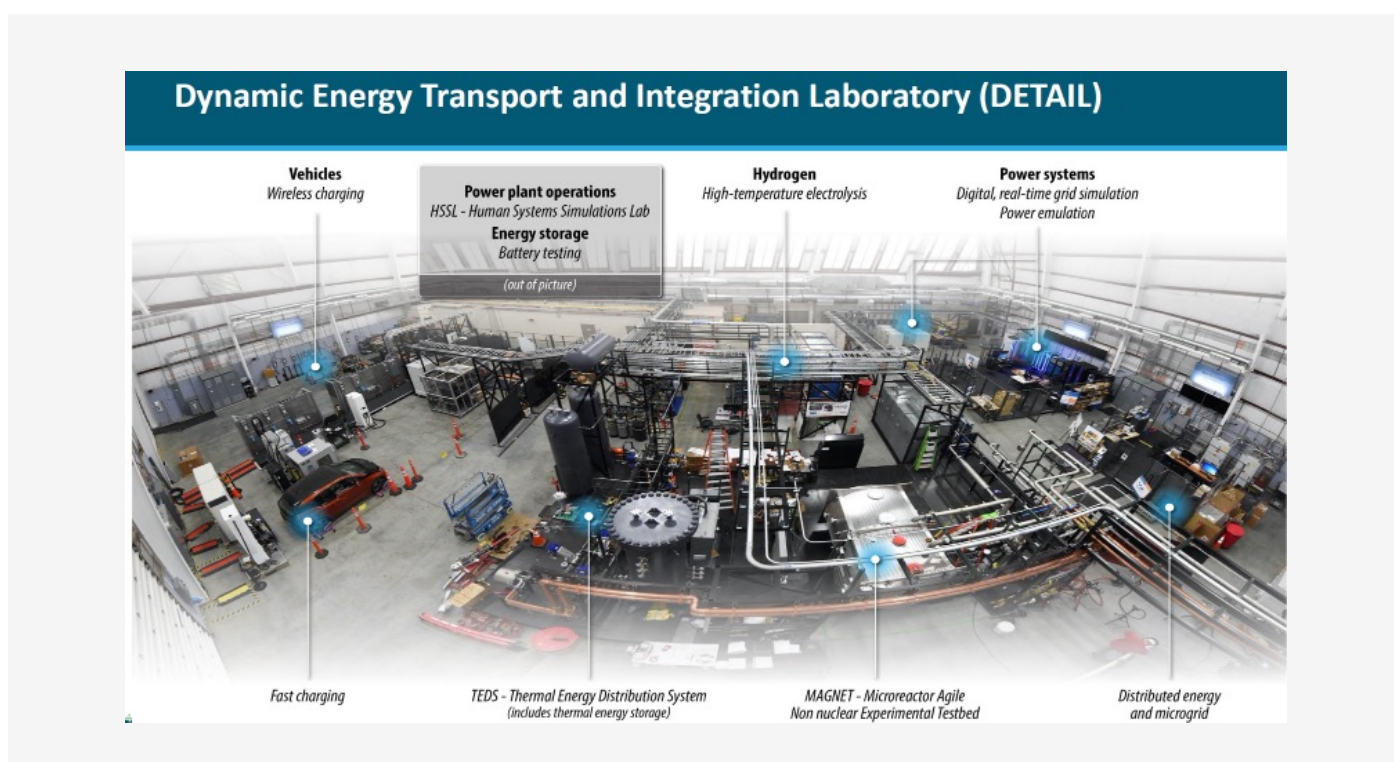
In the INL case the Mission Statement represented in the figure is: *"Maximize the use of nuclear energy by developing technologies to support chemical, thermal and electrical energy pathways that deliver nuclear energy to the industrial, transportation and commercial sectors".*

Consequently, the Integrated Energy System Guiding questions are summarised below:

- What are the **economically and technically viable options** for Integrated Energy Systems (IES) coupling to nuclear power plants in specific grid energy systems?
- What is **the statistically ideal mix** for Nuclear-IES within various markets?
- What are **driving economic factors** that existing and future nuclear technology can leverage though IES production coupling?
- What are **optimal coupling strategies** between IES technologies and nuclear power plants?
- What is **the governing control** scheme for IES?
- What are the **safety considerations** from the perspective of the nuclear and hydrogen plant?

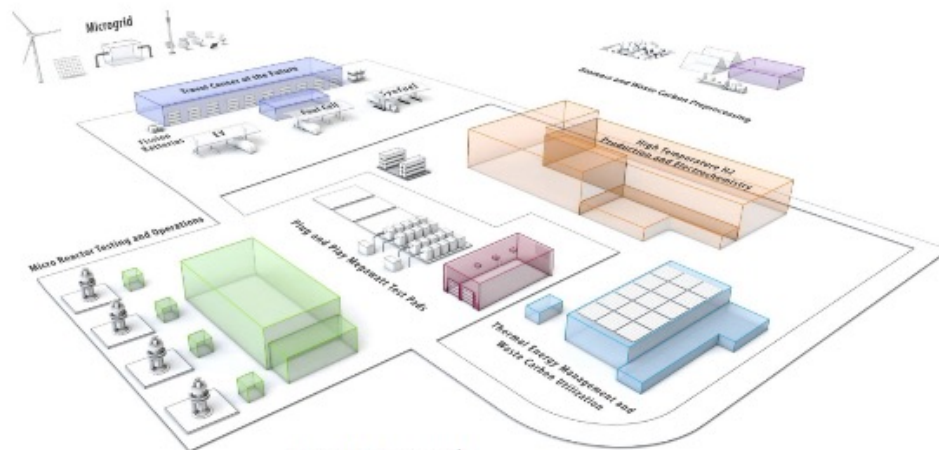
Answering this set of questions allows the corresponding program of work to be defined and to develop a research program and roadmap. The R&D and studies are implemented at INL around the following main pillars:

- Modelling the pre-selected systems to assess their technical viability, the economic viability<sup>58</sup> and their global monitoring.
- Technology development and test to increase the specific and global TRL of the whole system. This includes in particular:
  - HTSE materials and components (including stack cells, cell interconnects, charge connectors), systems performance (including gas circulators, heat recuperators, long test run performance, dynamic operation behaviour, and fabricability),
  - HTSE modules demonstration of performance and scaling up,
  - Safety analysis of the HTSE system itself and in its general and specific cogeneration environment,
  - Operation and monitoring in real cases and/or by modeling (i.e., real-time decision making & optimal control).
- Hydrogen pilot plant demonstration and extrapolation from lab scale until future factory (see following figure).



<sup>58</sup>: Cost analysis including the cost of hydrogen and the Levelized Cost of hydrogen.

## Non-Project Future Work - Proving Ground Integration

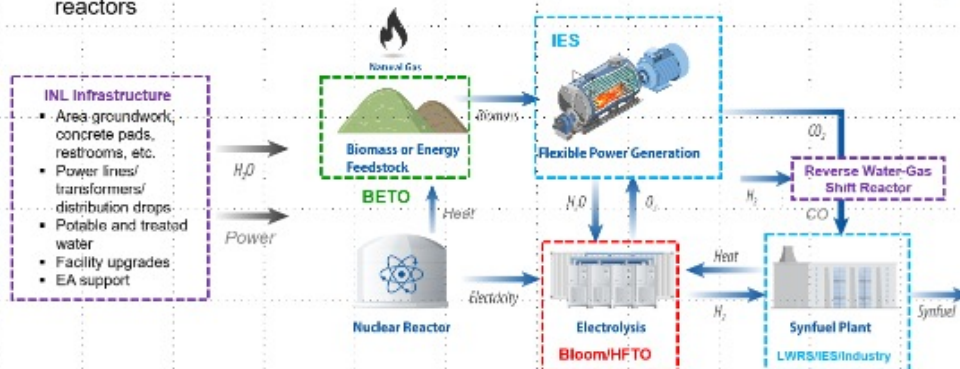


264,000 gross sq. ft.  
53 acres of test pad space

## Nuclear e-fuels and carbon conversion testing capability

### ❖ Approach:

- Establish a feedstock supply and product storage and testing system for testing nuclear e-fuels synthesis pathways
- Industry cost-share for validation and characterization of heat-recovery/steam-generation catalytic reactors



## Construction Underway (2025)



Figure 34: The INL Pilot plant demonstration: DETAIL [Source INL pres.]

*Insert 5: The HTGR/H<sub>2</sub> production case - A GIF-OECD joint study.*

## Insert 5: The HTGR / H<sub>2</sub> production case - A GIF-OECD joint study<sup>59</sup>

In 2025, GIF produced a joint system analysis in which several experts belonging to Task #44 participated.

This report highlights the opportunities and challenges associated with the development and commercialization of an integrated system combining an 800 MWth HTGR with HTSE for hydrogen production.

The report includes a comparison of independently developed modelling capabilities within GIF and NEA member countries, and consolidates expert opinion on the perceived readiness of the integrated system. The distributed modelling exercise used in this study was useful to demonstrate the similarities and differences amongst system codes in GIF and NEA member countries.

A co-generation system using HTGRs to produce hydrogen at a large and constant rate for immediate consumption proved to be a useful initial model for comparison purposes. The 800 MW HTGR system was shown to produce between 56-71 million kilograms of H<sub>2</sub> per year, which is within the expected order of magnitude for some large future off-takers of hydrogen for industrial applications, such as for steel production. Markets with high demand for hydrogen at a single point of consumption appears to represent a potentially competitive environment for nuclear energy to produce hydrogen.

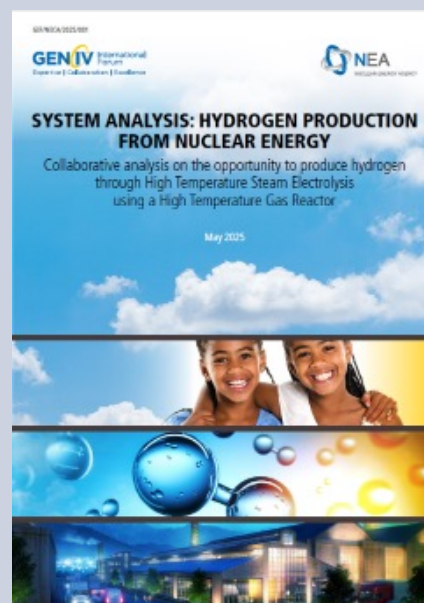


Figure 35: The cover page of the corresponding GIF document

Predicted costs of hydrogen were determined and constrained to be in a range of USD 3.04 and USD 3.72 per kilogram of H<sub>2</sub> when the cost of on-site storage is neglected. These values generally align with expected values in the literature, with improved costs expected for more-detailed systems with improved utilization of the available energy. Modelling performed from the Canadian Nuclear Laboratories compares the prescribed common scenario under varying storage conditions. Including the cost of storage increased the capacity factor of the HTGR system to the intended value of 90%, but also increased overall LCOH<sub>2</sub> costs. This suggests that the most profitable value for an integrated system is to be one where multiple markets can be served simultaneously to maximize the available energy from the reactor while minimizing the use of storage and its associated costs. Additional cost reduction strategies are expected to be implemented as technology develops for both HTGR and HTSE systems.

**Scenario 1:** No hydrogen storage or Thermal Energy Storage (TES) and all HTGRs provide a constant thermal power of 600 MWth which is split to generate electricity of 241.4 MWe and heat of 63.5 MWth. The system produces and supplies hydrogen at a constant rate of 6,353 kgH<sub>2</sub>/h or 55.6 MtH<sub>2</sub>/y. This scenario assumes an average HTGR capacity factor of 75%.

**Scenario 2:** All thermal power from all HTGR ranging between 600 and 800 MWth is used to produce hydrogen at rates of 6,353 and 8,471 kgH<sub>2</sub>/h. The system produces and supplies hydrogen at a constant rate of 7,481 kgH<sub>2</sub>/h or 65.5 MtH<sub>2</sub>/y. The average HTGR capacity factor is 90%.

<sup>59</sup>: Collective, "System analysis: Hydrogen production from nuclear energy", GIF/NECA/2025-001, May 2025.

**Scenario 3:** It assumes TES. Therefore, heat and power are used to produce hydrogen at a constant rate throughout the year. Thermal power ranging between 600 and 707 MWth from all HTGR is used to produce hydrogen and partly stored in TES, being used when needed. The system produced and supplied hydrogen at a constant rate of 7,481 kgH<sub>2</sub>/h or 65.5 MtH<sub>2</sub>/y. This scenario resulted in an average HTGR capacity factor of 90%.

| Parameter                       | Unit                  | Scenario 1 | Scenario 2 | Scenario 3 |
|---------------------------------|-----------------------|------------|------------|------------|
| Annual hydrogen production      | kgH <sub>2</sub> /y   | 55,645,412 | 65,528,037 | 65,528,037 |
| Hydrogen supply                 | kgH <sub>2</sub> /h   | 6,353      | 7,481      | 7,481      |
| Hydrogen storage capacity       | kgH <sub>2</sub>      | 0          | 1,397,037  | 0          |
| Thermal energy storage capacity | MWh-th                | 0          | 0          | 131,942    |
| HTGR capacity factor            | -                     | 75%        | 90%        | 90%        |
| HTGR electricity and heat cost  | USD /kgH <sub>2</sub> | 3.41       | 3.19       | 3.20       |
| H <sub>2</sub> production cost  | USD /kgH <sub>2</sub> | 1.11       | 1.25       | 1.10       |
| H <sub>2</sub> storage cost     | USD /kgH <sub>2</sub> | 0.00       | 2.03       | 0.00       |
| TES cost                        | USD /kgH <sub>2</sub> | 0.00       | 0.00       | 2.79       |
| O <sub>2</sub> revenue          | USD /kgH <sub>2</sub> | -0.80      | -0.80      | -0.80      |
| LCOH                            | USD /kgH <sub>2</sub> | 3.72       | 5.68       | 6.29       |

Figure 36: Table of LCOH<sub>2</sub> according to several scenarios

For a HTGR system, respondents noted that a similar system is already operating in China commercially, but not at the 800 MWth scale in the prescribed scenario. Notably, the lack of qualified materials and components for HTGRs globally inhibits its readiness as a commercially available product, which is somewhat unique to the nuclear energy industry. A similar case exists, for a HTSE plant, where stacks exist commercially but not at the scale of interest in the report. In both cases, a relatively high TRL for each system was proposed, with a TRL of 8 for HTGR and a TRL of 7 for HTSE. While these individual systems suggest relatively mature technical readiness, experts were much more critical on the perceived readiness of the integrated HTGR and HTSE system. There is a lack of data suggesting that this combined integrated system is technically mature, as there are uncertainties associated with the components required for integration.

Beyond technical readiness, a number of additional factors are required to have a commercially viable product. For the integrated system, the largest gaps preventing commercial adoption beyond technical aspects appeared to be in the areas of regulatory readiness, sufficient data on costs and potential revenue of this system and identifying specific markets that would be uniquely well suited to use this solution. Critically, the feasibility and applicability of this system is context-specific and largely depends on the target market that it intends to serve. Due to these uncertainties, the predicted timelines for an integrated system varied considerably, with an integrated demonstration expected between 2028 and 2035 by most experts, and an integrated commercial system expected between 2040 and 2050 by most experts. Experts also noted that given the uncertainties involved and the ever-changing policy and energy landscape, market demand may dramatically change and accelerate these expected timelines in support of climate change targets and to address national energy security. Generally, there appears to be no technical gaps that would prevent this system from operating successfully, but significantly more work is needed to advance the technological readiness and certainty of an integrated system at the relevant commercial scale.

The following recommendations as supported by the findings and discussions within this report: i) Pursue bilateral benchmarking of system codes ii) Make sensitivity analysis using system & techno-economic codes iii) Consider detailed business models, iv) Evaluate the value chain analysis for specific applications, v) Test scaling HTSE and HTGR separately before integration, vi) Demonstrate integration of HTSE with an existing LWR, vii) Share information and support regulatory engagement on non-electric systems, ix) Realize a continuous data update on costs, x) Compare this system against alternatives.

## 5.3 Safety approach

### Radiological Safety

The civil nuclear industry worldwide is regulated to ensure that hazards related to radiological materials and ionising radiation are conducted in a manner which adequately protects people, property and the environment. The demonstration of safe operation of any facilities and technologies required for hydrogen production at a nuclear licensed site will be key to enabling the development and successful deployment of Hydrogen from Nuclear Energy (HyNE).

Across the world, nuclear installations such as power reactors, are typically licensed and then regulated by nuclear and environmental regulators. These two regulators can be separate or part of the same oversight authority. In all areas of the world there is a legal framework which is specific to unique hazards posed by radiological materials, and this framework is in place to ensure safety to workers, members of the public and the environment from any harmful effects of the radiological materials at the site. Often higher-level legislation is supported by specific legislation and regulations related to things like ionising radiation, emergency planning zones, etc.

For a nuclear licensed site radiological / nuclear safety is demonstrated through safety assessments which follow a rigorous process, which is required as part of the site license conditions, and align to international guidance and best practice for nuclear; as detailed by International Atomic Energy Agency (IAEA) which supports the safe, secure and peaceful use of nuclear technology to support society. This guidance and best practice documentation are available through the IAEA safety fundamentals, safety requirements and safety guides, but also supported by additional technical documents (TECDOCs).

Nuclear safety assessments compare risk from a fault or accident by comparing the consequences of a committed effective dose against a set of numerical risk assessment criteria. This criterion is usually provided by a particular site or organization's safety guides for purposes of assessing radiological hazards to workers (i.e., those on-site) and members of the public (i.e., those off-site).

The concept of Defence in Depth (DiD) is fundamental to radiological safety to prevent accidents. If prevention fails to limit potential consequences, then the risk assessment criteria are met by adopting a DiD approach which is discussed in more detail below.

For new reactors there is a need to address what is considered "*beyond design*" basis for previous reactor generations, such as multiple failures and scenario which lead to core melt accidents (referred to a Design Extension Conditions (DEC))<sup>60</sup>. In the DiD approach, the objectives of the different levels of defence are mainly defined as successive steps in the protection against the escalation of accident situations. In response to this the Reactor Harmonization Working Group (RHWG) of Western European Nuclear Regulators Association (WENRA) have refined the structure of the level of DiD as detailed in an associated study report<sup>61</sup>. In each level of DiD, some situations need to be practically eliminated as it cannot be demonstrated that, should they occur, their radiological consequences would be tolerable. Situations that could lead to early or large releases of radioactive materials have to be practically eliminated. This is the approach stated in the IAEA Safety Standards for Safety of Nuclear Power Plants: Design, SSR-2/1<sup>62</sup>: "*the primary means of preventing accidents in a nuclear power plant and mitigating the consequences of accidents if they do occur is the application of the concept of defense in depth*".

---

<sup>60</sup>: IAEA Safety Standards, "Design Extension Conditions and the Concept of Practical Elimination in the Design of Nuclear Power Plants", IAEA Specific Safety Guide, No. SSG-88. 2024.

<sup>61</sup>: WENRA RHWG, "Report Safety of new NPP designs", March 2013.

<sup>62</sup>: IAEA Safety Standards, "Safety of nuclear Power Plants: Design", Specific Safety Requirements No. SSR-2/1 (Rev. 1), 2016.

In addition to the legal framework and regulations for ionising radiations and nuclear materials detailed above, nuclear sites are also expected to employ best practice from across other sites and industries. This can be referred to in numerous ways and may include; Relevant Good Practice (RGP), Learning from Experience (LfE), OPerational EXperience (OPEX), etc. But all have the same basis of understanding the root cause of previous fault or accident scenarios and designing out or providing suitable safety measures to prevent such events leading to accidents again. In this respect safety standards and specific safety guidance from national and international sources should be considered. There are specific IAEA safety guides for fire and explosion hazards<sup>63</sup> which provides relevant guidance on the hazard which HyNE could present and a technical report which reviews hydrogen production using nuclear energy<sup>64</sup> and provides insight into previous works and identifies things which should be considered for the coupling of a nuclear power reactor to a hydrogen production facility.

## Gas Safety and Hazards Associated with Hydrogen

The nuclear community has for a long time been involved in hydrogen safety studies, mainly in the consideration of severe accidents in nuclear power plants in its defence in depth approach. As mentioned in the foreword of the IAEA TECDOC<sup>65</sup>: *“The combustion of hydrogen, produced primarily as a result of heated zirconium metal reacting with steam, can create short term overpressure or detonation forces that may exceed the strength of the containment structure. An understanding of these phenomena is crucial for planning and implementing effective accident management measures. Analysis of all the issues relating to hydrogen risk is an important step for any measure that is aimed at the prevention or mitigation of hydrogen combustion in reactor containment”*.

Considering this, the nuclear research community has provided major efforts for the understanding and description of the hydrogen behaviour that serve the whole hydrogen community in its safety approach<sup>66 67</sup>. **Insert 6** provides a brief summary of the knowledge on hydrogen behaviour (properties, hazards, explosivity and consequence) and links to an in-depth thematic approach. The main body of this report will only consider areas in which the safety approach is specific to the case study of hydrogen production via a nuclear heat source.

### Motivation - H<sub>2</sub> risk in Nuclear Power Plant Station

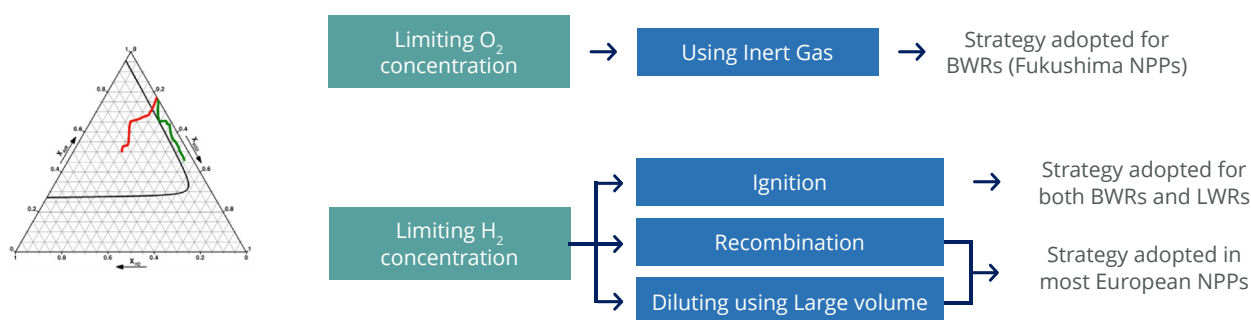


Figure 37: H<sub>2</sub> risk in Nuclear Power Plant [Source N. Chaumeix pres.]

<sup>63</sup>: IAEA Safety Standards Series, “Protection against Internal Fires and Explosions in the Design of Nuclear Power Plants”, IAEA Safety Guide, No. NS-G-1.7, 2004.

<sup>64</sup>: IAEA Nuclear Energy Series, Chapter 7 of “Hydrogen Production Using Nuclear Energy”, N0; NP-T-4.2, 2013.

<sup>65</sup>: IAEA TECDOC-1661, “Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants”, IAEA, Vienna 2011.

<sup>66</sup>: Bentaib et al., “ARNET hydrogen deflagration benchmarks: Main outcomes and conclusions”, December 2014, Annals of Nuclear Energy, 74:143-152.

<sup>67</sup>: Cheikhravat, H., Chaumeix, N., Bentaib, A., Paillard, C.-E., Flammability limits of hydrogen-Air mixtures, Nuclear Technology 178 (1), 2012, p. 5-16.

The most effective Hazard Management Strategy is to reduce the explosion hazards presented by hydrogen by preventing a significant hydrogen-air mixture from forming. This could, for example, be by suitable ventilation at high level if within a building or detection of any release quickly, triggering emergency isolation valves on pipework to minimize the amount of hydrogen released.

The main hazards which would be associated with hydrogen are already understood for nuclear licensed sites which assess fire and explosion hazards both internal and external to the facilities. Additional risk which would be introduced by new hydrogen production facilities can be managed and reduced to As Low As Reasonably Practicable (ALARP) or As Low As Reasonably Achievable (ALARA). Nuances which are specific to the technology chosen and site may arise as different designs and deployment scenarios develop and mature; but it is considered that a safety argument to demonstrate the safe operation of a hydrogen generating system would be feasible so long as appropriate safety controls can be implemented to reduce the risk. The introduction of hydrogen production systems, processing equipment, additional hazardous / flammable chemicals and any bulk storage facility will introduce hazards and additional risk. Therefore, siting of new equipment is important and will need to be considered as designs are developed.

## Co-generation

Using nuclear power reactors to provide steam for the production of hydrogen gas focuses the mind on how such deployment scenarios could be arranged and leads to the view of a co-generation facility. Co-generation is a way to use a single source of energy efficiently to produce electrical power and useful thermal energy. The idea of co-generation is to use rejected heat for the second production plant which naturally increases the efficiency of the heat engine, in this case the nuclear reactor. Since a great deal of heat energy is lost to the environment in a power plant making use of this wasted energy to produce useful outputs such as direct heating and/or production of hydrogen would be very advantageous.

The production of hydrogen using nuclear derived heat, i.e., HyNE (as opposed to conventional electrolysis using just electricity) requires additional plant / equipment to extract the heat energy from the nuclear reactor. Current interest for nuclear derived hydrogen looks to take advantage of using high temperature steam, i.e., > 300 to 900°C, to drive efficiency and greater yields of hydrogen from the energy being inputted into a high temperature electrolysis facility. It is therefore assumed that there would be the addition of the following systems to generate hydrogen: Heat Extraction System (HES) and Electrolysis Facility.

The HES (including heat exchangers and any safety related isolation equipment) is required to be located within the site boundary as there will be the need for isolation which should be under the control of the licensee / reactor duty holder. This control for stopping and isolating heat extraction would be considered an essential requirement for the safe operation of the reactor, and likely be treated like other steam by-pass systems as used in the turbine on the conventional island.

The electrolysis facility (which will produce hydrogen from water, and will take the steam energy for use in the electrolysis process), is not required to be on the site as this is essentially a chemical processing plant, which, once fed with the high temperature steam can be operated independently of the reactor site.

The following figure provides an overview of the main systems and the nuclear site boundary for hypothetical on-site and off-site electrolysis plants.

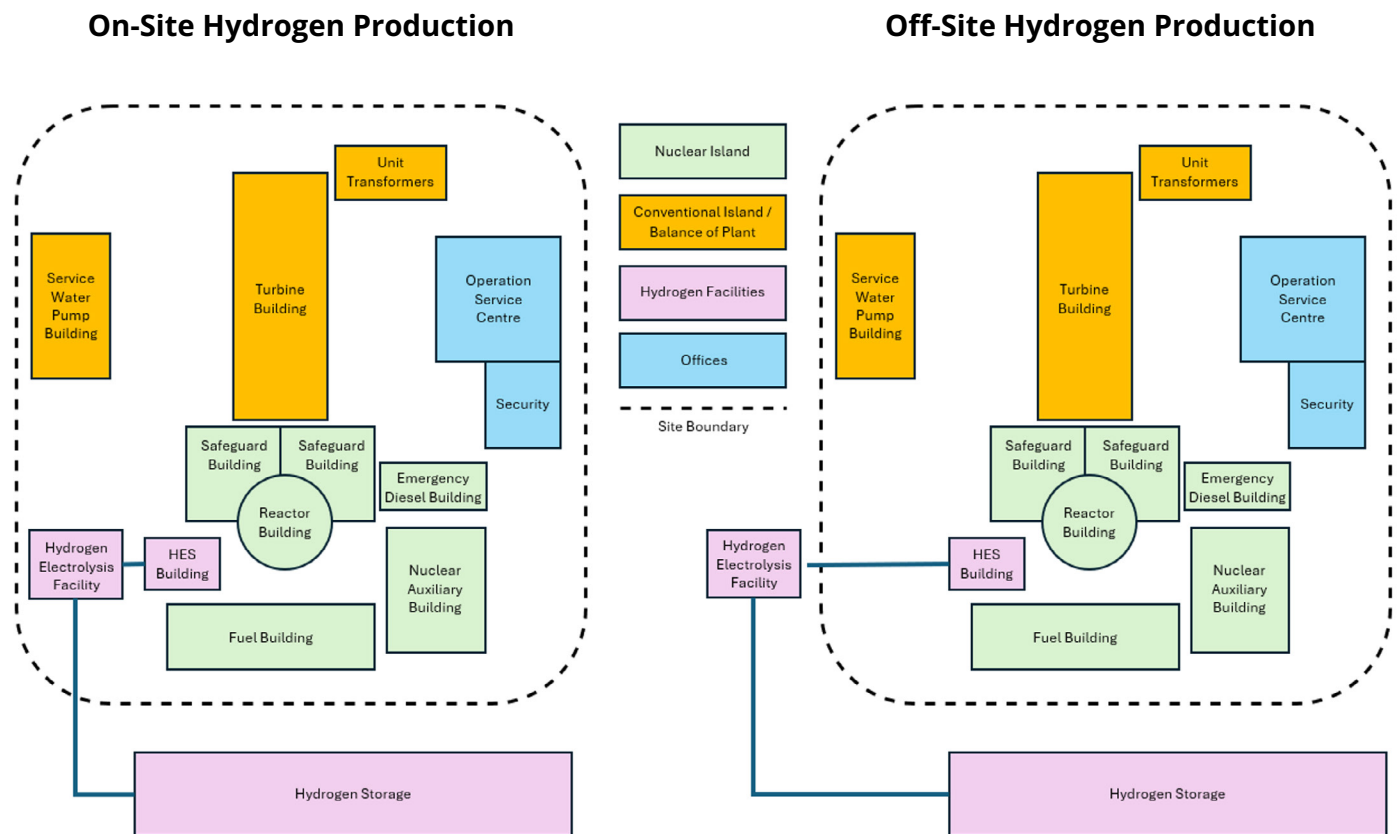


Figure 38: Hypothetical layout of a reactor site with typical Nuclear Island (NI) / Balance of Nuclear Island (BNI) and Conventional Island Balance of Plant (CI-BOP) buildings, including HES (on-site) and Electrolysis Facility (on-site and off-site) for hydrogen production.

**N.B.** the buildings are those expected on a large GW reactor site; a high temperature reactor may have different requirements and necessitate a different layout. It is assumed that the hydrogen storage would be off the licensed site.

There are a number of considerations which can make location of the hydrogen production facilities (i.e., electrolysis facility) on the licensed site potentially difficult during construction, commissioning and operation.

The placement of the electrolysis facility on the licensed site will likely necessitate it to be part of the Safety Case and this could prove costly in terms of the requirements for the nuclear site licence when the facility is being constructed, commissioned and operated. Given that the hydrogen production facilities (i.e., electrolyzers) would likely be new, novel or emerging technology it is expected that a period of testing would be required, resulting naturally in the requirement of changes to optimise the system integration, especially in the initial demonstrators used to prove the technology. If the hydrogen production facilities are located on the licensed site, there would be the need to control modifications or experiments carried out on existing plant and depending on the plant arrangements it may require regulatory approval for such changes.

The regulatory permissioning process would likely add a level of review and approvals which increases timescale for any changes to the hydrogen facilities, when compared to a conventional plant not located on a nuclear licensed site. Given that the hydrogen production facilities are essentially a chemical plant this level of nuclear regulatory validation and verification undertaken is not in line with the expectations for a conventional chemical plant located off a nuclear licensed site. Although, it is noted that any high hazard plant, especially one with a potential major accident hazard (i.e. COMAH<sup>68</sup> requirements), will have a system for review and approval to ensure safety and likely

include a Safety Case which would need changes to incorporate plant / system modifications. For a conventional plant, which is not regulated by a nuclear site license, this will be overseen by non-nuclear regulators. Modifications to the nuclear Safety Case would not be required if the facilities were located outside the site. Chemical plants are typically subject to more design changes over their plant lifetime than nuclear facilities and hence if located off-site these changes would be easier to administer.

Therefore, a sensible consideration would be to locate the hydrogen production facilities off the nuclear licensed site, leaving only the heat exchangers for the hydrogen facilities on the licensed site. The heat exchangers will directly interact with the secondary reactor systems due to their use of nuclear derived steam. Thereby, leaving the on-site fault studies to consider the new plant related faults in the hydrogen facility heat exchanger (IHx and its feedlines) where their failure could impact the reactor and/or its safety related equipment. The potential hazards arising from the electrolysis facility would be an off-site consideration as part of the nuclear Safety Case external hazard assessment. However, as the electrolysis facility will be positioned off site it will not be subject to the nuclear site licence.

There are other benefits associated with locating the electrolysis facility off the nuclear licensed site. These need to be balanced against any engineering challenges associated with delivering sufficient quality high temperature steam to the electrolysis facility over the distances required. For example, placement of the electrolysis facility to minimise heat losses and potential hazards associated with transporting high temperature steam would lead to smaller distances between the electrolysis facility and the heat generation source.

There is currently a good amount of literature being produced to explore off-site hydrogen production that takes steam from a nuclear reactor energy source, and the integration the whole safety approach<sup>69 70 71</sup>. This demonstrates an international interest in the subject.

## **Potential Design Strategies to Reduce Risk from Electrolysis Facility to Reactor and Nuclear Island Buildings**

In order to reduce the risk to the nuclear power plant from faults involving the electrolysis facility there are a number of potential arrangements which could be considered when siting and constructing the facilities. Safety to protect against the consequences of an explosion and chemical release hazard can generally be reduced with increasing separation distance or by the use of physical barriers to protect the nuclear facilities from the hazards associated with the electrolysis facility. There are numerous deployment scenarios which could be employed to reduce or remove the risk to the reactor and its safeguard buildings. Some considerations to reduce risk are detailed as:

- Increased separation distance / Raised land barrier between the facilities / Blast panels near the electrolysis facility / Move the reactor Central Control Room (CCR) off-site / Construct the nuclear reactor underground / Construct electrolysis facility underground.

---

<sup>68</sup>: Control of Major Accident Hazards Regulations (COMAH) 2015: <https://www.hse.gov.uk/pubns/books/l111.htm>

<sup>69</sup>: S. Wismer et al., "Fault tree and importance measure analysis of a PEM electrolyzer for hydrogen production at a nuclear power plant", International Journal of Hydrogen Energy, Volume 180, 21 Oct. 2025, 151773.

<sup>70</sup>: Q. Gao et al., "Influence of obstacle morphology on safety of nuclear hydrogen production system", International Journal of Hydrogen Energy, Volume 47, Issue 86, 22 Oct. 2022.

<sup>71</sup>: K. Verfondern et al., "Safety concept of nuclear cogeneration of hydrogen and electricity", International Journal of Hydrogen Energy, Volume 42, Issue 11, 16 March 2017.

The list above is not intended to be exhaustive but provides some ideas of methods which could be used to reduce the risk from explosion or chemical release from the electrolysis facility (shown in the following Figure).

### Potential Design Strategies to Reduce Risk from Electrolysis Facility to Reactor and Nuclear Island Buildings

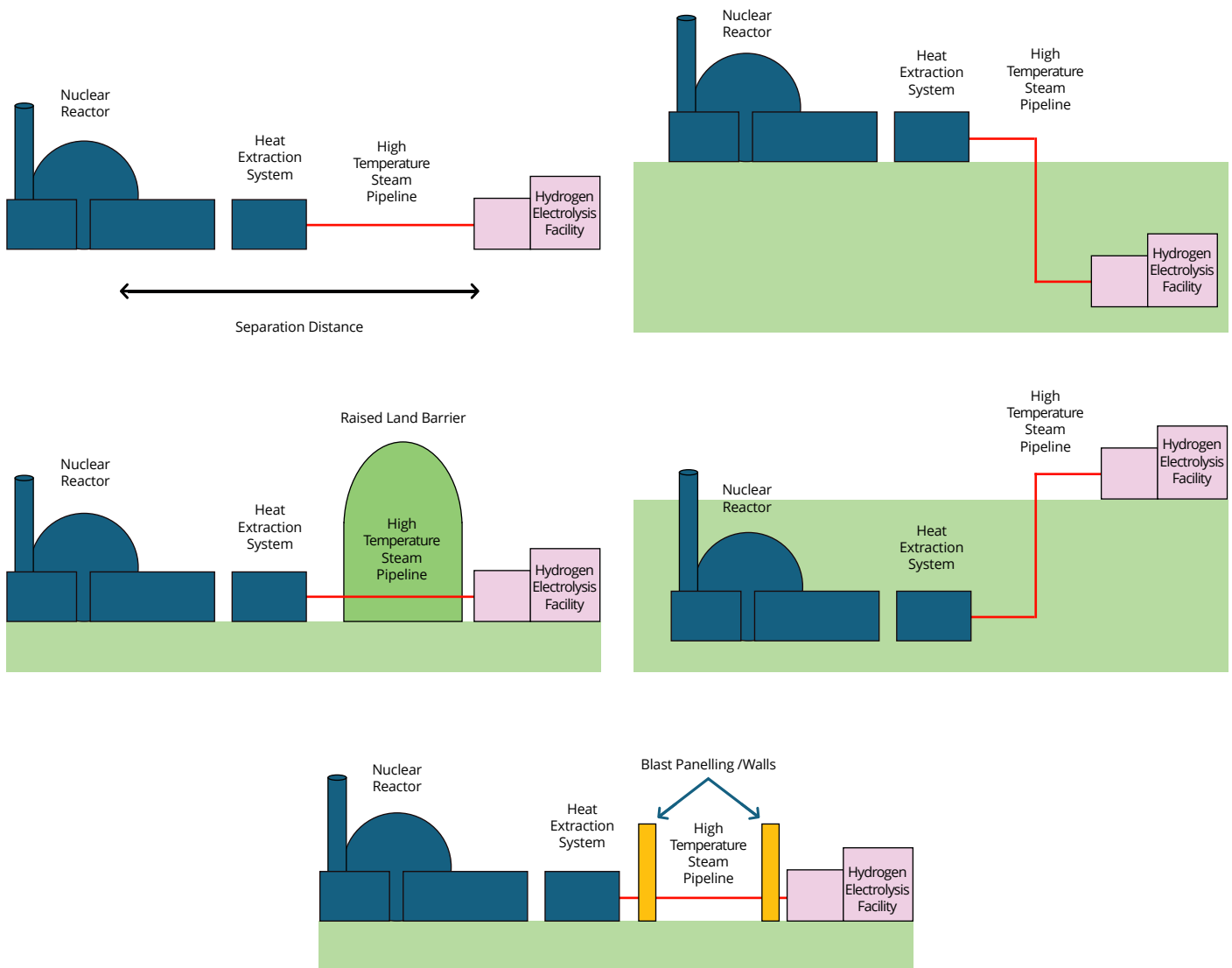


Figure 39: Potential design strategies to reduce risk from electrolysis facility to the reactor and nuclear island

Taking into account the discussion above a hypothetical arrangement for the reactor, hydrogen equipment and storage could be as shown in the following Figure, which utilises separation distances to reduce the risk to the nuclear site. In this Figure there is also an extension of the security boundary for the nuclear site. This takes into consideration that the electrolysis facility, which is a non-nuclear chemical plant if located off the licensed site would not be subject to the expectations of a nuclear regulator, but the appropriate conventional health and safety regulator to remove unnecessary regulations. However, a large collection of hazardous materials which could result in a major accident hazard may become a potential target for malicious attack to impact the operations of the nuclear island. Placing any high security risk chemical plants off the licensed site but within the security boundary of the site could provide a potential solution.

### Potential Arrangement for a co-generation Facility

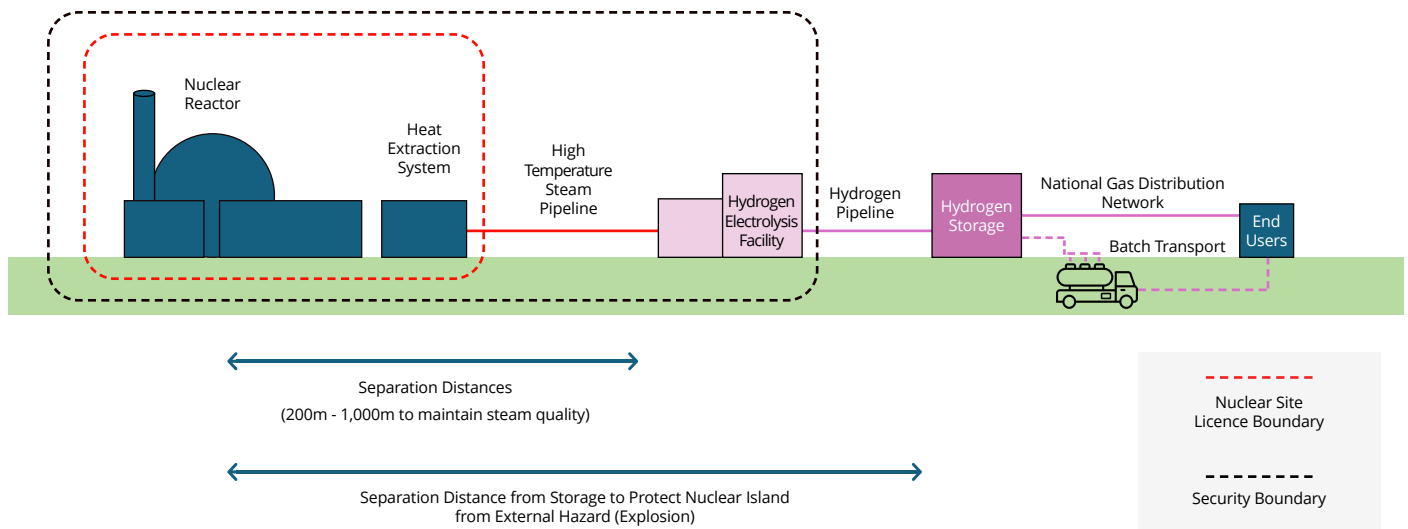


Figure 40: Potential Co-generation Arrangement for HyNE

Generation of hydrogen from a nuclear energy source is not in itself novel or likely to introduce a disproportionate level of risk to the nuclear site, so long as the hazards are managed in line with the current expectations for safety. Considerations of storage of chemicals and keeping the site informed of surrounding facilities in an intelligent way will be important. Extending this approach to other high hazard industries would help to improve site safety and the management of risk at other facilities co-located next to potential major accident hazard sites.

*Insert 6: Hazards related to hydrogen production, handling and storage***Insert 6: Hazards related to hydrogen production, handling and storage**

There are key properties of hydrogen that affect the hazards presented by the production, storage, and transportation of the material, usually as a gas. The potential impact of these properties can be best understood by using methane, the main component of natural gas, as a benchmark.

- Hydrogen is about one eighth the density of methane and about a factor of fourteen less dense than air. Hydrogen and methane gas are both less dense than air, so when released to the atmosphere they will disperse upwards, although hydrogen has much greater buoyancy compared to methane. This has implications for detecting releases in an accident scenario and the ventilation requirements for buildings where hydrogen equipment is present.
- Due to the lower density of hydrogen, the mass flow rate in any accidental release will be almost one third that for a like-for-like release of methane gas. However, the energy per kg of hydrogen is approximately 2.4 times that of methane, so the energy flow from like-for-like releases is generally similar.
- The explosion potential of hydrogen compared to methane is significantly different. The severity of an explosion has a strong dependency on the rate at which the fuel-air mixture burns (i.e. the burning velocity). The maximum burning velocity of hydrogen is about eight times that of methane and, as a result, clouds of hydrogen-air mixtures have the potential to produce much more severe explosions than methane-air explosions. The most severe explosion events occur when a transition to a detonation is triggered. A detonation involves a coupled shock wave and combustion zone that is self-sustaining, with a shock wave magnitude of twenty times atmospheric pressure and a flame front propagating at about 1.8 km/s. Detonations can be triggered if sufficient explosion energy is concentrated into a small volume. The energy required to trigger a hydrogen detonation is more than four orders of magnitude less than that for methane. It is very unlikely, in case of an accident to directly initiate a detonation even for hydrogen. But given the very large flammability domain, the high flame speed and sensitivity to detonation, the likelihood of a transition from an initial deflagration to a detonation can be high and may be considered as a realistic possibility for hydrogen releases.
- Hydrogen is also more ignitable than methane. The minimum spark energy required to ignite a hydrogen-air mixture is approximately one tenth that required for a methane-air mixture. This increases the likelihood of an accidental release igniting.

The generation of flammable gases, such as hydrogen, and the use of hazard / toxic materials, e.g. electrolyzers, naturally introduces hazards and potential fault scenarios. These types of hazards are well understood in the nuclear industry and although they will result in additional faults and increased risk they can be assessed and appropriately managed in line with the current hazard analysis undertaken for a reactor site.

The following hazards are identified for the introduction of hydrogen production at or in this review near to a licensed reactor site:

- **Fire and Explosion**

Since hydrogen has a very low ignition energy (the minimum is at 17 µJ), very large flammable domain (from 4 to 75% in volume when mixed with air), high speed flames and prone to flame acceleration and transit to detonation easily, a leak of hydrogen can easily lead to ignition. Several regimes can be observed depending on the leak scenario. Following a leak from a high-pressure tank an immediate ignition can be observed and a jet flame is observed. One has to keep in mind that even a 400 nm leak lead to a standing flame.

The first phenomenon is the jetting. Due to the very low molar mass, a break in a tank or pipe, the velocity at the exit of the jet will be very high forming an under-expanded jet. Depending on the pressure in the tank/pipe, it may ignite immediately leading to a jet-flame. Since hydrogen is characterized by flame temperature that are rather high, the burnt gases will radiate. This thermal radiation is mainly in the UV (due to spontaneous emission of radicals, OH mainly) and in the infra-red (due to water vapor). This thermal radiation is responsible for the fact a hydrogen flame is hardly visible and that the percentage of the energy released by the combustion that goes in the radiation is lower than any hydrocarbon flame. The thermal burn (radiant heat from the flame absorbed by a person) depends strongly on the humidity in air, the thermal burn can occur mainly due to the fact that in daylight, a person can hardly localize the flame and may be very close to it before realizing the hazard.

If the ignition does not occur upon accidental release, then the high velocity will be responsible for a very rapid dispersion of hydrogen in the environment aided by the buoyancy due to the very low density. The mass of the cloud that is within the flammability limit may ignite locally and lead to the formation a flame propagating to the entire combustible volume. Initially, the flame propagates at burning speed that are below the speed of sound in the unburnt gases, this flame called a deflagration with propagation speed ranging from a few meters per second to several hundred meters per second. The increase in the flame speed will be responsible for overpressures that can already threaten the equipment and the facilities. This acceleration is due to the enhancement of the burning rate by turbulence created initially by the flame and then by the interaction of the flame with the environment (obstacles).

Once a flame is strongly accelerated, a threshold can be reached where the flame reaches choked regimes (700 to 900 m/s) and it changes its nature and transforms to a detonation wave. A detonation is a combustion zone coupled to a leading shock wave. Detonation propagates at a velocity round 2 km/s and induces pressure peaks that are higher than for a deflagration.

When the combustion wave is fast enough or is a detonation, the overpressure will propagate in the atmosphere as blast waves. The overpressure due to a blast wave depends on its strength. The damages to the people and equipment depends strongly on the overpressure. An overpressure of around 130 mbar would lead to eardrum rupture and an overpressure of 480 mbar is the threshold for internal injuries. Damages to equipment and facilities can be observed: at 10 mbar glass shattering is induced, at 150 mbar collapse of unreinforced concrete or cinderblock wall, at 700 mbar total destruction of buildings and heavy machinery damages.

The overpressure of blast waves can also be indirect through the fragments and debris generated by the explosion. Owing to the combustion energy transmitted and the impulse of the blast waves, flying debris and fragments coming from collapsed structures can induce further damage to surrounding facilities/equipment and people. The rupture of a high-pressure reservoir will also generate these debris.

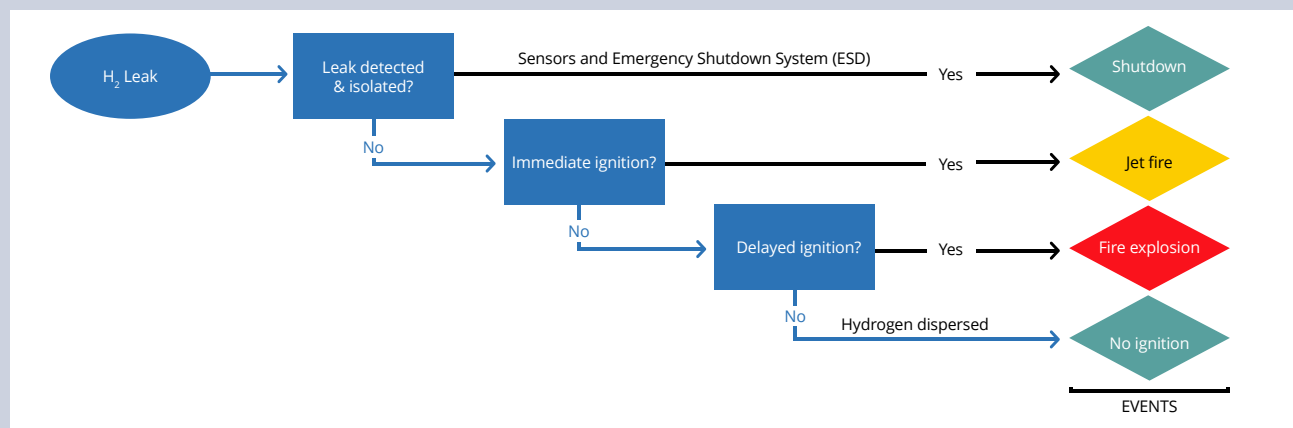


Figure 41: H<sub>2</sub> Event tree diagram [Source Z. Liang pres.]

- **Transporting / Storage of Hydrogen**

For effective storage and transport, there is a need to either liquify or compress hydrogen. Solutions will be adapted and implemented depending on the considered situation and event: Run up to detonation, Leaks, Fires, Jetting, Explosions, Vapour Cloud Explosion (VCE) / Boiling Liquid Expanding Vapour Explosion (BLEVE), Missiles effects.

- **Toxicity from Chemicals related to Hydrogen Processes**

Hydrogen is colourless and odourless gas, it has no toxicity just like methane. However, when leaking into a closed environment leads to a displacement of air, and the oxygen content in the environment can drop leading to asphyxiation. The oxygen content in air is 20.9%. When reaching the value of 19%, an impact on people can already be seen (dizziness, difficulty to perform tasks), at 10 %, unconsciousness occurs and below 8% death would occur in 8 minutes.

- **Domino Effects**

It is noted that the actual hazards associated with production, transport and storage of a flammable / explosive material remain unchanged whether located on-site or off-site. The reactor and its associated safety related equipment always require protection to prevent damage to the reactor (i.e. core damage) and ensure radioactive materials are not released to the environment. When located off the licensed site it is likely the potential for damage will be somewhat reduced due to the separation distance between the facilities. Although the level of damage to any sensitive nuclear structures following an explosion or chemical release will need to be assessed based on the specific fault scenario.

When off-site the fault scenarios would be treated as an external hazard to the nuclear installation - in much the same way as other man-made external hazards (i.e., aircraft impact, hazards from industrial activity, fires, missiles, etc.) that are not due to natural phenomena.

## 5.4 Regulation approach

### Nuclear and Gas Safety Regulation

Within the nuclear industry the principal safety requirement is that radioactivity is completely retained inside the plant and / or facilities, even in extreme accidents, with no severe consequences outside the site fence. The nuclear industry already has a wealth of knowledge in managing the hazards associated with using / storing hydrogen, and other flammable gases, at a licenced site. Generally, the safety management strategies are the same for different licensed sites within a given regulatory regime, as they are required to satisfy the expectations of the same nuclear regulator through assessment of the Safety Case. The Safety Case provides the duty holder and regulators with the information required to enable safe management of the facility and to reduce risks to ALARP / ALARA.

The fundamental requirement of any radiological Safety Case is to demonstrate that hazards presenting radiological exposure or harm can be safely managed and that the risks are ALARP / ALARA, with a clear link of how the assessment is implemented within the facility, known as the 'Golden Thread'. It is worth noting that the Safety Case is not a single document, but the totality of documented information, claims, arguments and evidence developed by the licensee which substantiates the safety of the plant activity, operation or modification in question. The Safety Case should provide sufficient information to demonstrate adequate protection of workers and members of the public during normal operations and fault conditions (when these cannot be prevented), to ensure that the risk is ALARP / ALARA. Within the UK, for large and/or complex Safety Cases, the ONR suggests that licensees produce a top tier document, which is generally referred to as the Safety Report. The licensee is ultimately responsible for the overall Safety Case.

The incorporation of Safety Case development within the design process helps to ensure that the design develops with normal and fault condition safety in mind, with the aim of minimising the hazards present and reducing the residual risks at the final design stage.

The nuclear power and gas industries are both highly regulated and observe strict standards of safety and environmental protection. The success of nuclear derived hydrogen technologies will require harmonisation of two different safety and regulatory governance regimes, which have not previously interacted in this way.

Both the nuclear and gas industries approach hazard assessment and management in a broadly similar way. That is, they identify and assess potential hazards related to their facilities and activities. These hazards are then compared against risk targets e.g., the potential consequences and frequency of each hazard and appropriate safety features / measures are identified. Although it is noted that the safety expectations and perceived risk for the nuclear industry is set at a higher standard.

Focusing on the harmonization between the nuclear and gas industries (specifically hydrogen), **Insert 7** provides an overview on Codes & Standards, Regulations and Guidelines.

#### *Insert 7: EU Codes & Standards, Regulations and Guidelines*

### Insert 7: EU Codes & Standards, Regulations and Guidelines

There are regulations that assure safety in the EU some of which also apply to hydrogen safety, production and applications. While this report focuses on European Directives and Standards, global operability is essential. According to the Task #44 specific objective of providing analysis on hydrogen from nuclear energy, we provide here a map for hydrogen codes & standards.

The purpose of this Insert is not to provide an exhaustive list of all international codes & standards related to hydrogen. The aim is to provide an overview with just some selected ones that we consider to be the most relevant. We also provide links to some of the most relevant hydrogen standardization sources.

#### **Concerning regulations:**

- *Pressure Equipment Directive (PED 2014/68/EU)* mandates rigorous safety requirements for hydrogen containment, ensuring equipment's integrity and material properties to ensure conformity (accessible [here](#)).
- *Other European directive that needs to be considered, is the ATEX Directive (2014/34/EU)* that requires minimizing ignition risks for equipment used in potentially explosive atmospheres like hydrogen (downloadable [here](#)).

**Concerning codes:** there are no codes dedicated specifically for hydrogen from nuclear energy. Nevertheless, the use of nuclear energy remains a possibility for hydrogen production. Nuclear reactors may be used for production of Hydrogen as they can provide electricity and heat. Concerning heat, *SMR – small modular reactors* are suitable and reactor-types such as High Temperature Reactors [HTR] and Very-High Temperature Reactors [VHTR] are the most promising. Those types of reactors are covered by the RCC-MRx code ([AFCE](#)).

**Concerning standards:** a standard is a document providing requirements, specifications, or characteristics to be used for fitting-for-purpose of products, services or processes:

- The harmonized **EN 13480 metallic piping** European standard is often used in industry (oil & gas and nuclear) to comply with the PED requirements. For information, there is a project in progress of EN 13480 part 11 that will cover additional requirements for hydrogen application piping.
- The **ISO/TS 19870 Hydrogen technologies** is a technical specification on methodologies for determining the GHG - greenhouse gas emissions associated with hydrogen production and transport ([iso](#)). This specification provides a comprehensive framework for assessing the carbon footprint of hydrogen technologies. Unveiled in 2023 during COP28 in Dubai, it supports global climate goals by offering a transparent, consistent benchmark for evaluating and comparing hydrogen's environmental impact.
- The *European Hydrogen Observatory* provides a great overview of **European** policies and legislations (regulations and directives), different **strategies** adopted by national governments, and codes & standards (in different categories: hydrogen production, distribution & storage, end-use-applications, etc.) that all impact deployment of hydrogen technologies. Accessible [here](#).
- For high pressure systems electrolyzers, transport and storage, international projects frequently reference standards like ASME B31.12 for Hydrogen Pipelines and BPVC VIII for Pressure Vessel guidance on piping and vessel design. These standards facilitate collaboration with global partners and can be applied in conjunction with European frameworks (EG: PED and ATEX) complementary to European and ISO standards.
- The *UNIDO - United Nations Industrial Development Organization* launched in 2021 its **Global Programme for Hydrogen in Industry** to support hydrogen development in developing countries, including assistance in facilitating standards (Accessible [here](#)).
- The *IEA - International Energy Agency* publishes the **"Global Hydrogen Review"** annual publication tracking hydrogen demand and production. This review (downloadable [here](#)) is an output of the *Clean Energy Ministerial Hydrogen Initiative* ([CEM](#)) intended to inform on hydrogen's state-of-the-art.

#### Other guidelines:

- The *ISPT - Institute for Sustainable Process Technology* has published the report **"Safety Aspects of Green Hydrogen Production on Industrial Scale"** that focus on hydrogen safety for large-scale electrolysis, downloadable [here](#).
- The *GH<sub>2</sub> - green hydrogen organization* has published the **"Green Hydrogen Standard"** that is actually a guideline proposing principles to consider a hydrogen production as green hydrogen, that is hydrogen produced through the electrolysis of water, downloadable [here](#).
- Under the common platform **Hydrogen safety** ([h2safety](#)), four regional industrial gases associations, including the *EIGA - European Industrial Gases Association*, provide easy access information on hydrogen intended for general public, from start-ups and big companies, over engineers and scientists, to legislators and policy officers. The information is provided in different categories: production, conditioning, storage, transport and applications.
- A similar platform exists in USA: **safe hydrogen project** accessible [here](#).

## Societal Risk from Major Accident Hazard Sites

Societal risk describes the risks, or threats, from hazards which impact on society and which, if realised, could have adverse repercussions for the institutions responsible for putting in place the provisions and arrangements for protecting people (e.g. Parliament or the Government of the day). These types of concerns are often associated with hazards that give rise to risks which, were they to occur, would provoke a socio-political response, e.g. risk of events causing widespread or large scale detriment or the occurrence of multiple fatalities in a single event. Typical examples relate to activities that are considered to be high risk industries or concern to public health such as: Nuclear Power Generation, Oil and Gas industry, Railway Travel, Aviation, Genetic Modification of Organisms.

For potential major accidents societal risk should be taken into account more explicitly when assessing safety measures for onshore, non-nuclear major hazards and for informing decisions on the use of land around such a site.

Societal risk related to a major accident hazard site can change over time. When the population in the surrounding areas next to a major accident hazard site build up there would naturally be an increase in the societal risk. It may also be appropriate and necessary to take account of societal risk explicitly when considering any further development proposals around a site.

There is a well-established process for ensuring that risks from major hazard sites are controlled and kept low. This takes a three-step approach, as follows:

- Identification: Understand which sites have the potential for major accident hazards based on inventory, toxicity, fire and explosion hazards;
- Assessment and Controls: assessment is undertaken and measures are applied by the operator to: (a) Prevent, so far as is reasonably practicable, major accidents; (b) Reduce the probabilities of any incident that does occur escalating to more serious consequences (e.g. one explosion leading to another).
- Mitigation: consequences of major accidents that occur after the loss of prevention and control.

This includes functions carried out by local authorities such as land use planning controls and emergency planning. This step is undertaken to lessen the effects from a major accident. This approach recognises the potential for an accident can never be completely eliminated, so mitigation is also required to ensure responses to an accident have been thought out and are in place before the occurrence of such a scenario.

## 5.5 Business case approach

The business case approach presented is based on the TANDEM<sup>72</sup> ("Small Modular Reactor for a European Safe and Decarbonized Energy Mix") Euratom project<sup>73</sup>. Several members of this project were also members of Task #44. The publication in this document is done under their authorization. A larger description of the TANDEM project is in Annex 4, in particular two other scenarios. An equivalent study is modelling the USA case (see FORCE initiative by INL on Insert 8). Insert 9 summarises an equivalent study carried out in the UK. Last, Insert 10 presents the vision of an international chemical supplier company (Air Liquide).

The study case for the energy hub configuration is inspired from a harbor-like infrastructure. In Europe, there are several examples of industrialized harbors, which are responsible for a significant proportion of CO<sub>2</sub> emissions and are engaged in a process of decarbonization. To define an energy hub configuration to be studied in the TANDEM project, it was decided to arbitrarily set constant loads of hydrogen and electricity to be produced in the South of France (Fos sur Mer) for the definition of the study case.

### Economic viability and environmental impact: The Industrial Hub modelling

The SMR use-case implemented in techno-economics optimizations of energy hub architectures is assumed to be operated at full power in cogeneration mode with a fixed heat extraction rate of 10% between the steam generators

<sup>72</sup>: <https://tandemproject.eu/>

<sup>73</sup>: C. Vaglio-Gaudard et al., "Integrating nuclear Small Modular Reactors into low-carbon energy systems: an illustration using a recent European R&D initiative", Sustainable Energy Technologies and assessments, Volume 86, Feb. 2026, 104787.

and the turbine, resulting in the delivery of 155 MWe of electricity and 50 MWth of thermal power from the reactor. A 20-year projected lifetime and a discount rate set at 5% are considered in the optimizations, which rely on time series of year 2019, related to Fos-sur-Mer in France, as input data. Data for CAPEX and variable costs in the study correspond to a forecast in 2035. All the costs are expressed in €2023. Fifteen simulation runs have been carried out to model the energy hub architectures; a brief analysis of the results is presented below:

- The reference Run0 corresponds to the architecture of the business-as-usual energy scenario: electricity and hydrogen productions are provided by a CCGT plant (producing only electricity), a photovoltaic (PV) field, and a Steam Methane Gas Reforming (SMGR) plant. In Run0 the Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH<sub>2</sub>) reach 35.1 €/MWh and 0.97 €/kg H<sub>2</sub> respectively, for a CO<sub>2</sub> intensity of 9.48 kg CO<sub>2</sub> eq/kg H<sub>2</sub>.
- Run-1 has been considered to evaluate the case where the PV field is removed.
- After Run0, the SMR and the HTSE plants are used with an increasing contribution. After Run6, all hydrogen production is provided by water electrolysis; SMGR is no longer used.
- Run7, integrating two 2 SMRs, renewables and a HTSE plant, shows that the system can be decarbonized by around 80% compared with the Run0. The LCOE and LCOH<sub>2</sub> are close to 61€/MWh and 3.2 €/kg H<sub>2</sub> respectively. The extra costs on LCOE and LCOH<sub>2</sub> for implementing low-carbon energy production are about 26.1 €/MWh and 2.2 €/kg H<sub>2</sub>, compared with the Run0 architecture. Considering a carbon cost of 100 €/ton CO<sub>2</sub> eq would lead to the same LCOE between Run0 and Run7 whereas a carbon cost of 172 €/ton CO<sub>2</sub> eq would lead to the same total costs between Run0 and Run7, thus to very similar LCOE and LCOH<sub>2</sub>. This order of magnitude for the cost of CO<sub>2</sub> can be considered plausible since the price of CO<sub>2</sub> emission allowances reached more than 100 €/ton CO<sub>2</sub> in EU in February 2023.
- Hydrogen storage is requested up to Run7 to store excess electricity generated by wind turbines. When the hydrogen tank (hydrogen pressure at 30 bar – the energy compression considered in the assessment) is full, electricity is released to the grid, presumably free of charge.
- After Run7 and until Run13, the CCGT contribution to electricity generation declines sharply and is partially replaced by the contribution of wind turbines. However, the CCGT contribution is never cancelled out due to the intermittency of renewables and the fact that the SMR always operates at full power by assumption. An additional optimization (Run14) has been proposed to analyse the behavior while imposing the size of the CCGT at zero. In this case, the wind farm becomes more important (contribution of wind turbines is multiplied by a factor of three in Run14). The LCOE and LCOH<sub>2</sub> are higher (74.10 €/MWh, 3.85 €/kg H<sub>2</sub>, compared to Run13: 66.74 €/MWh, 3.58€/kg H<sub>2</sub>), with a lower CO<sub>2</sub> intensity of hydrogen (0.50 kg CO<sub>2</sub> eq/kg H<sub>2</sub>).
- For all runs, the Levelized Cost of Heat is relatively constant (19.55 €/MWhth); the CO<sub>2</sub> intensity of the thermal energy is then determined by the E-SMR (1 kg/MWhth).

#### **The analysis of this study case shows that SMRs can be a relevant option to decarbonize Hybrid Energy Systems<sup>74</sup>.**

The energy hub case has been the subject of additional studies on the benefit of implementing complementary systems of decarbonization, such as a Carbon Capture Utilisation and Storage (CCUS) system. It showed that equipping the CCGT and the SMGR with CCUS components results in decreasing CO<sub>2</sub> emissions at low additional cost. However, the main disadvantage is the high carbon storage capacity required and the low maturity level of this solution.

<sup>74</sup>: However, it is important to be aware that the results obtained for the study cases deeply rely on the assumptions made in the optimization calculations, and are likely to be affected by the assumptions and uncertainties associated with the optimization input parameters.

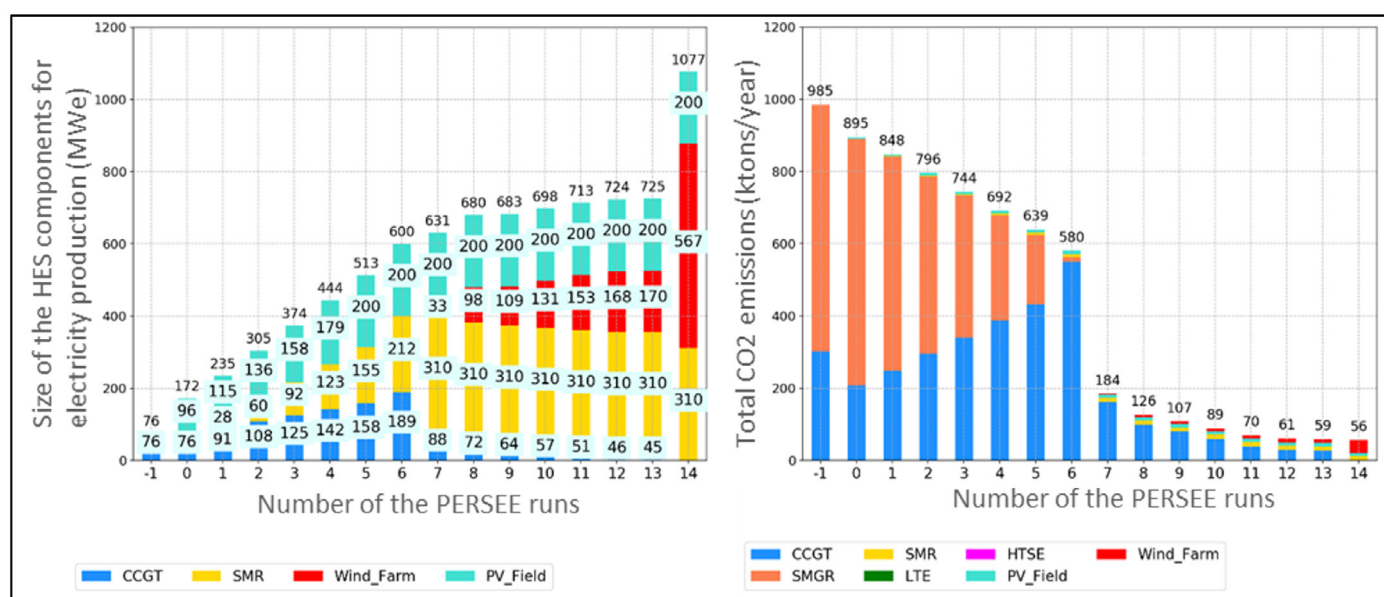


Figure 42: Optimization results of architectures for the energy hub case with the PERSEE tool: left= size of the HES components; right= total CO<sub>2</sub> emissions.

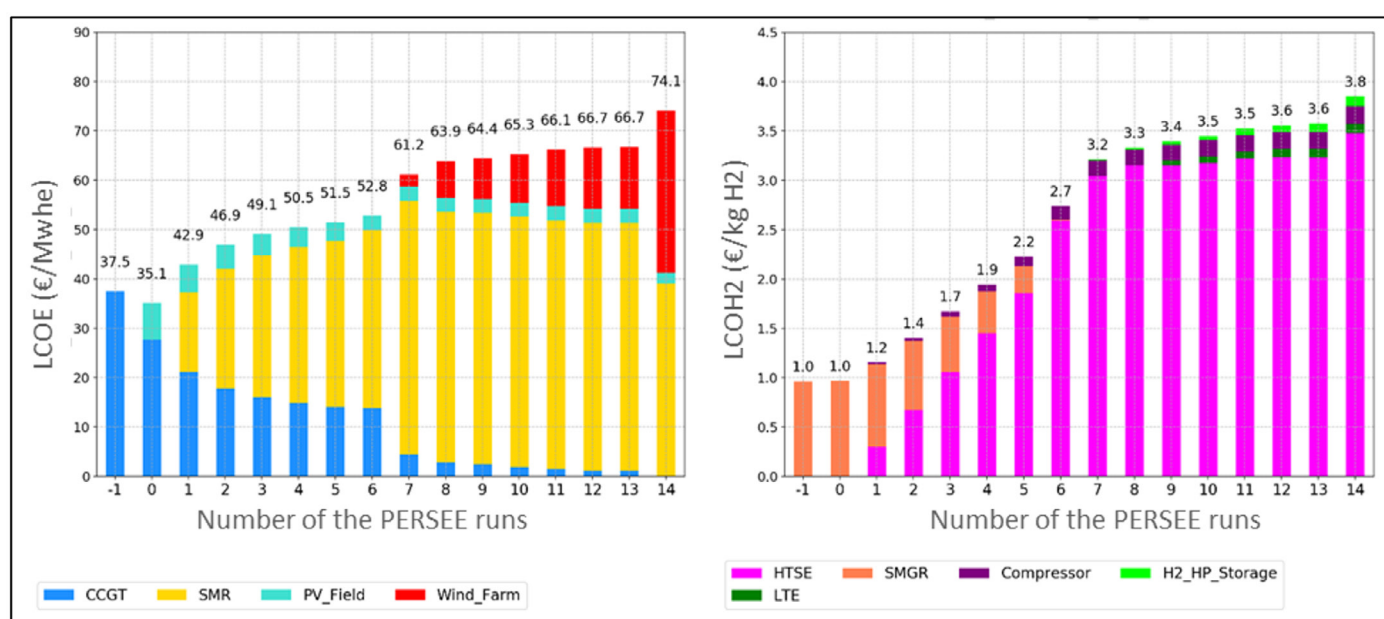


Figure 43: Optimization results of architectures for the energy hub case with PERSEE tool: left: LCOE; right: LCOH<sub>2</sub>.

## Key Challenges identified by the TANDEM project

- **SMR and electrolyser technologies face strong competition from other technologies** as well as energy imports, hampering potential investment. For example, hydrogen imported via global corridors could be cheaper in 2050. In addition, for some processes it could be easier to replace grey hydrogen (produced from natural gas) with blue hydrogen (produced from natural gas combined with carbon capture technologies). Therefore, construction and maintenance costs will need to be low enough to encourage investment in both SMRs and electrolyzers. A complementary view is brought in [Annex 6](#).

- Particularly when **dealing with H<sub>2</sub>, there is also competition between electricity production and H<sub>2</sub> production in terms of revenue maximisation**. If an SMR is dedicated to "cogenerating" electricity for both the grid and hydrogen production, then a mechanism to avoid distortions should be considered to ensure constant H<sub>2</sub> production.
- In some EU countries, such as France, operators of nuclear reactors have to pay taxes, which do not depend on the nominal power of the reactors. To support the deployment of SMRs and AMRs which will be smaller than current large reactors, taxes will need to be adapted to take into account the nominal power output of such reactors.
- Electricity can be sold directly to the market regardless of the location, but for now heat and hydrogen cannot be transported over long distances. Furthermore, there are uncertainties regarding the framework which will apply to hydrogen transportation. As a result, SMRs destined for non-electric applications will most likely need to be situated close to the end consumers.
- **Demand for low-carbon hydrogen still needs to be ramped up to stimulate investment in production.**
- Public acceptance will also play a key role in the deployment of such technologies, as this can help or hinder a project.

*Insert 8: INL FORCE Tool Suite and DOVE: Optimizing Integrated Energy Systems*

## Insert 8: INL FORCE Tool Suite and DOVE: Optimizing Integrated Energy Systems

Ever-increasing demands for electrical power to support data centers and artificial intelligence platforms, and aggressive electrification of transportation systems and energy-intensive manufacturing industries, along with the buildout of solar and wind energy in many parts of the country has led to the need to develop computational tools to support capacity expansion decisions and increasingly complex grid operating scenarios. Nuclear power plants, which currently provide steady baseload power, could play a new role by pairing with energy storage technologies—but utilities need better tools to evaluate these options. Over the past six years, INL developed the Framework for Optimization of Resources, Controls, and Economics (FORCE), a software suite that evaluates how nuclear power plants can operate as part of integrated energy systems rather than as standalone electricity producers. Unlike traditional grid models that focus only on electricity, FORCE analyzes multiple energy products—such as electricity, heat, hydrogen, and synthetic fuels—and determines how to allocate resources for maximum economic and operational benefit.

INL built **FORCE** around three core capabilities: (1) HYBRID, a physics-based modeling library, in collaboration with Oak Ridge National Laboratory and Argonne National Laboratory, that represents nuclear reactor heat production, power conversion systems, high-temperature steam electrolysis for hydrogen production, and other technologies such as wind and solar. (2) HERON (Holistic Energy Resource Optimization Network), which evaluates long-term economic performance under uncertain market conditions, including fluctuating weather, fuel prices, and demand. (3), INL implemented ORCA (Optimization of Real-time Capacity Allocation), which enables near real-time dispatch decisions to efficiently distribute energy production.

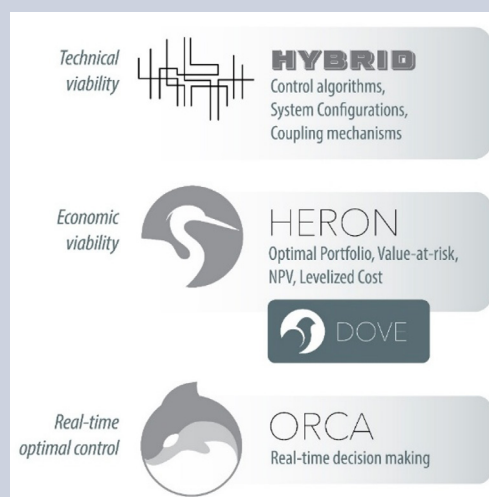


Figure 44: The FORCE architecture

In 2025, INL expanded these capabilities by introducing **DOVE** (Dispatch Optimization Variable Engine) as an extension of HERON, which enhances long-term planning by allowing minute-by-minute optimization of nuclear, natural gas, wind, and solar resources. DOVE captures market feedback and uncertainty, giving utilities and planners clearer insight into how different resource combinations affect cost, revenue, and resilience.

Through this effort, INL demonstrated that nuclear plants can increase revenue and reduce operational risk by flexibly producing electricity and alternative energy products, including hydrogen, when market conditions shift. INL proved advanced modeling and optimization can reveal profitable pathways for the current fleet that are not visible through traditional analysis.

INL delivered the FORCE tool suite, including DOVE, as accessible software for utilities, researchers, and policymakers, along with training materials and collaborative engagement with national laboratories and industry partners. These tools directly support the Department of Energy's mission to ensure the continued viability, reliability, and economic competitiveness of the existing nuclear fleet while strengthening grid resilience and establishing energy dominance.

Working with industry partners, we used FORCE derivatives to evaluate the benefits of increasing nuclear power in general, and how nuclear plants can be coupled with hydrogen production systems to add reliability and flexibility to future electric grid scenarios. This tool allows utilities to model how energy systems perform hour-by-hour over 20-year periods, accounting for uncertainty in weather, electricity demand, and fuel costs. This approach captures the actual availability of solar and wind power and optimizes how different technologies work together, as well as evaluating opportunities in multicommodity markets.

As an example of the use of this new tool, the following figure plots the power production and consumption optimization for a Southwest U.S. region market scenario, where solar power capacity reaches around 40% of the total grid capacity. The analysis highlights the value of nuclear-hydrogen systems when paired with the solar generation assets. During sunny midday hours when solar power exceeds demand, nuclear plants can redirect some energy to produce hydrogen instead of curtailing generation. This stored hydrogen then provides power during evening peak demand when solar output drops but electricity needs remain high.

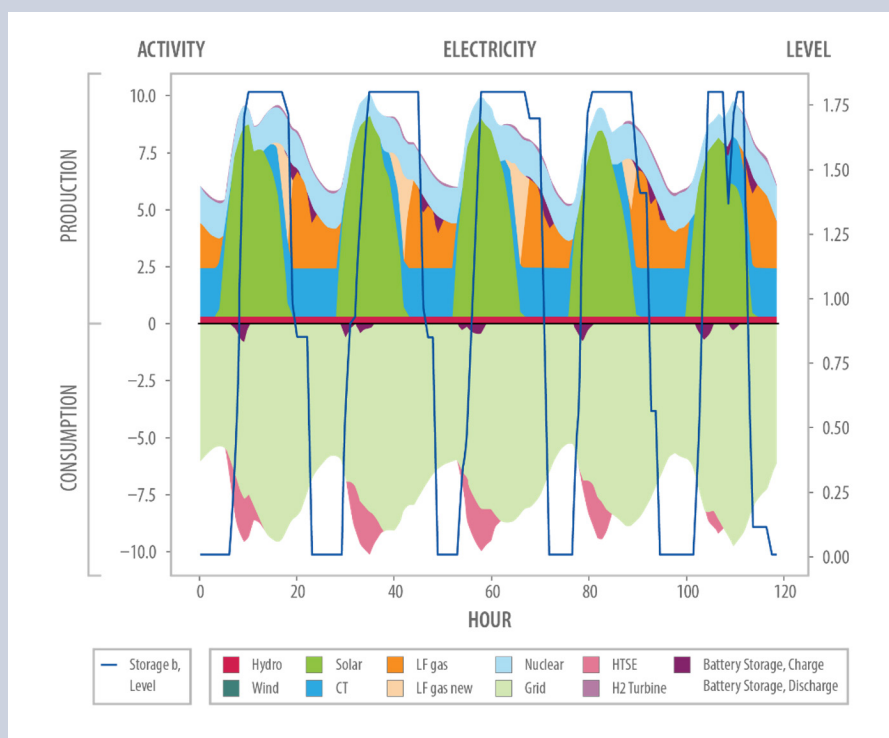


Figure 45: Dispatch over one 120-hour segment showing how the system balances solar generation, nuclear power, and natural gas to meet demand.

*Solar energy peaks during daytime hours, while natural gas and batteries fill evening demand gaps.*

*Acronyms: CT: Combustion Turbine, LF: Large Frame, HTSE: High Temperature Steam Electrolysis, H<sub>2</sub>: Hydrogen*

INL future explored whether existing light-water reactors can improve profitability by producing hydrogen for industrial users. This offers a potential second revenue stream that can stabilize operations and advance fleet reliability while maintaining electrical power generation for the grid during peak demand and producing hydrogen for oil refining, chemicals and fertilizer production, and steel manufacturing.

With roughly 200 to 500 MW output from the nuclear plants regulated between the electricity grid and an HTSE plant, INL evaluated the U.S. Code of Federal Regulations production tax credits for hydrogen under Section 45V and 45U, while factoring in ancillary service revenues that reward fast grid response. The model predictions show that integrated hydrogen production can significantly improve plant revenues compared to power-only sales in several markets. In grid markets in the United States, hydrogen prices near \$1.50/kg were predicted. This price is competitive with natural gas reforming using cheap gas in the U.S. The study also confirmed that high-temperature electrolysis improves efficiency and value by reducing electricity demand per kilogram of hydrogen produced.

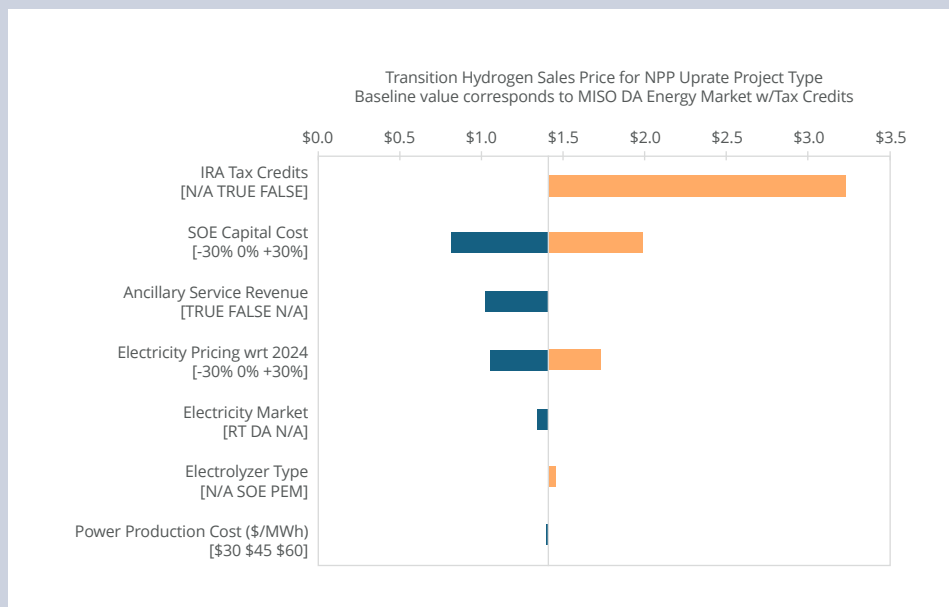


Figure 46: Hydrogen Profitability: Transition hydrogen sales price (in \$/kg-H<sub>2</sub>) sensitivity for NPP uprate in one U.S. Day-Ahead (DA) market

### Insert 9: UK Bay Hydrogen Hub – Nuclear-Enabled Hydrogen to Decarbonise Industry and Beyond

## Insert 9: UK Bay Hydrogen Hub – Nuclear-Enabled Hydrogen to Decarbonise Industry and Beyond

The Bay Hydrogen Hub project<sup>75</sup> consortium explored the potential of nuclear enabled low-carbon hydrogen production and its application in hard-to-abate industrial sectors such as asphalt and cement. This two-stage project, supported by grant funding from the UK Government Department for Energy Security & Net Zero (DESNZ), successfully delivered both a feasibility study by exploring the entire value chain of hydrogen, from production to end use:

### Investigating Innovative Nuclear Enabled Hydrogen Production

EDF Energy and United Kingdom National Nuclear Laboratory (UKNNL) assessed the co-location of a nuclear power station with a high-temperature solid oxide electrolyser to produce low-carbon, cost-competitive hydrogen. By leveraging both nuclear electricity and heat (as steam), it was determined that solid oxide electrolyzers can achieve a 20–30% improvement in efficiency and economic benefits compared to conventional electrolysis.



Figure 47: Schematic of co-location of a nuclear power station with a high-temperature solid oxide electrolyser

A “Nuclear Enabled Hydrogen Handbook” was produced, providing a practical and accessible guide to give developers and operators a head start to demonstrate how a nuclear enabled hydrogen project could be delivered in the UK and how key issues associated with integrating a hydrogen production project near a nuclear site could be addressed. More information can be found on the project website<sup>76</sup> and within the Handbook<sup>77</sup>.

The Handbook is strongly informed by work on the previously planned 1MW feasibility study, and expands on nuclear specific aspects (e.g. Safety Case, licencing, security) looking at a commercial scale facility (24MW & 96MW).

<sup>75</sup>: <https://www.edfenergy.com/energy/power-stations/heysham-1/bay-hydrogen-hub>

<sup>76</sup>: <https://www.edfenergy.com/about/nuclear/hydrogen-handbook>

<sup>77</sup>: <https://assets.publishing.service.gov.uk/media/69135fd81fcc92b3f34963e1/bay-hydrogen-hub-hydrogen4Hanson.pdf>

### Nuclear Enabled Hydrogen Concept Design

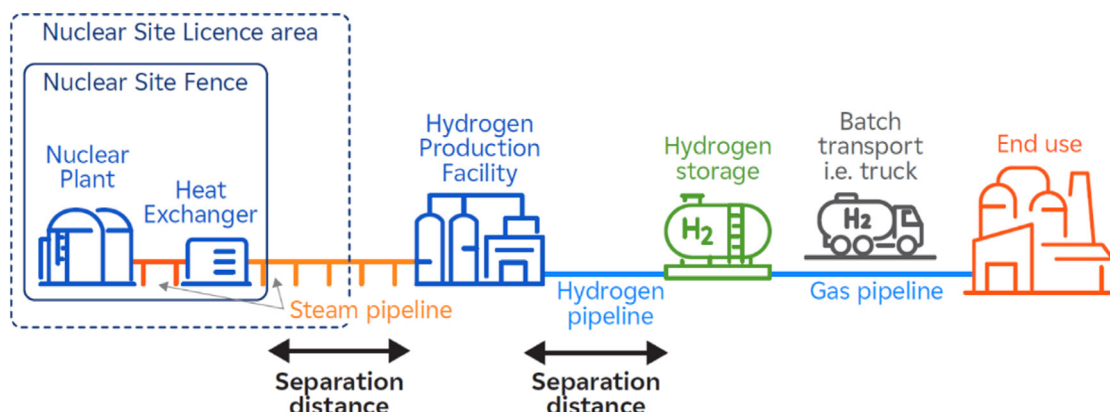


Figure 48: Schematic of co-location of a nuclear power station with a high-temperature solid oxide electrolyser

A key conclusion is that the cost to produce hydrogen was calculated at ~£6/kg H<sub>2</sub>, using 2024 day ahead prices, depending on off-taker requirements. This compares favourably to UK Hydrogen Allocation Round 1 (HAR1) project (~£9.50/kg H<sub>2</sub>). The work also confirmed the potential for cost to fall to ~£3.50/kg H<sub>2</sub> by 2035 (in 2024 money, for a 100MW plant, assuming an electricity price of £60/MWh).

#### Successful Industrial Demonstration

As part of this project, hydrogen was successfully used at a commercial-scale asphalt production site (Heidelberg Materials, Criggion in North Wales), replacing processed fuel oil with hydrogen, piloting a novel application of burner technology from Vulcan Burners. This fuel-switching demonstrated substantial CO<sub>2</sub> emissions reductions and provided a blueprint for other industrial sites where electrification is not feasible due to high-temperature requirements, costly retrofits or infrastructure limitations<sup>78</sup>.



Figure 49: The asphalt production site (Heidelberg Materials, Criggion in North Wales)

<sup>78</sup>: More details can be found at this link: <https://www.newcivilengineer.com/opinion/pioneering-a-way-for-nuclear-energy-to-create-hydrogen-to-decarbonise-asphalt-production-21-02-2025/>

*Insert 10: Low-carbon hydrogen production, the example carried out by an international chemical supplier company*

## Insert 10: Low-carbon hydrogen production, the example carried out by an international chemical supplier company

Air Liquide is a world leader in gases, technologies and services for industry and healthcare. Present in 60 countries with approximately 66,500 employees, the Group serves more than 4 million customers and patients. Oxygen, nitrogen and hydrogen are essential small molecules for life, matter and energy. They embody Air Liquide's scientific territory and have been at the core of the Group's activities since its creation in 1902. The following figure is showing the Air Liquide holistic vision and industrial model of hydrogen delivery going from its production, transportation, distribution and final delivery. In this model hydrogen is made either by water electrolysis or by Steam Methane Reforming associated with CO<sub>2</sub> capture.

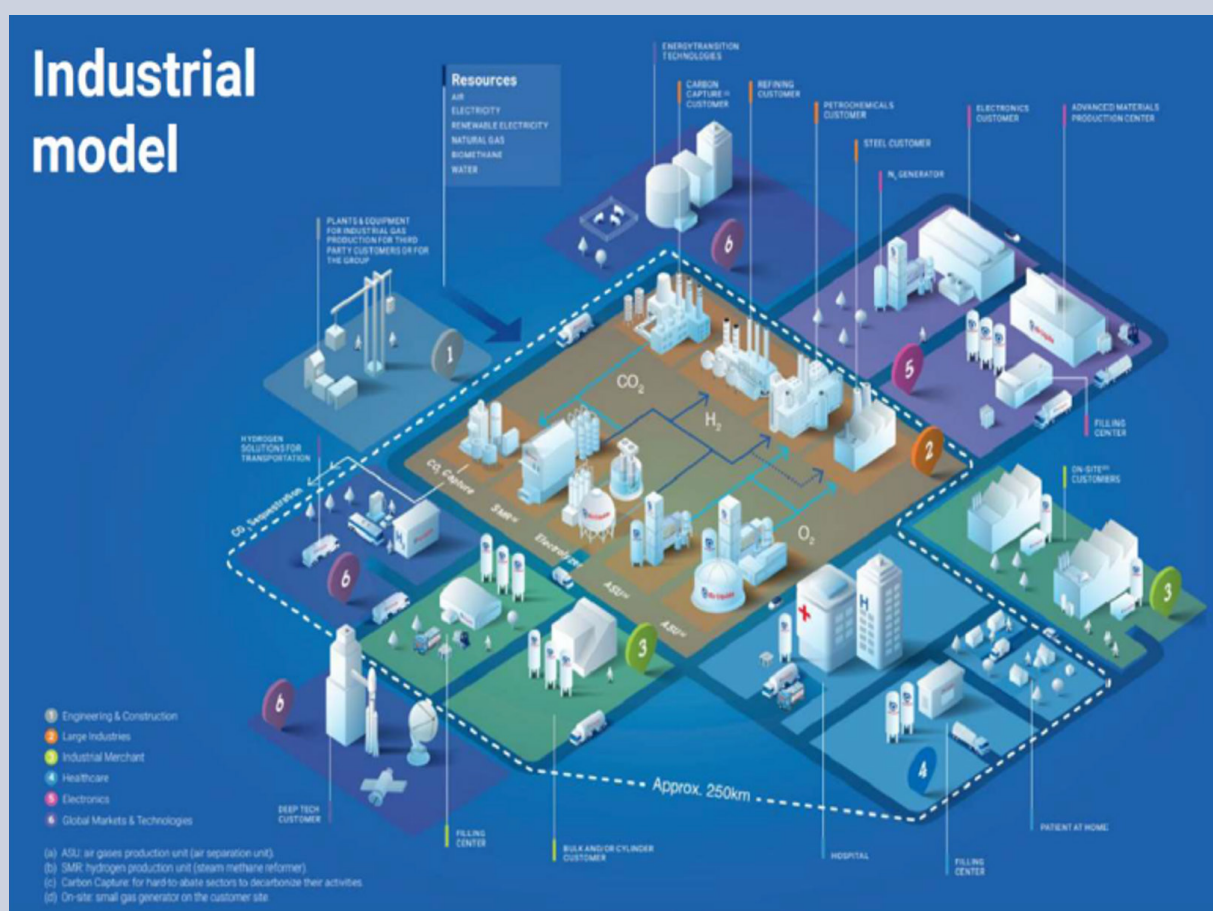


Figure 50: Air Liquide Industrial Model

Going further with this scheme, hydrogen is seen in the future as a promising candidate to decarbonize heavy industries (e.g., refining, cement) as well as heavy-duty mobility. The potential future hydrogen demand could significantly increase, potentially leading to i) a scaling up of the existing infrastructures, and/or ii) a change of paradigm in the way of producing this hydrogen.

Air Liquide and Siemens operate a gigawatt electrolyser factory in Berlin, Germany, which is running at a sustained load of orders to fulfil the demand of Air Liquide and Siemens Energy projects and successes on the market (1 GW achieved as of October 2025). The factory design emphasizes flexibility, allowing to scale production in response to market changes. Currently, the Air Liquide Group operates large-scale units such as the 20 MW "Trailblazer" electrolyser in Germany and a facility in Bécancour, Canada. Significant projects under development include the 200 MW Normand'Hy electrolyser in France (expected in 2026), the 200 MW ELYgator project in the Netherlands (final investment decision reached in 2025), and a 250 MW joint venture with TotalEnergies in Zeeland, Netherlands.

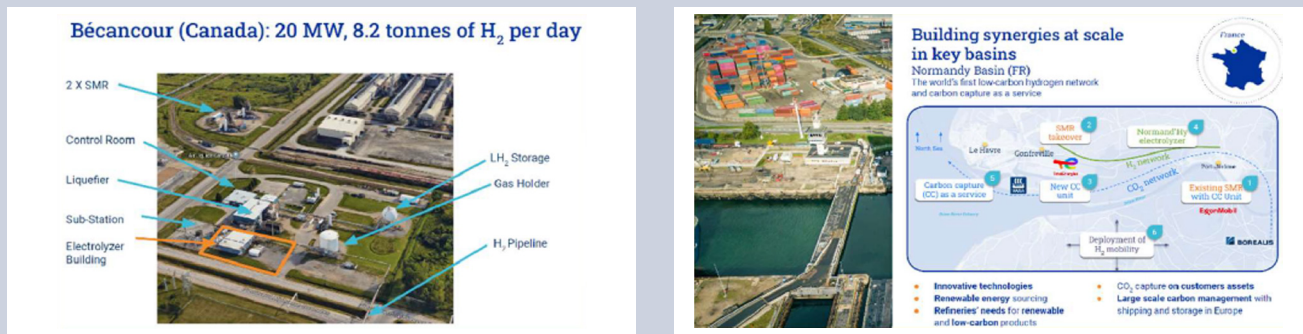


Figure 51: Air Liquide Bécancour hydrogen factory and Normand'Hy low-carbon hydrogen network

In this context, Air Liquide's interest in nuclear to power H<sub>2</sub> production is fueled by the following positive drivers: i) it is a low carbon energy, ii) it can provide predictable cost of energy for long term, iii) it offers a high and reliable availability, and iv) its power density implies a small footprint.

In these conditions the HyNE is evaluated with interest by Air Liquide, considering the current state of the art of these solutions and perspectives, in comparison with target techno-economics KPIs to assess commercial potential of H<sub>2</sub> production pathways.

## CHAPTER 6

# The Synthesis of the case study approach

## §6 - KEY TAKE AWAYS

- i. *The energy transition emphasizes the integration of independent sectors. Hydrogen can serve as a key energy vector linking electrical, gas, and chemical networks, moving away from fossil hydrocarbons.*
- ii. *HyNE solutions have moved from joint R&D (Task #25) to concurrent engineering actions (Task #44). Various aspects are being investigated and developed simultaneously across multiple countries.*
- iii. *This system remains complex due to the integration of nuclear and electrochemical processes and the wide variety of possibilities. A matrix of solutions has been evaluated leading to 11 selected cases. Task #44 is proposing a global graph to visualise and compare these 11 cases using the TRL approach, the time to deployment, and a ranking of various factors gathered under the designation: Optimisation of the solutions.*
- iv. *The graph ranking the cases is subjective and intended to initiate debate. Most of the cases need efforts to improve TRL and deployment time. The cases are interdependent, with progress in one potentially benefiting others.*
- v. *The graph is an initiative for future updates and adjustments by readers and members. It may be dynamically updated over time.*

A common theme of the energy transition is the integration or cross coupling between sectors that have traditionally been largely independent of each other. The new focus on hydrogen emphasizes this. Hydrogen as an energy vector provides a new linkage from the electrical network to both the gas network and the chemical network. The HyNE position in the energy transition is therefore both a move away from fossil hydrocarbons as the primary energy sources, and an integration of distinct energy networks into an overall energy architecture.

The previous chapters (§ 4 & 5) have presented the state of the art of this process and its current development. The feasibility and viability of the whole system have been demonstrated independently (technological bricks demonstrated or developed independently). There is a holistic view of this solution where all aspects are investigated in parallel and are progressing simultaneously in several countries. These aspects are positive and it is possible to say that HyNE solutions have passed from a joint R&D development (observed during the Task #25 period, early 2000's) to a concurrent engineering approach observed at the time of Task #44.

This technology remains complex because it mixes different engineering systems not previously done at an industrial scale: nuclear and electrochemical processes. The matrix of solutions as presented in § 4 is an attempt in clarifying the overall understanding of this system.

Among the matrix of possibilities, 11 cases have been selected by Task #44 members and a first evaluation of these systems has been proposed using the TRL approach (see Table 3 in § 5.1). The next step is to try to represent an evaluation of this system allowing their global comparison and their respective challenges. This is what is proposed in the following graph. This evaluation is based upon 2 axes and a third data given in colour.

- The X axis is evaluating the global TRL of the different cases (plotted as an average of TRL1 to 3).
- The Y axis is evaluating the time to deployment for a First of a Kind (in 5-year blocks 0-5 years, 5 to 10 years, 10 to 15 years).
- The colour evaluation is globally ranking by an average the system optimisation evaluated upon: Techno economy: H/M/L - Market: H/M/L - Deployment: H/M/L - Performance: H/M/L - Adaptability: H/M/L - Financial Support: H/M/L - Experimental Support: H/M/L.
- The geometric form of the different cases symbolizes the different hydrogen production technologies (Circle: HTSE, Triangle: thermochemical cycle, Square: alkaline or Steam Methane Reforming).

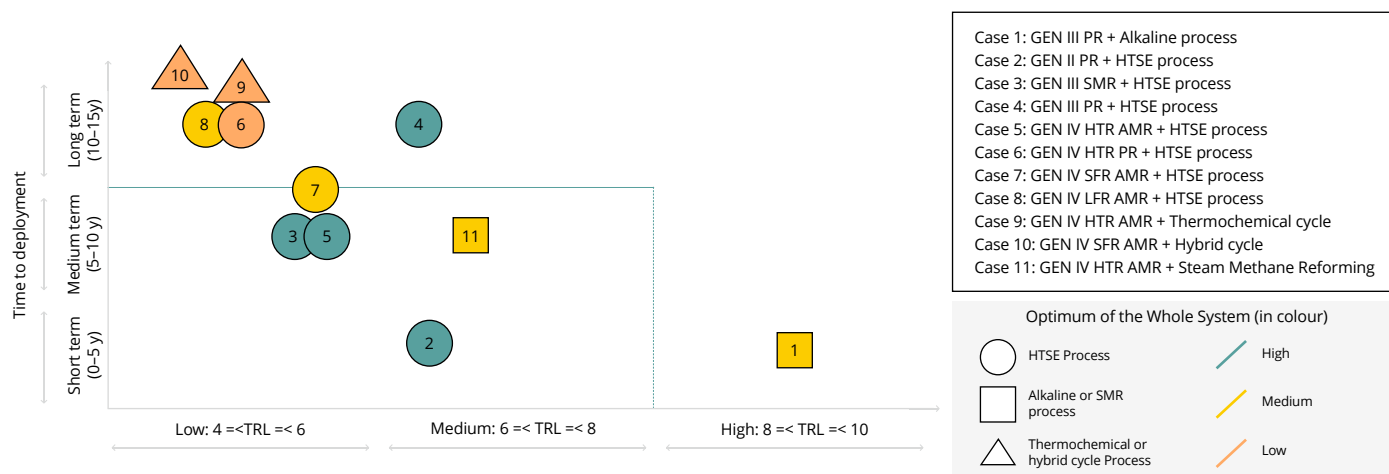


Figure 52: The ranking of the several cases analysis

The following analysis of this graph can be proposed:

- As a preamble, it is important to underline there was a lot of discussion upon this graph among Task #44 members. This third variable (level of whole system optimisation, in colour) is still so subjective that we hesitated producing it. In final we decided to present it in order to initiate a debate among members and readers too.
- Case 1 is the most interesting system even if, from the perspective of making an efficient solution, is not the most promising in the long term.
- Effort is still required to achieve (raise the TRL, decrease the time to deployment) the most promising cases in the short term.
- What is important to underline is that these cases will not move independently. For example:
  - If Case 5 is providing good results, Case 6 will consequently become more optimal.
  - If one case demonstrates the efficiency of the coupling design (anticipated to be Case 11), then all other cases where coupling is prevalent (Case 3 to 10) will benefit from these good results by increasing their overall TRL.
- Case 3 which was first seen as one of the most promising appears to be behind others. It could be explained by the fact that no land-SMR<sup>79</sup> is in operation yet and the coupling is not completely demonstrated. With the big investment of SMRs worldwide the following years will likely improve that ranking.

In final, this graph is a proposal that all readers can use and adjust with time for their own use<sup>80</sup>. We are still in a rough evaluation. The matching of reactor types with hydrogen production technologies and economic evaluations are closely related to application scenarios. In the future, a full chain evaluation of hydrogen production, storage, transportation, and application should be carried out for specific situations. Given the relatively low current R & D level, it is not appropriate to give overly one-sided suggestions on the technical route. The Figure can be considered as a snapshot between these 11 different cases. A regular update of this snapshot – including potential additional scenario – is strongly recommended.

<sup>79</sup>: Land SMR is expressing SMR built on earth by opposition to maritime SMRs that already exist (i.e. Russian icebreakers).

<sup>80</sup>: Our biggest hope would be this graph to be online updated with time among future members and readers of this document.

## CHAPTER 7

# Recommendations & future needs for a hydrogen production deployment

## S7 - KEY TAKE AWAYS

- i. *The technical solutions of producing hydrogen from nuclear are identified to be in a “Valley of death” situation. Today the low-carbon hydrogen global market is not pulling this solution. At the same time the limited public investment is restricting its development as a push technology. For instance, the world investments on nuclear experimental reactors for real case demonstrations of cogeneration are far too limited (only one exists which is in Japan – HTTR / Steam Methane Reforming unit).*
- ii. *To overcome this situation, Task #44 members carried out a PESTEL and a creative SWOT analysis to be proactive and to provide realistic recommendations.*
- iii. *Task #44 is proposing to think beyond hydrogen production to the online fabrication of e-fuel or more generally chemical molecules of high interest. The potential of hydrogen is then shifting towards the asset of this molecule for its chemical properties, and not as an energy carrier. In this perspective, a startup model approach proposing a “chemical e-factory” could be the future game changer.*
- iv. *Following the example of DOE/INL, the investment in a micro testbed nuclear reactor (MARVEL) could also be a pragmatic answer to “build a bridge” crossing the gap of this “Valley of death”. Their financial approach with a mixed financing system (Federal – DOE / Private – End-users) is an inspiring example to take into consideration for other demonstration deployments. Unfortunately, in the MARVEL current roadmap, the first five end-users’ experiments are not focused on hydrogen production.*
- v. *The prospective analysis carried out for the HyNE concept under several potential futures provides interesting clues to what could (would) be the cogeneration solutions (nuclear + hydrogen production) in the future.*

As noted by the Hydrogen Council<sup>81</sup>: “There is a lot of noise around hydrogen right now – which makes it more important than ever to have a fact-based and look at the full picture in context.”

On one hand, several referenced documents explain that the growth in hydrogen needs is, and will be, slower than expected. They highlight recent project cancellations, some of which come from major oil companies (such as BP, Shell and ExxonMobil)<sup>82</sup>. These announcements are detrimental to the future low carbon hydrogen market since the power of these large companies can be, by their decision, a real-world game changer. On the other hand, other experts’ analysis indicates positive 2025 figures<sup>83 84</sup>: 1,700 projects announced globally, 510 projects pass final investment

<sup>81</sup>: <https://www.linkedin.com/feed/update/urn:li:activity:7404503690507722753/>

<sup>82</sup>: “Hydrogen dreams meet reality as oil and gas groups abandon projects”, Financial Times Dec. 14 2025.

<https://www.ft.com/content/b0981f8a-d115-4779-bbed-75a87316a892?segmentId=2c1df321-36a4-1206-2c08-112c059dd69d>

decision, in construction or operation, \$110 billion in committed capital – up \$35bn since last year and a ten-fold increase since 2020, 6 Mtpa of committed clean hydrogen capacity, with 1 Mtpa already operational. They prefer to look at the positives, considering that: *“What we are seeing is a natural, expected phase of market maturation – similar to what wind, solar, and battery industries experienced in their early scale up, where roughly one in 10 projects ultimately came online”*. In that case it could be considered that the hydrogen market and economy is moving from a “hype situation” towards consolidated and mature future needs.

As proposed in this document, low carbon hydrogen production has to turn this situation into an opportunity, providing enough time to increase the maturity of these technologies for when the demand will increase significantly. However, the situation remains rather uncomfortable, feeling a “chicken and egg” loop: There are limited perspectives of Low-carbon hydrogen demand, so low need of low carbon hydrogen production.

- As a consequence, the global investment in these technologies is scarce and demonstrations even rarer.
- As a result, there are fewer possibilities to create a dynamic to decrease the estimated costs of low carbon hydrogen production because the maturity of systems is not growing as expected and the learning curves cannot be yet considered.
- The solutions of demonstrating the production of hydrogen with nuclear energy is facing a halt which is difficult to go beyond the techno-economic modelling; especially towards demonstrations which implies high capital investments.
- And so, the solution of hydrogen from nuclear heat appears to be a potential technical solution that is not deployable as a global model.

In this situation, also known as “The valley of death”<sup>85</sup>, the key question always remains: “Today who should take the financial, technical and project risks?”.

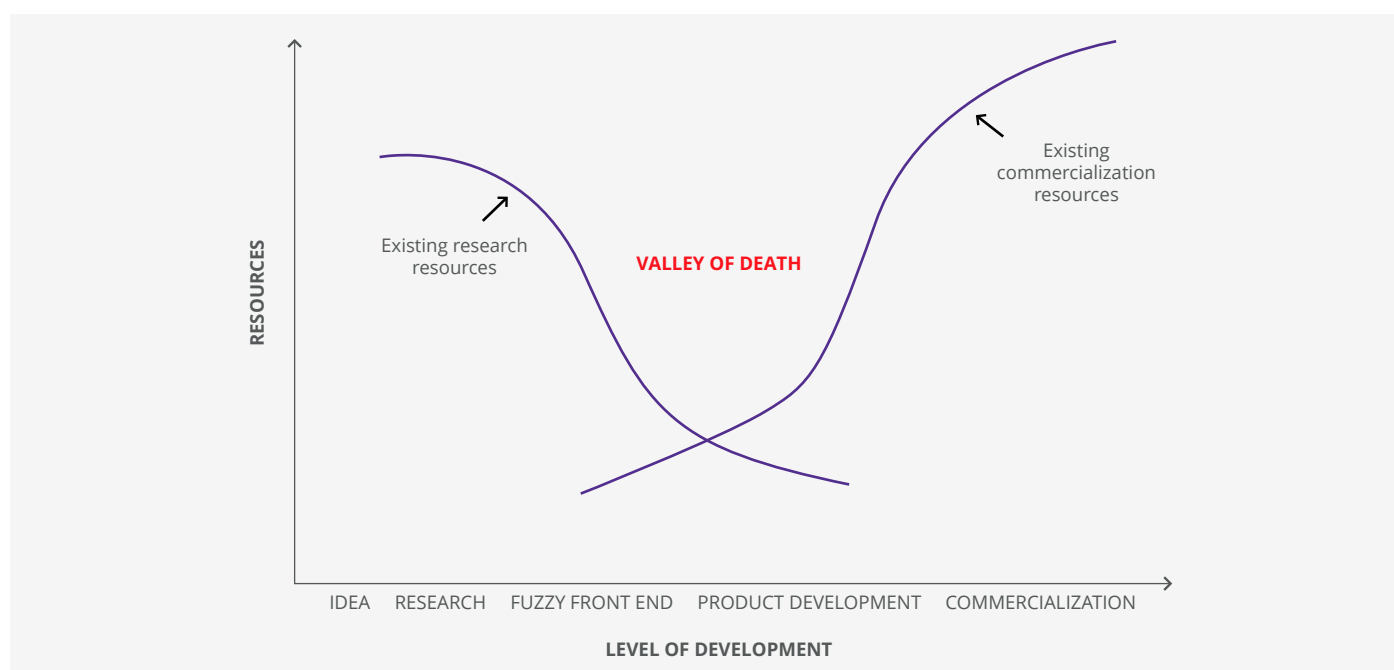


Figure 53: A graph representing what is known as “The valley of death”

<sup>83</sup>: <https://www.linkedin.com/feed/update/urn:li:activity:7404503690507722753/>

<sup>84</sup>: <https://compass.hydrogencouncil.com/wp-content/uploads/2025/09/Hydrogen-Council-Global-Hydrogen-Compass-2025.pdf>

<sup>85</sup>: S. A. Gbadegeshin et al., “Overcoming the Valley of Death: A New Model for High Technology Startups”, Sustainable Futures 4 (2022) 100077.

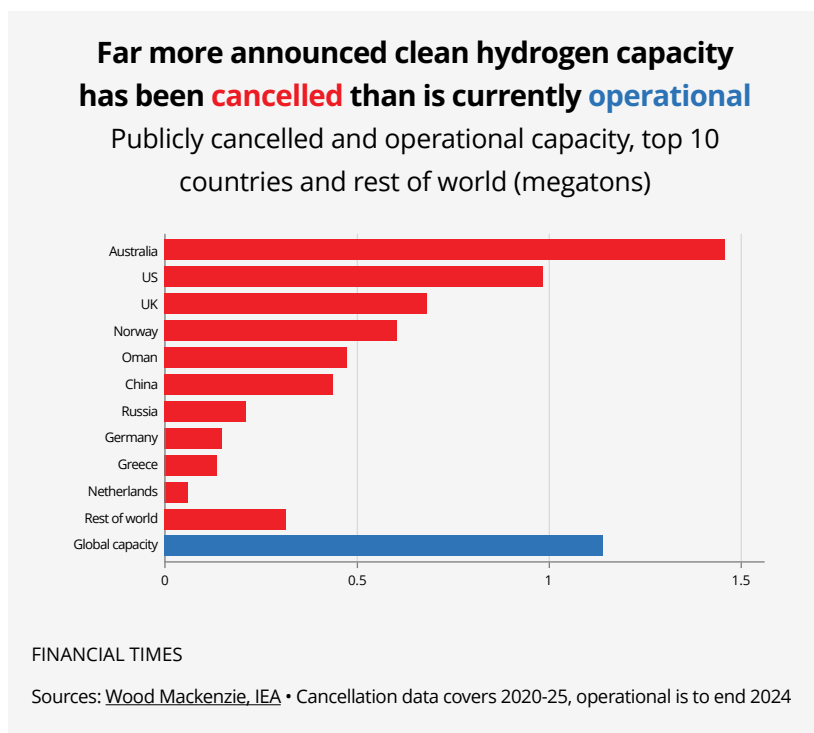


Figure 54: Bad news and good news related to Hydrogen

## 7.1 The main breakthroughs

Task #44 members tried to summarize in a single table the major breakthroughs (see the PESTEL analysis in [Insert 11](#)). Beyond this global analysis converged on by experts, any country can add its personal filter, by simplifying or complexifying this general assessment.

Globally, we can say that today the quick and growing need of energy in any form is so important that it hampers investment for longer term solutions. Consequently, investment in solutions for low carbon hydrogen from nuclear heat stays in strong competition with the need for electricity and for primary heat. As long as the hydrogen produced by steam methane reforming is at low cost and that the pressure to produce low carbon hydrogen remains low, there is no need to motivate other more expensive solutions.

How can the situation positively evolve? By higher tax prices of CO<sub>2</sub> emissions? By regulations to force industries to transition towards low carbon solutions? By proposing viable solutions to replace the current ones? By incentivising positive measures (and financial) to move to low carbon hydrogen production and use? The answer may be all of these proposals and probably all at the same time. But the most important is that in these first steps towards transition, the state, federal and public funds have to take charge of the main project risks, technical & financial ([see Annex 5](#)).

It is important to build trust with, and create confidence for, the industrials to allow them to progressively raise their investment in these technical solutions. To do so, Task #44 recommends leaning on two pillars: technical recommendations and strategic recommendations. They all arise from the related PESTEL & SWOT analysis.

### Insert 11: The creative SWOT & PESTEL analysis

## Insert 11: The creative SWOT & PESTEL analysis

In strategic planning and strategic management, a SWOT analysis (also known as the SWOT matrix) is a decision-making technique that identifies the Strengths, Weaknesses, Opportunities, and Threats of an organization or a project. The SWOT analysis evaluates the strategic position and is often used to identify internal and external factors that are favourable and unfavourable to achieving goals. Users of a SWOT analysis ask questions to generate answers for each category and identify competitive advantages. Unlike a standard SWOT, the creative SWOT approach used by Task #44 incorporates a strategic perspective, examining potential go-forward or mitigation strategies for each scenario, enabling experts to propose solutions rather than merely listing elements. This method has proven effective by integrating technical, economic, and market considerations to provide a comprehensive view of hydrogen production from nuclear energy. In conclusion, it allows a clear statement to be made of the situation analysed and to start the process of: "What would the next actions be for Task #44 to go forward according to the internal and external constraints?".

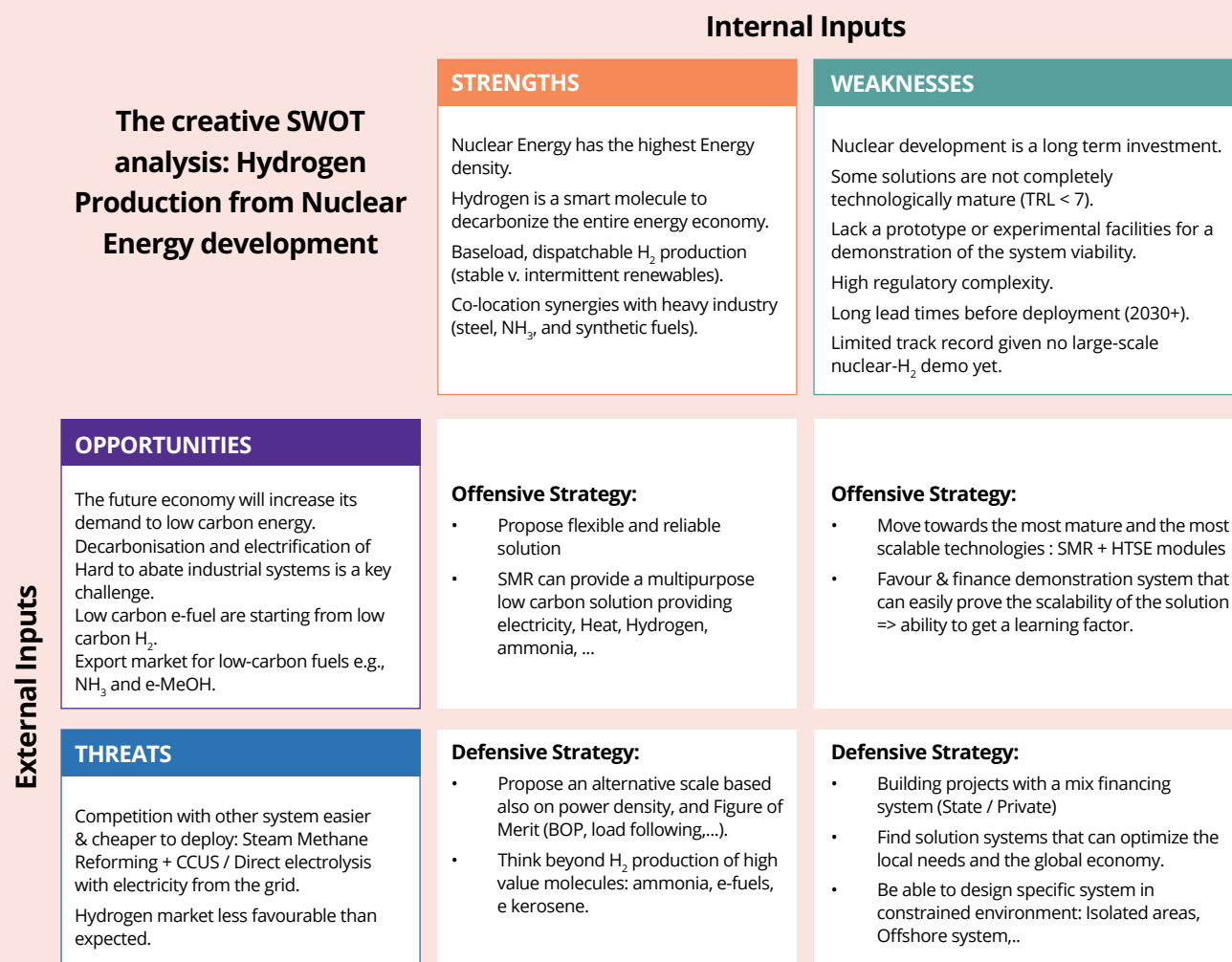


Figure 55: The HyNE creative SWOT analysis

Answering of this last question is more efficient if the creative SWOT analysis is coupled with a PESTEL analysis. A PESTEL analysis is an acronym for a tool used to identify the macro (external) forces facing an organisation or project. The letters stand for Political, Economic, Social, Technological, Environmental and Legal. The framework is also used to identify potential threats and weaknesses which are used in a SWOT analysis when identifying any strengths, weaknesses, opportunities and threats to a business or a market.

Conducting a PESTEL analysis can be challenging, particularly due to varying political conditions across countries and the complexity of interpreting social factors. Ideally, each country could develop its own PESTEL analysis, either following the Task #44 methodology or adapting it to local circumstances. Solutions are often highly context-dependent, and what works in one region may not be applicable in another. The same is true between countries.

Nevertheless, it is worth proposing this Task #44 PESTEL study as a common shared view where any country will be able to apply its own “tracing paper” to fit it to its respective country constraints and strategy.

### PESTEL analysis: Hydrogen Production from Nuclear Energy development

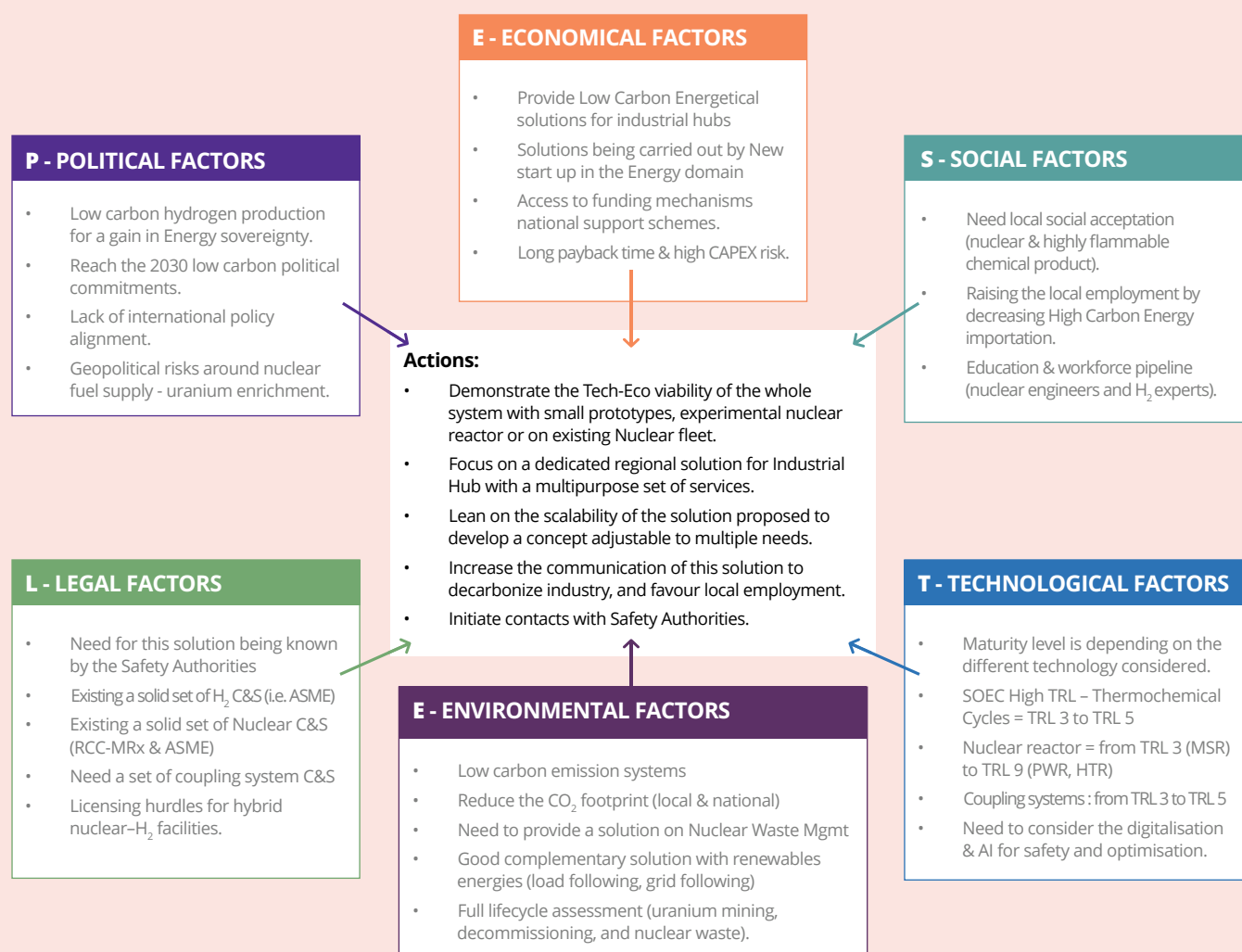


Figure 56: The HyNE PESTEL analysis

These two tools are largely helping the definition of the future proposals to go beyond Task #44.

## 7.2 The technical recommendations

Nobody will invest in a solution if there are too many uncertainties in its technical achievements. Today the solution of nuclear and hydrogen cogeneration appears to be too immature to be convincing for industrials. This is the result of multiple factors:

- All demonstrations to date are with separated elements (demonstration of the HTSE viability with electricity from the grid<sup>86</sup>) or a dummy representative of some systems (the nuclear heat input for instance) or with too low a power to be extrapolated (demonstration on existing nuclear plant).
- The only real case demonstration expected in the near future is the work by JAEA (see Insert 3 in 54) by coupling the HTTR with a steam methane reforming facility. This is a significant Game Changer but it is far too scarce. Several equivalent demonstrations should be under process worldwide.

The reason why it is so difficult to find real case demonstrations is listed below:

- The nuclear crisis in large power reactor development during the 1990's – 2000's was accompanied with a quick depletion of the test reactor fleet worldwide. A look at the IAEA Research Reactor Database<sup>87</sup> shows this alarming situation. Today, with the projected nuclear renaissance it will be impossible to support all these growing needs if there are so few research reactors operating in the world. Moreover, very few of them have been designed to test cogeneration systems. This situation must imply the design of some new research nuclear reactors dedicated among others to non-electric and cogeneration applications.

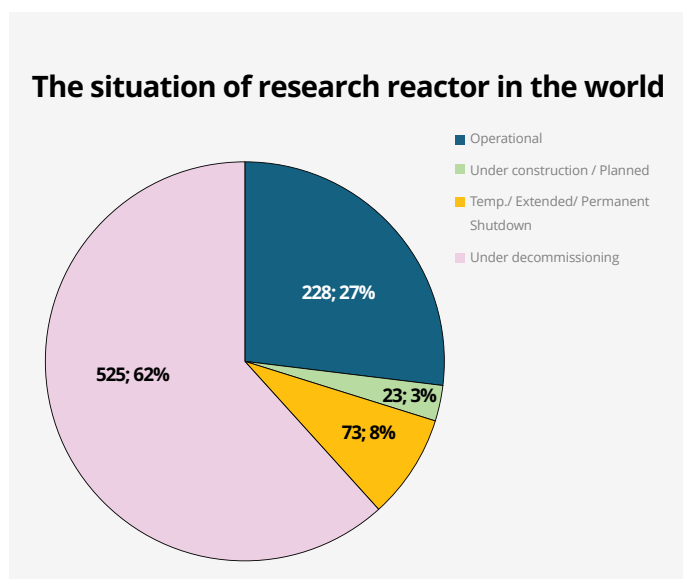


Figure 57: The worldwide situation of research nuclear reactor  
[Extracted from data Source IAEA open database, 2026]

- Considering this situation, several solutions are possible:
  - Solution A: Some existing research reactors modify their portfolio to support these new needs;
  - Solution B: The research reactors under construction expand their specifications to allow such demonstrations;
  - Solution C: Future new research reactors are conceived to fulfil the non-electric and cogeneration demonstration needs;
  - Solution D: Existing nuclear power reactor modify their perspective to industrially move towards such large-scale demonstrations.

If solutions A and D seem to be the most pragmatic (because they are starting from already existing facilities) they have several limitations. Indeed, due to high demands (in particular for neutron flux for new nuclear materials and fabrication of radioisotopes for medicine), operating research reactor programs are almost fully booked and they do not need to seek for new opportunities today. Moreover, except HTTR, most of them were not initially designed for heat delivery purposes. For solution D, large power reactors' mission is to deliver electricity to the grid and

<sup>86</sup>: As an illustration the MultiPLHY project has realized in January the world's largest high temperature electrolyser installed in a real industrial environment. (<https://multiplhy-project.eu/>)

<sup>87</sup>: <https://nucleus.iaea.org/rrdb/home#/home>

to ensure grid load following. In these conditions their business model limits any risk that could halt their production or block their electricity production<sup>88</sup>.

Solution B is dependent on how far the construction and design progression is. In any case, this new input may add additional costs and delays. Solution C is the most coherent one. But it will be accompanied by the highest costs since its investment has to start from scratch. No industry or big company can cover such high investments today. In the past, the funding of all new research reactors was covered by public funding.

The most likely situation envisaged is that along with some R&D small scale progress, either a country, an international consortium or a funded start-up - or a combination of all of them - take the plunge to launch such real case demonstration project with a limited R&D backup project support. The use of a micro power reactor to significantly decrease CAPEX and OPEX must be investigated. We can underline the innovative way paved by INL with its MARVEL nuclear microreactor. However, unfortunately hydrogen production is not in the first group of end-user experiments (*see Insert 12*). Other opportunities may appear later with the use of the PRECURSOR facility invested and built by newcleo start-up company<sup>89</sup>.

*Insert 12: MARVEL a new microreactor developed by INL (Microreactor Application Research Validation and Evaluation program)*

### INSERT 12: MARVEL a new microreactor developed by INL (Microreactor Application Research Validation and Evaluation program)<sup>90</sup>



Figure 58: Artistic view of the MARVEL reactor [Source INL Brochure]

<sup>88</sup>: i.e. In some countries like France changing the final output of a nuclear reactor (producing heat/hydrogen/electricity instead of 100% electricity) will need to change the regulatory framework with the requirement of a new public inquiry that could stop the nuclear reactor operating process, until positive feedback is obtained.

<sup>89</sup>: Extracted from the article: "In parallel, to further analyse the operational characteristics of its future reactors, newcleo is building Precursor, a non-nuclear reactor mockup rated at 10 MW thermal with power conversion of approximately 3 MWe. Precursor is expected to be completed by the end of 2026 at Brasimone (Italy)". <https://www.nucnet.org/news/newcleo-reaches-milestone-with-key-submission-to-french-nuclear-regulator-1-5-2026>

<sup>90</sup>: <https://inl.gov/marvel/> and <https://inl.gov/news-release/idaho-national-laboratory-announces-initial-selections-for-first-marvel-experiments/>

MARVEL is a nuclear testbed designed for real-world applications. At the heart of the initiative MARVEL is a compact nuclear micro-reactor being developed by the US Department of Energy. The system uses a sodium-potassium coolant and is designed to produce around 85 kilowatts of thermal energy and up to 20 kilowatts of electrical output. While modest in scale, the reactor is purpose-built to validate how microreactors can operate safely, reliably, and flexibly in demanding environments. MARVEL is installed at INL's Transient Reactor Test Facility, giving private companies and research partners rare access to an operational nuclear microreactor.

This setting allows developers to move beyond simulations and laboratory models to test how advanced nuclear systems perform when connected to real equipment and real-world use cases.

At the end of 2025, the Idaho National Laboratory announced initial selections for MARVEL end user demonstrations. The five competitively selected end user companies will demonstrate several test cases, including desalination of remote operations and advanced sensors. The tests will also be amongst the first to demonstrate the viability of powering data centers with advanced nuclear technologies.

The following companies were selected as the first potential end users for MARVEL.

- Amazon Web Services Inc. proposes coupling the MARVEL reactor with a modular data center.
- DCX USA and Arizona State University propose to use MARVEL to demonstrate the feasibility of a microreactor to power a data center for artificial intelligence.
- General Electric Vernova proposes to use MARVEL to demonstrate remote and autonomous reactor operations and establish controls standards for broader application with commercial reactors.
- Radiation Detection Technologies Inc. proposes to use MARVEL to test advanced high-performance sensor technologies.
- Shepherd Power, NOV and ConocoPhillips propose to leverage MARVEL for a pilot-scale desalination project using nuclear-generated process heat.

## 7.3 Strategic recommendations

Today – due to the growing energy demand – the solution of producing low carbon hydrogen is in competition with other energetic solutions. Even if some solutions to the growing energy demand are not that virtuous in terms of carbon emissions, the pressure is so intensive that the asset of producing low carbon energy is in some context put back to a secondary priority. This situation may change in the coming years but it is the observed situation today.

In the specific field of the hydrogen economy, the production of low-carbon hydrogen on-site is in strong competition with scenarios like producing hydrogen from natural gas combined with carbon capture technologies.<sup>91 92</sup>

Based on these statements, it is important to maximise the hydrogen value for what it is at its origin: an important and necessary chemical molecule used as the basis for the production of many other chemicals. Playing on this particular strength against the external threats, the creative SWOT analysis proposed to think beyond hydrogen to the production high value molecules like e-fuels and e-kerosene (use for SAF (Sustainable Aviation Fuel) and SMF (Sustainable Maritime Fuel)).

<sup>91</sup>: H. Lu et al., "Hydrogen production in integration with CCUS: A realistic strategy towards net zero", Energy 315 (2025), 134398.

<sup>92</sup>: R. Roy et al. "Comparative techno-environmental analysis of grey, blue, green/yellow and pale-blue hydrogen production", International Journal of Hydrogen Energy, Volume 116, 4 April 2025, Pages 200-210.

In this scenario, low-carbon hydrogen is no longer considered as an energy vector but as a “chemical vector”<sup>93</sup> in the transition towards low-carbon high value chemical products. This solution consists in producing directly high value molecules (ammonia, SAF, SMF, methanol) by integrating additional chemical steps beyond the production of low-carbon hydrogen. These chemical steps are well known, for example, the Haber-Bosch and Fischer-Tropsch chemical process<sup>94 95</sup>. In this specific case, the exothermicity of these chemical reactions can be an asset to realize a global energy heat balance and an increase of the global yield. Moreover, in this prospective scenario where an SMR is dedicated to provide all its energy to the synfuel factory with CO<sub>2</sub> taken from Direct Air Capture (DAC), it can then certify a fully carbon free synfuel<sup>96</sup>.

### Hybrid systems already studied by IDNES teams

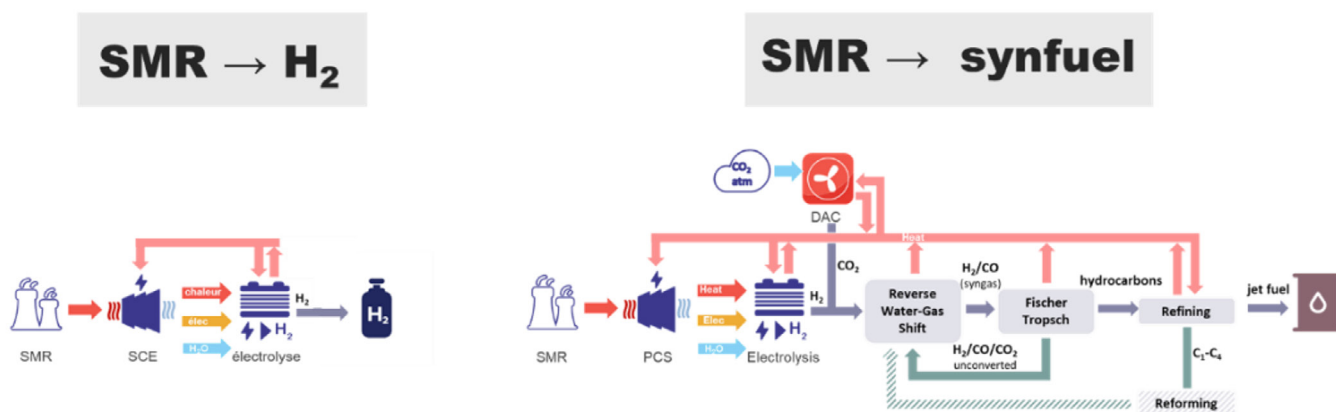


Figure 59: The IDNES team approach (CEA) moving from H<sub>2</sub> production to e-fuel on-line production

Going further with this approach, the challenge is to move from a concept of a nuclear reactor producing hydrogen in cogeneration mode to a more global concept of a “low-carbon chemical e-factory”. This global vision is, for instance, proposed by one of the Task #44 members and start-up company: *newcleo*.

<sup>93</sup>: This concept of “Chemical vector” is proposed by the Task #44 experts.

<sup>94</sup>: M. Mehrara, “Electrification-enabled production of Fischer-Tropsch liquids – A process and economic perspective”, Applied Energy 393 (2025) 126083.

<sup>95</sup>: G. Zang et al., “Performance and cost analysis of liquid fuel production from H<sub>2</sub> and CO<sub>2</sub> based on the Fischer-Tropsch process”, Journal of CO<sub>2</sub> utilization, 46 (2021) 101459.

<sup>96</sup>: J. Cardolaccia, P. Amphoux et al., “Fully Dedicated Nuclear Power Plants for the Low-Carbon Production of Energetic Molecules”, ICAPP Conf 2025, 17-19 Sept, Antibes, France.

### newcleo combined heat and power: the chemical e-factory

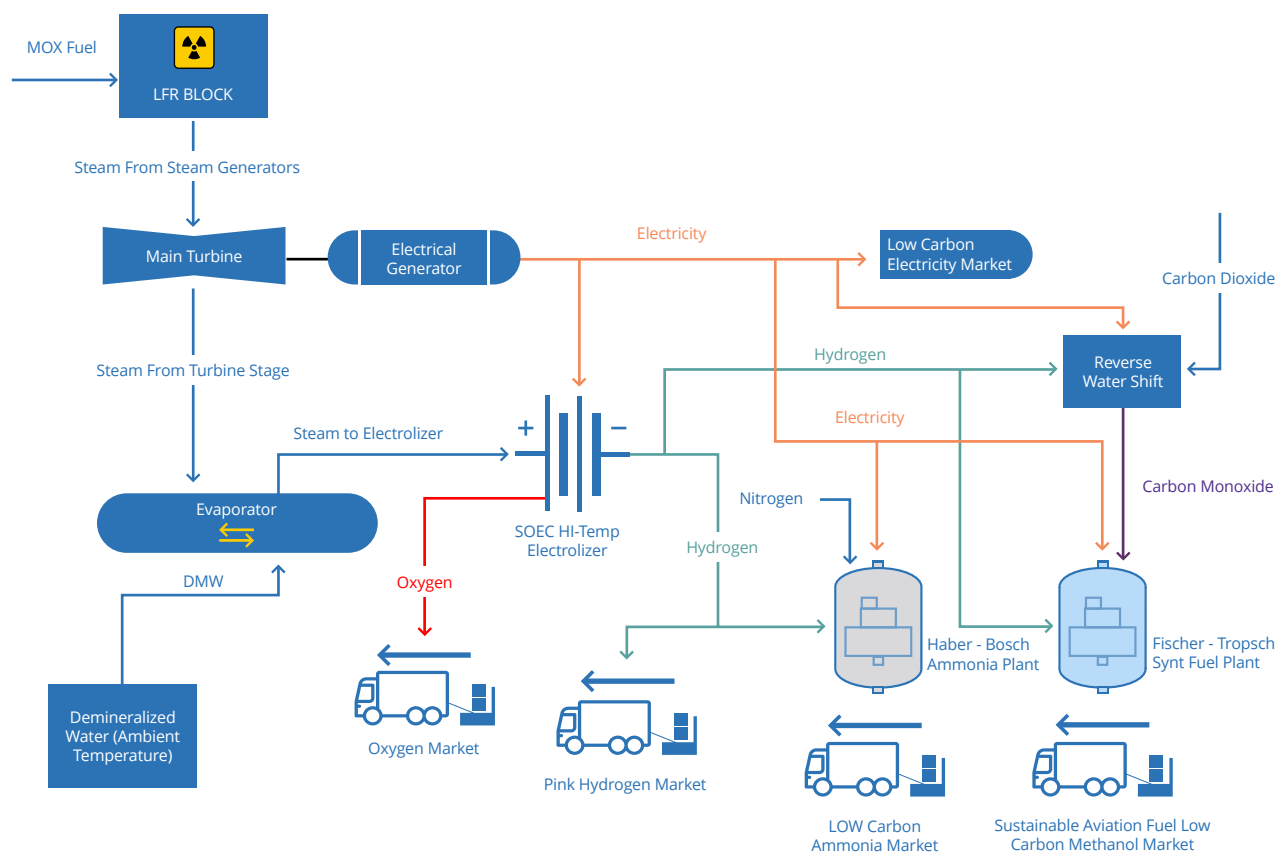


Figure 60: The chemical e-factory proposed by newcleo [Source newcleo pres.]

In a nutshell, the hydrogen economy is today in a turbulent phase which is aligned with the global world energy situation: Volatile, Vulnerable, Unpredictable, Non-linear<sup>97</sup>. In this context the hydrogen economy situation is looking for a new equilibrium position amongst all the other energy vectors. The competition is fierce and the hydrogen economy has to return to its fundamental values to show its strength. Hydrogen is a unique molecule for its chemical applications and for these opportunities it can play a major role in the low-carbon chemical sector.

For the nuclear case, the situation is diametrically different. The future nuclear market is so demanding that it is not adequate with today's supporting structures: the ageing state of nuclear research reactors. In this context, prioritizing an existing nuclear research reactor to demonstrate hydrogen production is not (and may be in too very rare cases) a priority. It is important to favour and promote some ambitious nuclear scale demonstration projects to overcome the "Chicken and Egg" situation present today. In this context, the SMR approach carried out by innovative start-up companies can be a significant game changer. The investment in testbed microreactor is also another promising solution.

<sup>97</sup>: These adjectives are inspired by the two last concepts to describe the today world: VUCA (Volatile, Uncertain, Complex and Ambiguous) and BANI (Brittle, Anxious, Non-linear, Incomprehensible).

<sup>98</sup>: [https://www.linkedin.com/posts/damiernerst\\_spatial-and-material-requirements-by-energy-activity-6963244253976137728-z8XX?trk=public\\_profile\\_like\\_view&originalSubdomain=fr](https://www.linkedin.com/posts/damiernerst_spatial-and-material-requirements-by-energy-activity-6963244253976137728-z8XX?trk=public_profile_like_view&originalSubdomain=fr)

Another key point must be highlighted. Nuclear power is often criticized for its long-term deployment, and its investment cost. The SMR approach is trying to provide an answer to these down-sides. But another key asset of nuclear energy is its power density that can be expressed by a low balance of plant expressed in m<sup>2</sup>/kW and its frugality expressed in material throughput in tons/TWh. Analysing the Figure of Merits of nuclear energy according to these two criteria positions it in the fore of all energy sources (see corresponding graph below and [Annex 5](#)).

### Spatial and material requirements by energy source\*

Bubble size represents each source's use of critical metal use\*\*

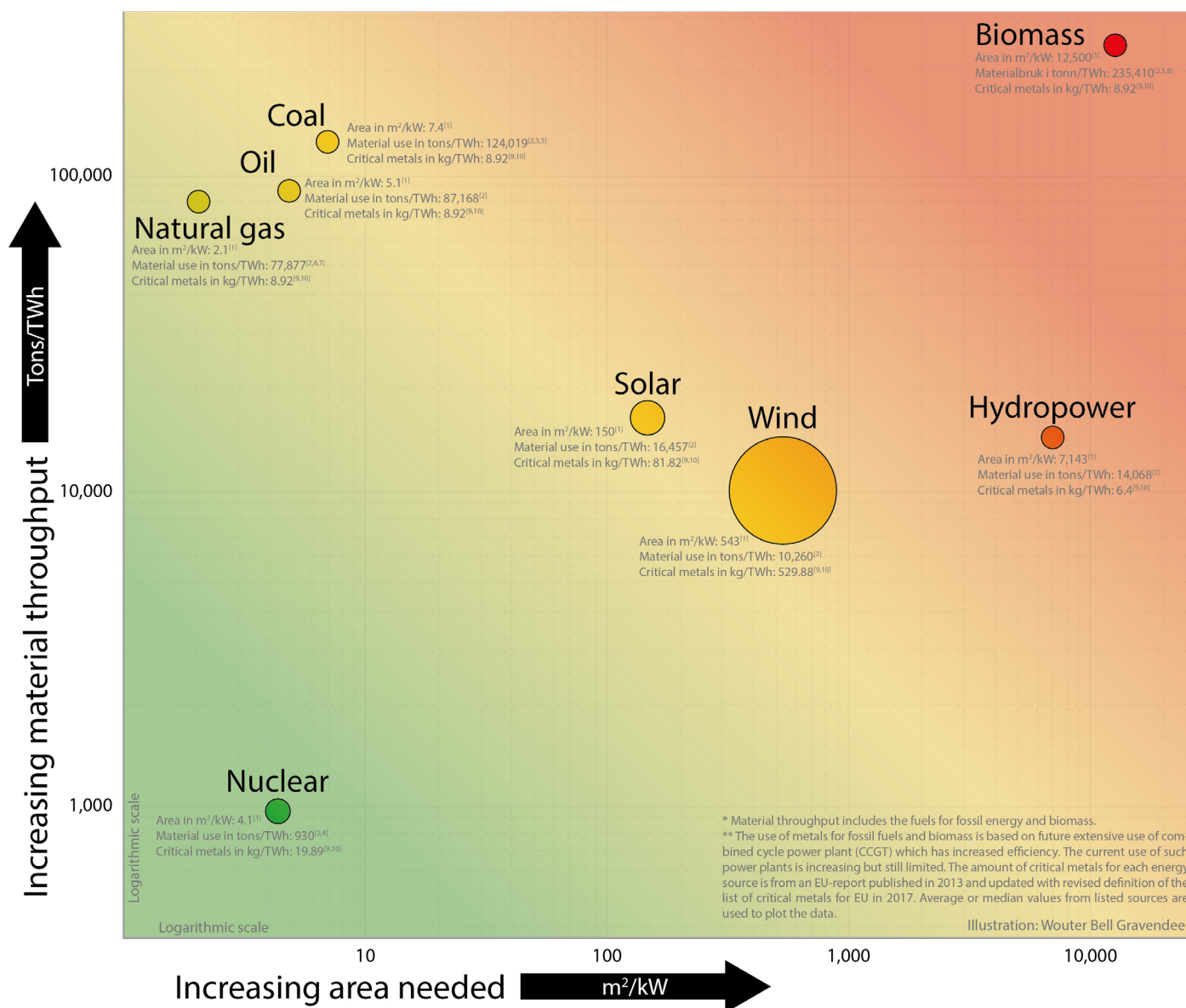


Figure 61: Spatial and material requirement by energy source [source Damien Ernst from LinkedIn<sup>98</sup>].

<sup>99</sup>: « La prospective opérationnelle. Pourquoi ? Comment ? », Document cadre DC-007\_PO (2022), 2022 (in French only).

## 7.4 A prospective analysis

In the worldwide context it is rather difficult to predict what the future on hydrogen cogeneration will be, because the future itself is highly uncertain. The use of a prospective analysis by building prospective scenarios can help position the future of the HyNE solution under different potential contexts. This analysis is presented in **Insert 13**.

*Insert 13: The production of hydrogen with nuclear energy – A future position using prospective analysis by postulated future scenarios*

### INSERT 13: The production of hydrogen with nuclear energy – A future position using prospective analysis by postulated future scenarios

The method partially used in the Task #44 originates from a French army document<sup>99</sup>. The objective is to cross two axes with different extreme variables. Each sector creates specific conditions that allow the definition of different global futures. In this specific exercise carried out by Task #44 members, the energy availability was plotted on the X axis and the policy on CO<sub>2</sub> reduction of the Y axis. This representation can be seen in the following figure.

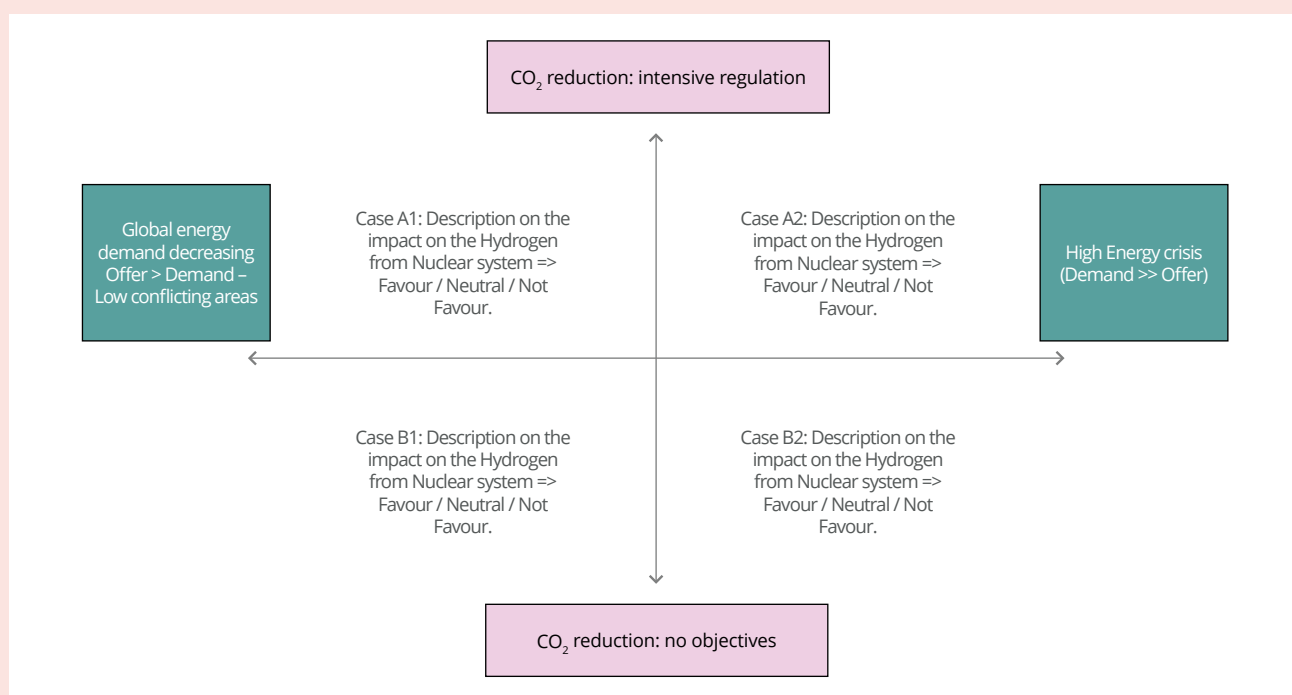


Figure 62: Crossing two axes to define 4 future scenarios.

The second step consists in determining a title for each sector that will best describe the “future world” that was artificially created by crossing these variables. It is recommended to find sharp and concise titles of world inspired by analogy with movie or famous song titles or in a slogan mode. This step facilitates fast understanding of the kind of world situation the system will investigate. The purpose is not to define how it is possible (or feasible) to meet this kind of world (it is postulated), but what the situation of the HyNE system proposed within this type of world could be. Then can the analysis start.

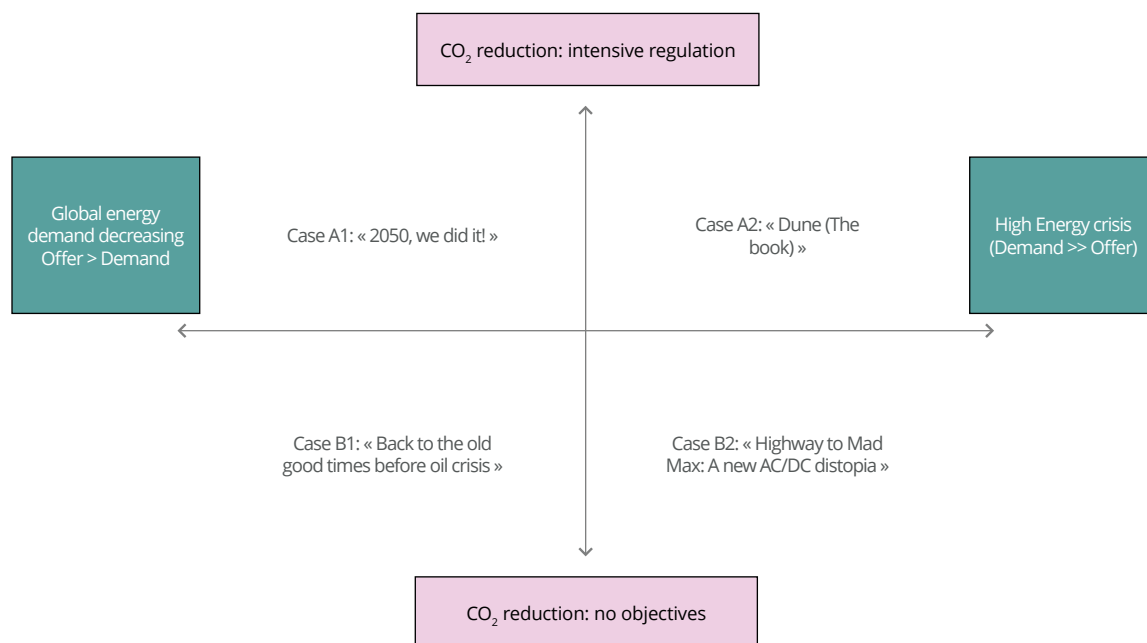


Figure 63: Four sectors = 4 worlds with 4 given titles.

A synthetic graph of this analysis is provided below. A more detailed approach is given in [Annex 7](#).

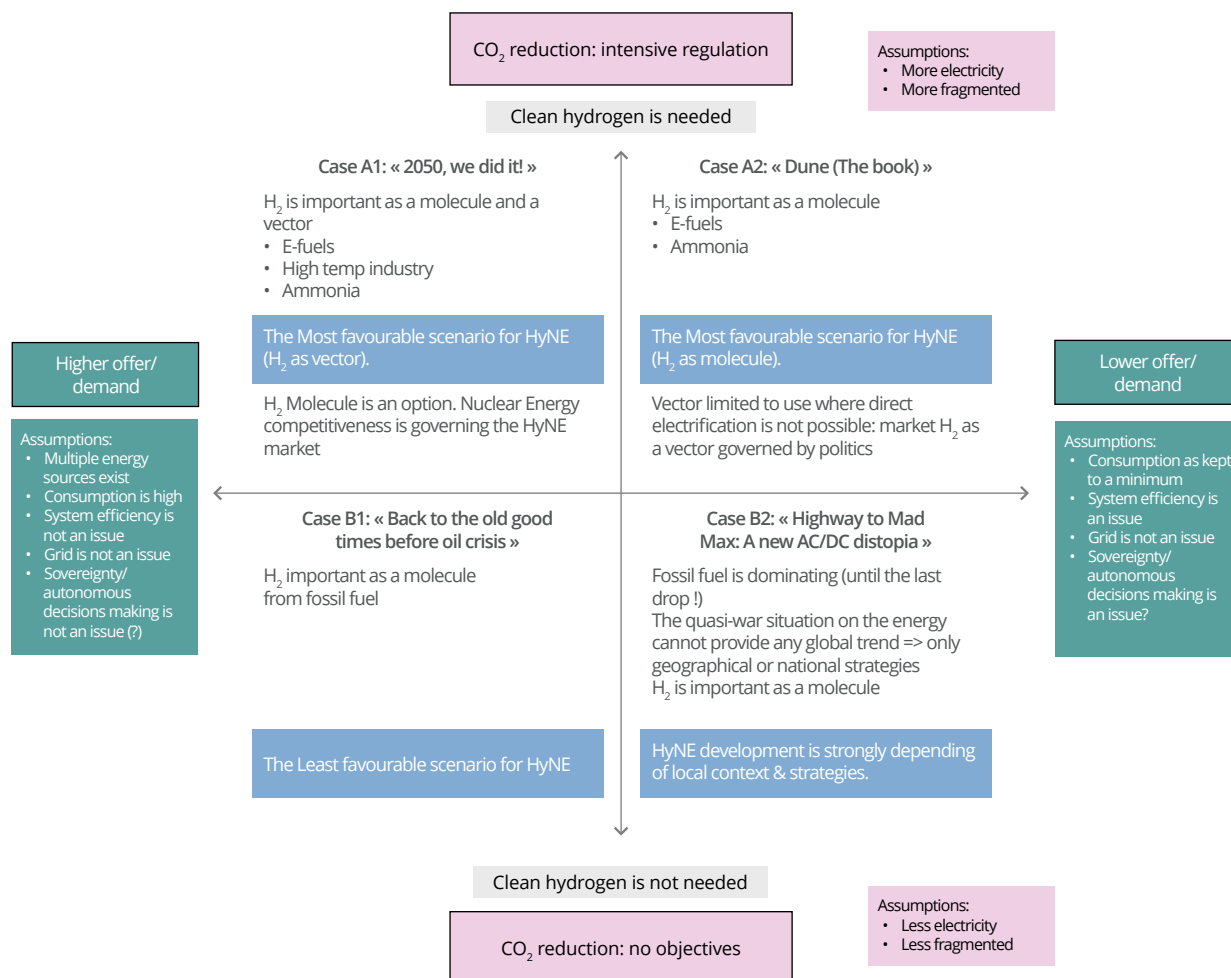


Figure 64: Synthesis of the prospective analysis for HyNE in four different world scenarios

## CHAPTER 8

# HyNE: perspectives for a future IEA/H<sub>2</sub> TCP Contribution

## §8 - KEY TAKE AWAYS

- i. Task #44 (HyNE, 2023–2026) marked a major evolution from Task #25, focusing on industrial-scale deployment, techno-economic viability, and higher TRLs rather than purely academic R&D progress. The shift toward the perspective of industrial deployments was one of the conditions for proposing a new Task following this one.
- ii. The Task #44 served as a collaborative platform, complementing work by international organizations such as OECD/NEA, IAEA, and GIF. Its role in organizing joint international workshops has been very valuable and positively remarked.
- iii. Task #44 demonstrated that hydrogen production from nuclear energy is already feasible at proof-of-concept and small demonstration levels. The technical maturity of the individual systems is confirmed. However a technological gap remains in the coupling (cogeneration approach) between the nuclear reactor and hydrogen production facility.
- iv. While a Task #44 time extension was deemed unnecessary, a new task could emerge with a focus on high-value chemical hydrogen applications (e-fuels), and stronger demonstration-driven roadmaps, alongside continued dissemination of Task #44 results.
- v. Introducing innovative management and analysis tools (creative SWOT, PESTEL, shared digital platform, e-reputation analysis, prospective tools) was an asset that should be shared with other IEA H<sub>2</sub> TCP Task leaders.

The Task #44 named HyNE (Hydrogen from Nuclear Energy) operated from 2023 to 2026 (see Insert 14). The previous Task dealing with this subject at IEA H<sub>2</sub> TCP was Task #25 (High Temperature Processes for Hydrogen Production) from 2007-2010<sup>100</sup> managed by CEA<sup>101 102</sup>.

Task #44 had a role as a platform for sharing information on hydrogen production from nuclear energy. The situation has significantly evolved in the last 15 years. Contrary to Task #25, Task #44 members' objectives were primarily focused on industrial deployment rather than academic research, addressing both technical and economic aspects, with some solutions already at relatively high Technology Readiness Levels (TRLs). Within Task #25 the studies carried out were more academic looking for R&D performances, innovations and promising perspective to pursue the research in progress.

<sup>100</sup>: F. Le Naour et al. « IEA-HIA Task #25: High Temperature Processes for Hydrogen Production - Three Year Progress Review of the Project », 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Proceedings of the WHEC, May 16.-21. 2010, Essen.

<sup>101</sup>: Gilles Rodriguez, then Sabine Poitou and François Le Naour in its end.

<sup>102</sup>: It is worth noting that Task #01 and #02 were also dealing of this subject at the early years of the IEA H<sub>2</sub> TCP but very few data were archived from these two first tasks.

From a methodology perspective, Task #44 has utilised creativity tools like the “creative SWOT analysis” and the PESTEL analysis (see § 7). Task #44 also tried to innovate in managing this Task by creating a dedicated shared platform to minimize the number of exchanges sent through emails. They also made an e-reputation enquiry at the beginning and the end of the Task to evaluate the Task #44 footprint on the internet (see Annex 8).

Task #44's yearly strategy and objectives were the following:

- 2022 = Year 0: Actions => Definition of the potential members and the Task Program of Work. The task was proposed to the IEA/H<sub>2</sub> TCP ExCO, accepted in December => Creation of Task #44.
  - Technical position => A joint meeting took place with IAEA in June 2022 to define the state of the art of this subject.
- 2023 = Year 1: Actions => Team definition. Creation of the network with other organizations (OECD, IAEA, GIF). The tools were in operation for Task Management, Monthly newsletter, Social platform.
  - Technical position => Hydrogen from nuclear energy is not an engineering dream, it already exists at the proof-of-concept level. It is possible to present several real demonstration cases and explain the different coupling approaches of nuclear reactors with different H<sub>2</sub> production technologies.
- 2024 = Year 2: Actions => The Task #44 was fully operational and in addition with the on-going program of work, members investigated the complementary items coming from the gap analysis: Safety approach and Codes & standards.
  - Technical position => All the relevant on-going projects were followed and we defined a position paper on the techno-economic systems of Hydrogen from Nuclear Energy based upon different relevant studies. A PESTEL analysis was initiated.
- 2025/2026 = Year 3: Actions => Task #44 provided output coming from the SWOT & PESTEL analysis produced jointly. The discussion to extend the Task was engaged.
  - Technical position => The Task delivered the final report that gathered, analysed and synthetized all the newsletters, technical data and paper positions that were regularly produced.

In Year 3 (2025/2026) conclusions on whether to extend the task were presented to the Executive Committee (Dec 2025 in Paris). While a direct extension of the current Task #44 was considered not relevant, the creation of a new task under specific conditions was agreed to be of interest. A new task could be considered if most of the following conditions are met:

- Propose a new direction more focused the use of H<sub>2</sub> for high value molecules (e-kerosene, e-fuel).
  - In keeping with the Task recommendations (see §7) it is important to evaluate the trend of this subject to evaluate if conditions are fulfilled to move out of the “Valley of death” situation toward real cases demonstrations.
- Define a new roadmap integrating the higher importance of demonstration systems.
  - Demonstration of significant progress or an efficient coupling system will increase the motivation to pursue the subject of this Task.

The coordinated approach of Task #44 ensures the work was complementary to rather than duplicative of other international organisations like OECD/NEA, IAEA and GIF (Generation IV International Forum).

During the gap between the Task #44 closure and a potential new Task, communication around this Task's main results & achievements will be an asset. It is planned to produce one or two review papers in Scientific journals based on all the data accumulated during these three years in addition to this current final report. Preparing an education set on this subject may also be an asset<sup>103</sup>.

#### Insert 14: The Task #44 timeline (2023 – mid 2026)

### Insert 14: The Task #44 timeline (2023 – mid 2026)

Rather than producing a long detailed (and potentially tedious) table of all actions carried out in Task #44, it is, instead, illustrated through the three timelines below.

#### Task #44 2023 - Mid-2024 (activities)

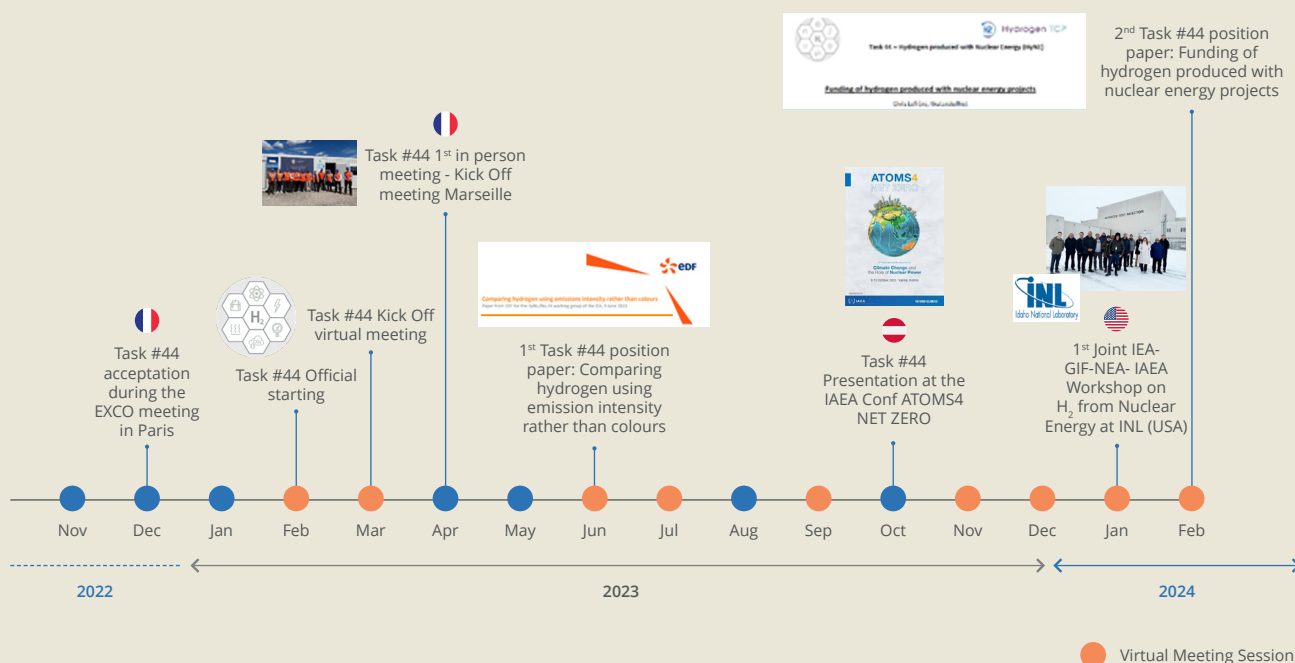


Figure 65: The Task #44 roadmap 2023 to mid-2024

<sup>103</sup>: Still under debate at the publication stage of this report.

### Task #44 2024 - Mid-2025 (activities)

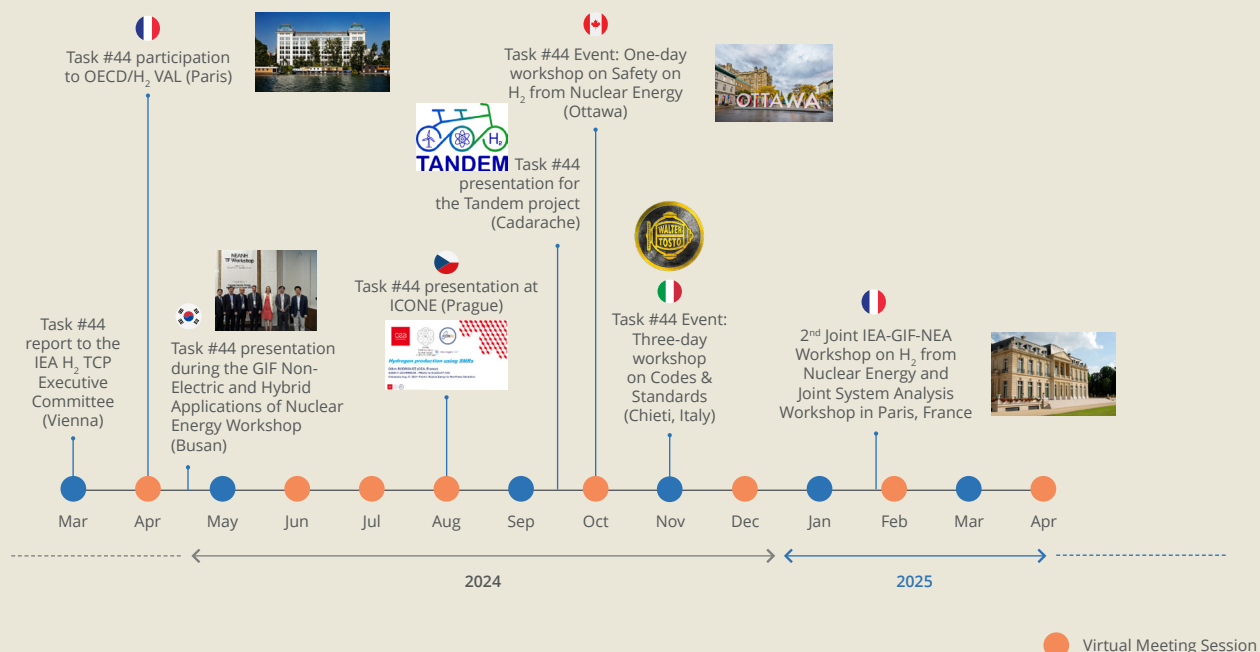


Figure 66: The Task #44 roadmap mid-2024 to mid-2025

### Task #44 Mid-2025 - 1<sup>st</sup> semester 2026 (activities)

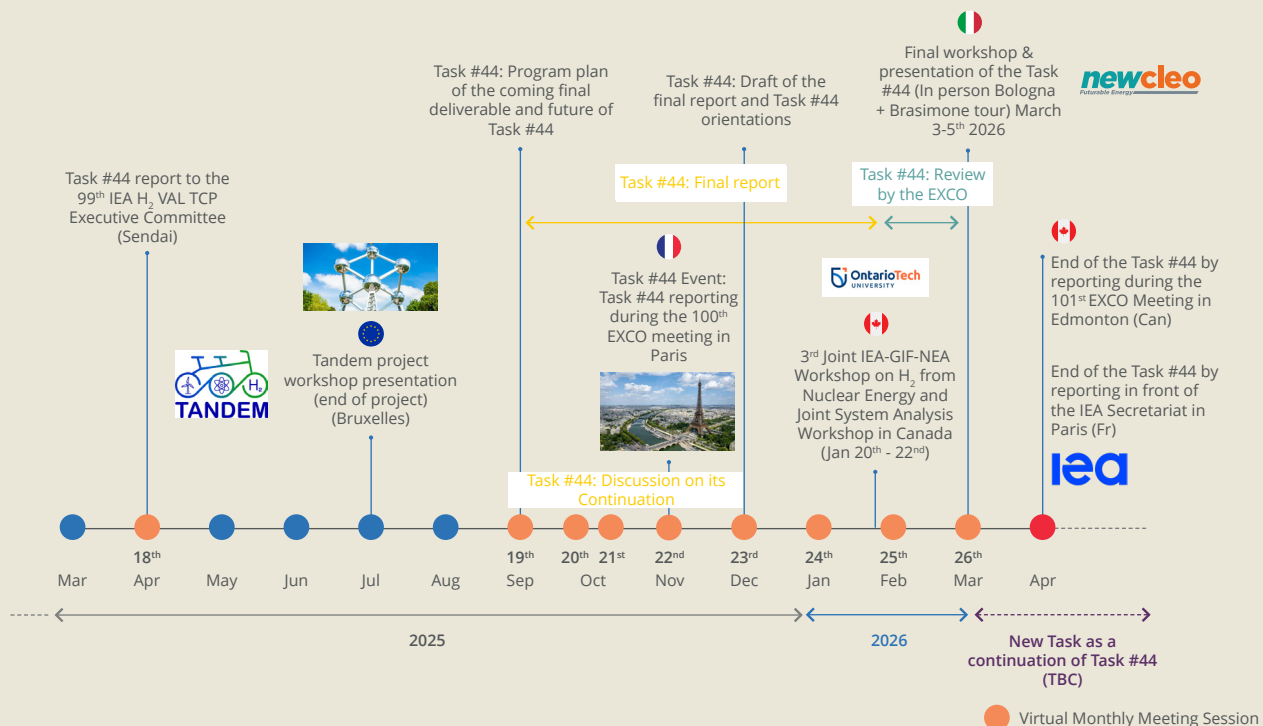


Figure 67: The Task #44 roadmap mid-2025 to Task end

## CHAPTER 9

## Some last remarks

The path to achieving net-zero emissions by 2050 hinges on our collective ability to transition away from fossil fuels—a commitment reaffirmed at COP28 in Dubai. To accelerate this transition, societies must have access to abundant, low-carbon, and cost-competitive energy. While electrification remains the most effective solution for many applications, certain sectors—such as aviation, maritime transport, steel production, and fertilizer manufacturing—cannot be fully electrified due to technical constraints. For these industries, low-carbon hydrogen and its derivatives (e.g., e-fuels) offer a viable complementary solution.

However, the low-carbon hydrogen market is not scaling up as rapidly as needed. The primary barriers are twofold:

- Cost competitiveness: The production of low-carbon hydrogen remains significantly more expensive than fossil-based alternatives.
- Scale of demand: Decarbonizing the aforementioned industries requires massive quantities of low-carbon hydrogen, which in turn demands a corresponding surge in low-carbon electricity production.

The challenge, therefore, is twofold: how to produce hydrogen at scale in a predictable and continuous manner, while ensuring cost efficiency? Nuclear power emerges as a compelling solution. Unlike intermittent renewable sources, nuclear plants can provide a stable, baseload supply of low-carbon electricity—essential for meeting industrial demand. However, nuclear energy alone is not sufficient. To achieve cost-competitive low-carbon hydrogen, the entire production system must be optimized for efficiency, from electricity generation to hydrogen synthesis and distribution. Integrating nuclear energy with hydrogen production can create a resilient, low-carbon energy system capable of meeting the demands of hard-to-abate sectors.

There is a wide variety of potential nuclear hydrogen cogeneration systems, and among them this report provides a view on the eleven most promising. The future will determine which ones will develop into technical realisation. Definitely, the HyNE solution complies to future energy needs.

In 2025, IEA first identified key technology milestones related to energy security, sustainability, and economic benefit<sup>104</sup>. Since 2026, 19 key technologies are followed online<sup>105</sup>. According to this report's conclusions and to the great potentiality of some solutions proposed and analysed, Task #44 members deeply think that the HyNE technology could be proposed as the 20<sup>th</sup> key technology to follow.

---

<sup>104</sup>: IEA, "The State of Energy Innovation", 2025, <https://www.iea.org/reports/the-state-of-energy-innovation-2025>

<sup>105</sup>: <https://www.iea.org/data-and-statistics/data-tools/races-to-first-in-energy-innovation>

# Contributor's list and Task #44 members

Philippe Amphoux, CEA French Atomic Commission, France, [philippe.amphoux@cea.fr](mailto:philippe.amphoux@cea.fr)

Todd Combs, INL, USA, [todd.combs@inl.gov](mailto:todd.combs@inl.gov)

Robert Alford, UKNNL, UK, [robert.e.alford@uknnl.com](mailto:robert.e.alford@uknnl.com)

Jean-François Dhedin, EDF, France, [jean-francois.dhedin@edf.fr](mailto:jean-francois.dhedin@edf.fr)

Bora Aydin, Walter Tosto SpA, Italy, [b.aydin@waltertosto.it](mailto:b.aydin@waltertosto.it)

Rami El-Emam, Ontario Tech University, Canada, [rami.Elemam@ontariotechu.ca](mailto:rami.Elemam@ontariotechu.ca)

Claire Barou, Air Liquide, USA, [claire.barou@airliquide.com](mailto:claire.barou@airliquide.com)

Aaron Epiney, INL, USA, [aaron.epiney@inl.gov](mailto:aaron.epiney@inl.gov)

Ahmed Bentaib, ASNR, France, [ahmed.bentaib@irsn.fr](mailto:ahmed.bentaib@irsn.fr)

Francesco Ganda, IAEA, Italy, [f.ganda@iaea.org](mailto:f.ganda@iaea.org)

Richard Boardman, INL, USA, [richard.boardman@inl.gov](mailto:richard.boardman@inl.gov)

Christophe Gaspard, John Cockerill Hydrogen, France, [christophe.gaspard@johncockerill.com](mailto:christophe.gaspard@johncockerill.com)

Caroline Bono, EDF, France, [caroline.bono@edf.fr](mailto:caroline.bono@edf.fr)

Pierre Gavaille, CEA, [pierre.gavaille@cea.fr](mailto:pierre.gavaille@cea.fr)

Shannon Bragg-Sitton, INL, USA, [shannon.bragg-sitton@inl.gov](mailto:shannon.bragg-sitton@inl.gov)

Gérard de Giovanni, Meije development, France, [gerard.degiovanni@meijedevelopment.eu](mailto:gerard.degiovanni@meijedevelopment.eu)

Marina Buzzi, TOPSOE, Denmark, [mbuz@topsoe.com](mailto:mbuz@topsoe.com)

Giancarlo Gobbi, ASME EU Division, Italy, [gobbiG@asme.org](mailto:gobbiG@asme.org)

Aymeric Canton, CEA French Atomic Commission, France, [aymeric.canton@cea.fr](mailto:aymeric.canton@cea.fr)

Joe Hargreaves, CONSULTARC, UK, [joe.hargreaves@consultarc.com](mailto:joe.hargreaves@consultarc.com)

Christopher Cantrell, ASME, USA, [cantrellc@asme.org](mailto:cantrellc@asme.org)

Claude Heller, ARCLES, France, [claud.heller@arcles.com](mailto:claud.heller@arcles.com)

Guilherme Cardoso, nucleareurope, EC, [guilherme.cardoso@nucleareurope.eu](mailto:guilherme.cardoso@nucleareurope.eu)

Amandine Idasiak, EOWIN, France, [amandine.idasiak@cea.fr](mailto:amandine.idasiak@cea.fr)

Jérôme Cardolaccia, CEA, Fr, [jerome.cardolaccia@cea.fr](mailto:jerome.cardolaccia@cea.fr)

Slavica Ivanovic, Tractebel, Belgium, [slavica.ivanovic@tractebel.engie.com](mailto:slavica.ivanovic@tractebel.engie.com)

Gianluca Carigi, Monaco Engineering Solutions (MES), UK, [gianluca.carigi@mes-international.com](mailto:gianluca.carigi@mes-international.com)

Andreas Johansson, RISE, Sweden, [andreas.johansson@ri.se](mailto:andreas.johansson@ri.se)

Nabiha Chaumeix, CNRS-ICARE Orléans, France, [chaumeix@cnrs-orleans.fr](mailto:chaumeix@cnrs-orleans.fr)

Ishii Katsunori, JAEA, JP, [ishii.katsunori01@jaea.go.jp](mailto:ishii.katsunori01@jaea.go.jp)

Michiel Korthals Altes, ASSYSTEM, France,  
[mkorthalsaltes@assystem.com](mailto:mkorthalsaltes@assystem.com)

Karla Kwiatkowski Lepetitgaland, Eletronuclear, Brazil,  
[karlakq@eletronuclear.gov.br](mailto:karlakq@eletronuclear.gov.br)

Benjamin Laredo, Institut TERRAWATER,  
[benjamin.laredo@institut-terrawater.org](mailto:benjamin.laredo@institut-terrawater.org)

Alain Le Coguiec, retired from EDF, France,  
[palecog@gmail.com](mailto:palecog@gmail.com)

Chris Lefrère, Retired from Waterstofnet, Belgium,  
[chris.lefrere@waterstofnet.eu](mailto:chris.lefrere@waterstofnet.eu)

Olivier Libouban, CEA, France,  
[olivier.libouban@cea.fr](mailto:olivier.libouban@cea.fr)

Edward Macfarlane, Abbott Risk Consulting Ltd., UK,  
[ed.macfarlane@consultarc.com](mailto:ed.macfarlane@consultarc.com)

Oliver Martinez, ASME, USA,  
[martinezo@asme.org](mailto:martinezo@asme.org)

Franco Michel-Sendis, OECD/NEA, France,  
[franco.michel-sendis@oecd-nea.org](mailto:franco.michel-sendis@oecd-nea.org)

Lucas Mir, OECD/NEA, France,  
[lucas.mir@oecd-nea.org](mailto:lucas.mir@oecd-nea.org)

Jorge-Enrique Munoz-Garcia, CEA, France,  
[jorge-enrique.munoz-garcia@cea.fr](mailto:jorge-enrique.munoz-garcia@cea.fr)

Paul Nevitt, National Nuclear Laboratory (NNL), UK,  
[paul.nevitt@uknnl.com](mailto:paul.nevitt@uknnl.com)

Sylvain Nizou, HEXANA,  
[sylvain.nizou@hexana.fr](mailto:sylvain.nizou@hexana.fr)

Hiroki Noguchi, Japan Atomic Energy Agency, Japan,  
[noguchi.hiroki@jaea.go.jp](mailto:noguchi.hiroki@jaea.go.jp)

Didier Ohayon, AIEA, France,  
[d.ohayon@iaea.org](mailto:d.ohayon@iaea.org)

Henri Paillere, IAEA, France,  
[henri.paillere@iaea.org](mailto:henri.paillere@iaea.org)

David Proult, CEA/ITESE, France,  
[david.proult@cea.fr](mailto:david.proult@cea.fr)

Anne Quincy, EOWIN, France,  
[anne.quincy@cea.fr](mailto:anne.quincy@cea.fr)

Gilles Rodriguez<sup>106</sup>, CEA French Atomic Commission, France,  
[gilles.rodriguez@cea.fr](mailto:gilles.rodriguez@cea.fr)

Augustin Alejandro Rodriguez Riccio, TOPSOE, Denmark,  
[aarr@topsoe.com](mailto:aarr@topsoe.com)

Rebecca Rosling, EDF Energy, UK, [Rebecca.Rosling@edfenergy.com](mailto:Rebecca.Rosling@edfenergy.com)

Anne Sager, RISE, Sweden,  
[anne.sager@ri.se](mailto:anne.sager@ri.se)

Gianfranco Saiu, NEWCLEO, Italy,  
[gianfranco.saiu@newcleo.com](mailto:gianfranco.saiu@newcleo.com)

Long Sang, CNL, Canada,  
[long.sang@cnl.ca](mailto:long.sang@cnl.ca)

Pierre Serre-Combe, CEA French Atomic Commission, France,  
[pierre.serre-combe@cea.fr](mailto:pierre.serre-combe@cea.fr)

Myrto Tripathi, Terrawater, France,  
[myrtotripathi@gmail.com](mailto:myrtotripathi@gmail.com)

Nicolas Trosino, HEXANA, France,  
[nicolas.trosino@hexana.fr](mailto:nicolas.trosino@hexana.fr)

Claire Vaglio-Gaudard, CEA, France,  
[claire.vaglio-gaudard@cea.fr](mailto:claire.vaglio-gaudard@cea.fr)

Brent Wilhelm, OECD NEA, Canada,  
[brent.wilhelm@oecd-nea.org](mailto:brent.wilhelm@oecd-nea.org)

Marianne Wilson, Abbott Risk Consulting Ltd., UK,  
[marianne.wilson@consultarc.com](mailto:marianne.wilson@consultarc.com)

---

<sup>106</sup>: Task #44 leader and main writer of this final report.

# List of acronyms

AECL: Atomic Energy of Canada Ltd

AFCECEN: Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires.

AI: Artificial Intelligence

ALARA: As Low As Reasonably Achievable

ALARP: As Low As Reasonably Practicable

AMR: Advanced Modular Reactor

ANL: Argonne National Laboratory

ATEX: ATmosphère EXplosible

BANI: Brittle, Anxious, Non-linear, and Incomprehensible

BNI: Balance of Nuclear Island

C&S: Codes & Standards

CAPEX: Capital Expenditure

CCGT: Combined Cycle Gas Turbines

CCR: Central Control Room

CCUS: Carbon Capture Utilisation and Storage

CEM: Clean Energy Ministerial Hydrogen Initiative

CI-BOP: Conventional Island Balance of Plant

COMAH: Control of Major Accident Hazards Regulations

CSP: Concentrated Solar Power

Cu-Cl: Copper-Chlorine thermochemical cycle

DAC: Direct Air Capture

DEC: Design Extension Condition

DESNZ: Department for Energy Security & Net Zero

DiD: Defence in Depth

DOD: Department of Defence

DOE: Department Of Energy

DOVE: Dispatch Optimization Variable Engine

EDF: Electricité de France

EIGA: European Industrial Gases Association

FORCE: Framework for Optimization of Resources, Controls, and Economics

GFR: Gas Fast Reactor

GIF: Generation IV International Forum

GIF NECA WG: Generation IV / Non-Electric and Cogeneration Applications Working Group

HERON: Holistic Energy Resource Optimization Network

HES: Hybrid Energy System

HT: High Temperature

HTGR: High Temperature Gas-cooled Reactor

HTR: High Temperature Reactor

HTSE: High Temperature Steam Electrolyser

HTTR: High Temperature Engineering Test Reactor

HyNE: hydrogen from Nuclear Energy

IAEA: International Atomic Energy Agency

IEA: International Energy Agency

IEA H<sub>2</sub> TCP: IEA Hydrogen Technology Collaboration Program

IES: Integrated Energy System

IHX: Intermediate Heat Exchanger

INL: Idaho National Laboratory

IRL: Integration Readiness Level

I-S: Iodine-Sulfur thermochemical cycle

JAEA: Japan Atomic Energy Agency

LCOH<sub>2</sub>: Levelized Cost of Hydrogen

LFR: Lead Fast Reactor

LLM: Large Language Model

LOFC: Loss Of Forced Cooling

LSR: Large Scale Reactor

LTE: Low Temperature Electrolyser

LWR: Light Water Reactor

MMR: Micro Modular Reactor

MultiPLHY: Multimegawatt high-temperature electrolyser to generate green hydrogen for production of high-quality biofuels

MSR: Molten Salt Reactor

MWe: Electrical MegaWatt

NEA: Nuclear Energy Agency

NI: Nuclear Island

NPP: Nuclear Power Plant

NZE: Net Zero Emission

OECD: Organisation for Economic Co-operation and Development

ONR: Office for Nuclear Regulation

OPEC: Organization of Petroleum Exporting Countries

OPEX: Operational Expenditure

ORCA: Optimization of Real-time Capacity Allocation

PEM: Proton Exchange Membrane

PESTEL: Political, Economic, Social, Technological, Environmental and Legal

PPA: Power Purchase Agreements

PR: Power Reactor

PV: Photovoltaic

PWR: Pressurized Water Reactor

R&D: Research & Development

RHWG: Reactor Harmonization Working Group

SAF: Sustainable Aviation Fuel

SCWR: Super Critical Water Reactor

SFR: Sodium Fast Reactor  
SMF: Sustainable Maritime Fuel  
SMR: Steam Methane Reforming or Small Modular Reactor  
*(depending on the context)*  
SOEC: Solid Oxide Electrolyser Cell  
SOFC: Solid Oxide Fuel Cell  
SSR: Specific Safety Requirements  
SWOT: Strengths Weaknesses Opportunities Threats  
TANDEM: Small Modular Reactor for a European sAfe aNd  
Decarbonized Energy Mix  
TC: Thermochemical Cycle  
TECDOC: Technical Document  
TFE: Twenty-Foot Equivalent  
TRL: Technology Readiness Level  
UKNNL: UK National Nuclear Laboratory  
VHTR: Very High Temperature Reactor  
VRE: Variable Renewable Energy  
VUCA: Volatile, Uncertain, Complex and Ambiguous  
VVER: Vodo-Vodianoï Energuetitcheski Reaktor - Russian  
type nuclear reactor  
WENRA: Western European Nuclear Regulators Association

# Acknowledgements

*This document is a collaborative effort resulting from the contribution of all members participating in Task #44. As the leader of this Task for the past three years, I wanted to express my sincere gratitude to all members who contributed to this shared work, which is the fruit of their input data and their willingness to dedicate a part of their precious time to make this task so efficient.*

*This unique network of experts gathered around this Task could not have functioned so effectively without the support of the IEA H<sub>2</sub> TCP structures: the Executive Committee and above all the ARIEMA Support Secretariat. I would like also to thank the country representative members for their encouragement, and the mutual and friendly support among Task leaders. A special thanks to the peer reviewers of this document from Canada (Claudie Roy), China (Teng He, Lijun Jiang & Ping Chen), and UK (Fran Jones & Frances Buckingham).*

*I would like to extend my sincere thanks to all who opened the doors of their companies and facilities. The frank and open discussions we had during these field visits greatly helped us to solidify our ideas and recommendations coming out from this Task. They were fundamental, and that is why I wanted them to be namely represented in this report (see Annex 1).*

*The world of hydrogen is a complex domain, and the nuclear sector too! We hope this report will shed some light on the subject. Beyond the production of this document, we welcome all of your feedback. Please send to: [gilles.rodriguez@cea.fr](mailto:gilles.rodriguez@cea.fr) or [technicalsecretariat@ieahydrogen.org](mailto:technicalsecretariat@ieahydrogen.org).*

## ANNEX 1

## Field-testing hydrogen production

During the three years of Task #44, members had regular in-person meetings to realize the progress of hydrogen production field-tests. These facility tours were particularly important to really make the link between studies and theories and the real case situation. We visited several very significant and inspiring places. Through this small Annex we tried to down select the most relevant ones.

### April 2023: Meeting in Marseille (France) and visit of the Jupiter 1000 project

JUPITER 1000 is the first industrial demonstrator of Power to Gas in France. Its power is 1000 kW (2 hydrogen production lines of 500 kW each). Through this visit, HyNE members could appreciate the experimental feedback of two water electrolysis (Alkaline and PEM) hydrogen production technologies. This hydrogen is either blended in a natural gas stream or combined online with a CO<sub>2</sub> inlet to produce e-Methane (methanation process). Even if this experimental platform was not connected with nuclear reactors, it must be recalled this facility was taking its electricity from the French grid – which is for more than 70% coming from nuclear reactors. This facility was useful to visit and openly discuss to understand all constraints (some of them are administrative or under the regulatory framework) passing from design to operation.

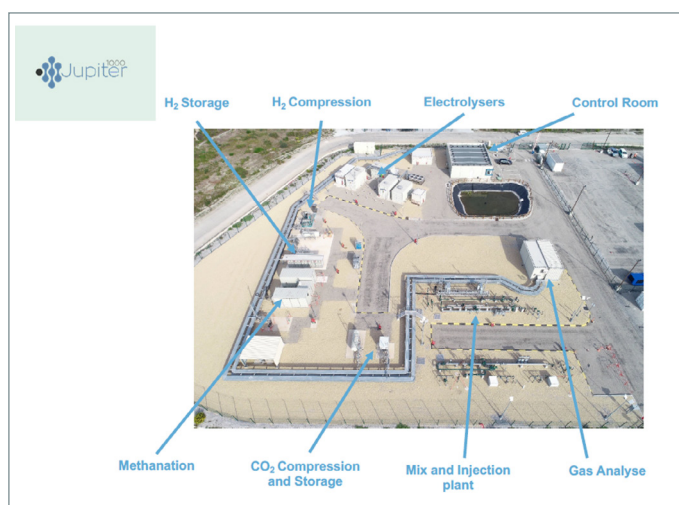


Figure 68: The Task #44 team in front of the Jupiter 1000 building (France)

### January 2024: 1<sup>st</sup> Joint Workshop at Idaho National Lab (USA) and visit of the HTSE stack modules validation

During the 1<sup>st</sup> joint workshop at the INL, all Task members were really impressed by the huge investments deployed by DOE and industry-supported hydrogen research at INL. Among all facilities visited the most significant one was the HTSE stack module systems, some of them in operation. It was also the opportunity to visit the MARVEL reactor, under construction inside the TREAT facility.

### Technology Validation: Stack Module and System Testing

- INL supports commercial developers design, operate, and V&V the performance of fully integrated HTE electrolysis modules
- Multiple 30-250 kWe units
- Co-Electrolysis of CO<sub>2</sub> and H<sub>2</sub>
- Reversible SOEC/SOFC
- Balance of plant equipment testing
- Dynamic Testing – tied to grid

Heat Exchanger ready for heat recuperation



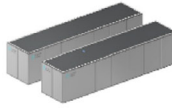
HTE Utilities Facility:  
• Power Converters (180 kW)  
• Steam Generator



Bloom Energy 100 kWe Stack Module



Operator Control / Grid Integration



Purolit Energy 250+ kW Stack Module

IDAHO NATIONAL LABORATORY



Figure 69: Task #44 members observing an HTSE stack module tested at INL (USA)

### October 2024 Chieti: Specialist workshop on Codes & Standards => The industrial fabrication at Walter Tosto factory

The workshop hosted by Walter Tosto (Chieti, Italy) gave the opportunity to visit the Walter Tosto factory where large scale components are produced on-site. It provided an understanding of the quality and safety assessments required in these huge factories to respect C&S rules. During meetings we were able to identify existing codes and make a gap analysis.



Figure 70: Task #44 members with WalterTosto members during the Codes & Standards workshop (Italy)

### January 2025 Paris: 2<sup>nd</sup> Joint workshop at OECD Headquarter (Paris) => Visit of two start-up using hydrogen for vehicles (HYLIKO and HYSETCO)

The tour of hydrogen end-use facilities in the Parisian suburb (HYLIKO heavy duty vehicle fuelling station and HYSETCO production and fuelling for light duty vehicles) gave the opportunity to investigate the current hydrogen economy for mobility and their current needs to increase the future hydrogen market. Both start-up companies claimed for a quick massive low-carbon hydrogen production to decrease the costs. One of the astonishing parts of this tour was to see the hydrogen production by electrolysis, 100% automatic, at the close vicinity of first Parisian habitations (Hysetco factory and hydrogen mobility).



Figure 71: Task members visiting Hysetco & Hyliko start-up companies (France)

### January 2026: 3<sup>rd</sup> joint international workshop: Toronto & Ontario Tech University. Visit of Enbridge company and CH2nge Energy start-up

Enbridge hosted Ontario Tech University and the Task #44's guests for a visit to Ontario's hydrogen blending facility and the first hydrogen combined heat and power unit in Ontario. The hydrogen blending pilot project started in 2019. Today, Enbridge provides a blend of natural gas with 5% hydrogen by volume to 3,600 customers in Markham, Ontario. The main advantage of this blending ratio is that it can fit to all existing infrastructures for an adapted “well to wheel”<sup>107</sup> concept: production – transportation – use – burning with gas cooker in the kitchen.



Figure 72: Task #44 members visiting Enbridge solutions on hydrogen production & blending station

Despite a  $-15^{\circ}\text{C}$  wind chill, we enjoyed the site visit and live demonstration, 200 m from the Pearson airport runway, by **Ry Smith** and **David Hardy** on **Hone** mobile hydrogen power service at Pearson Airport.

<sup>107</sup>: Well-to-wheels (WtW) is used to assess the Life Cycle Assessment of fuels, including all phases of its life cycle - from the extraction of raw materials to their use. There are two components to the well-to-wheels assessment: well-to-tank (WtT) and tank-to-wheels (TtW). WtT includes the fuel production phases, and TtW the use of fuel.



Figure 73: Visit of Hone facilities fueling H<sub>2</sub> reservoirs in trucks to provide solution of low-carbon electricity on remote area for movie projects

### March 2026: The 2026 in person semestrial meeting: Bologna & Brasimone facility (Italy). Visit of the lead benches developed by the newcleo start-up

The meeting concluded with a visit to the lead-based facilities built by newcleo at Brasimone on the site of the PEC reactor. Newcleo's substantial R&D program includes the imminent arrival of a 10 MWth PRECURSOR model (1/3 scale), powered exclusively by electricity, to demonstrate the full feasibility of the NEWCLEO concept. Beyond this demonstration phase, this facility could find new opportunities to demonstrate the hydrogen production system coupled with a real reactor (without nuclear fuel but electrically heated). The overall coupling system could be demonstrated with a significant potential power (10 MWth), allowing correct scaling-up.

#### Building upon 30+ years of EU Research and ENEA Research Center Brasimone

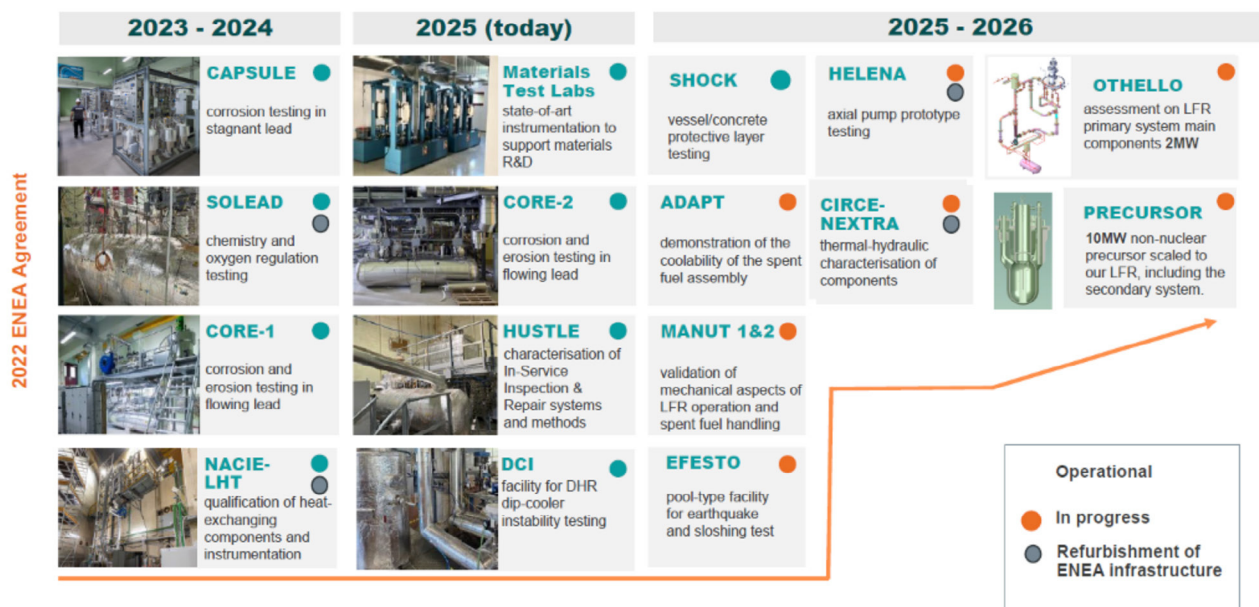




Figure 74: The ENEA & newcleo lead facility fleet erected at Brasimone (Italy) & an artist mock-up of the PRECURSOR facility (scale 1) [©Agnese Bedini/DSL Studio/newcleo]

## ANNEX 2

# Comparing hydrogen by emissions intensity rather than colours

*The use of colours to describe different forms of hydrogen production is common and easy to understand. The colours are, however, not designed as a tool to objectively compare the merits of the production routes they represent. There is potential for misleading assumptions, inconsistencies in use, and for the definitions of what the colours represent to vary and lack precision. Classification of hydrogen based on its carbon emissions intensity is an alternative, technology-neutral approach, seen in hydrogen policies and certification schemes that are emerging internationally. It has advantages over using colours: it is transparent, demonstrates low carbon credentials and if used internationally could limit market fragmentation and support trade in low carbon hydrogen. It would be an effective indicator for use in industry, government and policy frameworks.*

## 1 Using colours to describe hydrogen

Colours are used to distinguish the different ways hydrogen can be produced. For production routes that are being developed more widely, there are a few commonly used terms:

- Green hydrogen is made by using electricity from renewable energies to electrolyse water.
- Blue hydrogen is produced mainly from natural gas, using steam methane reformation, combined with carbon capture, utilisation and storage.
- Grey hydrogen is created from natural gas using steam reformation, but without capturing greenhouse gases.
- Pink hydrogen is generated through electrolysis, powered by nuclear energy
- Yellow hydrogen is hydrogen from electrolysis of water using solar power.
- Black hydrogen is when black coal is used, usually in a gasification process, to make hydrogen.
- Brown hydrogen is when lignite (brown coal) is used to make hydrogen, also usually in a gasification process.
- White hydrogen refers to naturally occurring hydrogen, found underground and exploited through fracking.
- Turquoise hydrogen is made using methane pyrolysis to produce hydrogen and solid carbon.
- Red or orange hydrogen can refer to hydrogen made from biomass, usually via gasification.

### Colours are easy to understand

Colour is a concept that is familiar to everyone, and distinguishing between different colours is something we do instinctively every day. It is no surprise that using colours to identify the different ways hydrogen is produced has caught on. A colour, or the word for the colour itself, stimulates a reference point in the mind that a description of a hydrogen production plant cannot compete with. The colour can be used as a shorthand to add brevity to a discussion and can widen interest in hydrogen by using more accessible language for technical concepts.

But colour comparisons could lead to misleading assumptions. Although using colours to describe hydrogen is accessible, it could also give rise to misunderstandings or misappreciations of the differences between different production routes. The list of colours is an evolving characterisation of technologies, rather than being designed as an objective tool to compare their merits on carbon emissions, production costs, technology readiness, etc. But there is a natural inclination to compare, particularly when coming across colour names for the first time. We naturally attribute values to colours. This could lead to assumptions being made, which miss some key points of comparison.

For example, one could understandably form a quick conclusion that electrolysis using nuclear energy is not a favourable method because it is not “green” the colour naturally associated with nature, progress and sustainability. But lifecycle greenhouse gas emissions from nuclear power are among the lowest of any electricity source that could be used to produce hydrogen.

### Colour definitions are not consistent

There is no universal agreement on colour designations, which causes variation and overlap in how the colours are used. For production pathways that are more frequently discussed, definitions are more established, particularly green and blue. Other definitions are less fixed. The use of nuclear energy is a good example. In the sources used for the colour list in this document, pink, red and purple are at times used to refer to all electrolytic hydrogen production using nuclear energy, but equally they can also be used to differentiate between electrolysis using nuclear-generated electricity (pink), nuclear heat (red) or both (purple).

The IEA concluded<sup>108</sup> that the existing colour definitions are generally considered insufficient to be used as a reference in regulations or supply contracts. The lack of consensus on definitions, potential gaps in the coverage of production methods and a lack of quantification of emissions all mean their use would be imprecise and not transparent.

## 2 Using emissions intensity to compare hydrogen

Measuring carbon emissions, or carbon equivalent greenhouse gas emissions, from the production of hydrogen provides a consistent comparator across production methods and indicates the true contribution of the hydrogen to decarbonising the energy system. It is used by some governments in regulation to support the development of the hydrogen sector. It does not exclude the ability of governments, or buyers of hydrogen, to explicitly favour one method of production over another. However, emissions intensity is inherently technology neutral.

### Where emissions intensity is used

Emissions intensity is being used in some hydrogen certification schemes that are emerging internationally<sup>109</sup> to demonstrate the low-carbon credentials of hydrogen that reaches the market. As a means of transparency, the schemes require or encourage the declaration of the carbon content per unit of energy. The certification schemes can also use emissions intensity as a standard, which sets a threshold in emissions intensity to distinguish low-carbon and non-low carbon hydrogen (or multiple thresholds to define the degree of carbon intensity).

The UK is an example where 20 gCO<sub>2</sub>e/MJ is the threshold below which hydrogen can be considered low-carbon. If hydrogen is produced to this Low Carbon Hydrogen Standard, regardless of the production pathway, it can be certified as such, and is also a requirement for government funding for production projects, across different technologies<sup>110</sup>.

The EU has also introduced low-carbon hydrogen must respect a 28.2 gCO<sub>2</sub>e/MJ threshold, which corresponds to a 70% reduction in emissions intensity compared to a 94 gCO<sub>2</sub>e/MJ fossil fuel equivalent. In addition, renewable hydrogen must comply with certain electricity sourcing rules (such as additionality and temporal correlation) to qualify

---

<sup>108</sup>: Towards hydrogen definitions based on their emissions intensity International Energy Agency, 2023.

<sup>109</sup>: <https://www.certifyhy.eu/> and UK Low Carbon Hydrogen Standard ([www.gov.uk](http://www.gov.uk)).

<sup>110</sup>: ([www.gov.uk](http://www.gov.uk)), <https://www.gov.uk/government/publications/hydrogen-production-business-model>

the electricity as renewable and be counted as zero emission. The EU experience shows that technology-neutral and technology-specific definitions are not mutually exclusive in a complex regulatory framework.

### **Move away from colours**

The use of colours has captured the imagination, despite the drawbacks. Abandoning them fully is perhaps unrealistic, however there is scope for them to be reserved for where they have most value, to engage non-expert audiences. Emissions intensity should be the key differentiator in all policy and regulatory frameworks at an industry, government and international level.

## ANNEX 3

## Funding of hydrogen produced with nuclear energy projects

Despite the cost per unit of energy produced being only tens of USD per MWh and competitive with renewables, nuclear projects require a high upfront multiple billion USD investment per nuclear power plant. Under regulatory pressure, industry plants need to decarbonize, requiring low carbon heat, electricity, hydrogen and other molecules. The new modular nuclear reactor approach is an interesting option to get new nuclear power plants to address future low carbon industry plants. In this paper we look at different funding strategies for nuclear power plants, while at the end zooming in on a nascent new funding mechanism: industry.

### Incumbent nuclear power plant operators

Incumbent nuclear power plant operators have an existing customer base and associated revenues and have significant operational experience with nuclear power plants. This puts them in a relatively low risk position to replace an end-of-life power plant with a new one or to perform a lifetime extension on an existing one. Investing in non-electrical applications like hydrogen production is a relatively low marginal investment to them, compared to the investment in nuclear power plant or the investment risk taken by a newcomer without an established customer base for electricity and who needs to invest in a new nuclear power plant. This explains why first movers in the hydrogen produced with nuclear power are existing nuclear power plant operators. They need to acquire operational experience though, in non-electrical applications, and can do so by forging partnerships or performing acquisitions.

### Incumbent power plant operators

Incumbent power plant operators that replace their old carbon power plants with a new fleet of nuclear power plants, have an established customer base and the revenues that come with that. They have the operational experience of operating power plants in specific countries but lack the specific operational experience of nuclear power plants. Investing in non-electrical applications like hydrogen production is a relatively low marginal investment to them. They need to acquire operational experience in both nuclear and non-electrical applications and can do so by forging partnerships or performing acquisitions.

### New entrant nuclear power plant operators

New entrant nuclear power plant operators in each country do not have an existing customer base and the revenues that come with that and do not have operational experience of operating nuclear power plants in that country. From a funding perspective that seems a rather insurmountable challenge.

### Industry

As soon as the share of variable renewable energy sources reaches 30 to 40% of the total electricity production on a grid, the full system costs per unit of electricity grow exponentially with the further increase of that share of variable renewable energy sources on the grid. The more intermittent sources on a grid, the more indirect costs they cause on that grid: 1. The more the grid must be over dimensioned to transport the intermittent power peaks (solar up to 90%, on-shore wind up to 80% and off-shore wind up to 66% grid capacity not used). 2. The more power

storage and back-up electricity production plants are required to balance the grid. 3. The less controllable power plants are utilized and so the higher their cost per unit of power produced becomes.

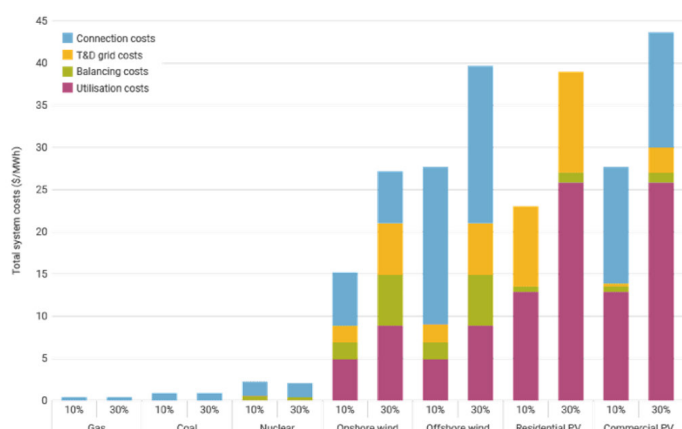


Figure 75: Indirect costs of electricity production<sup>111</sup>

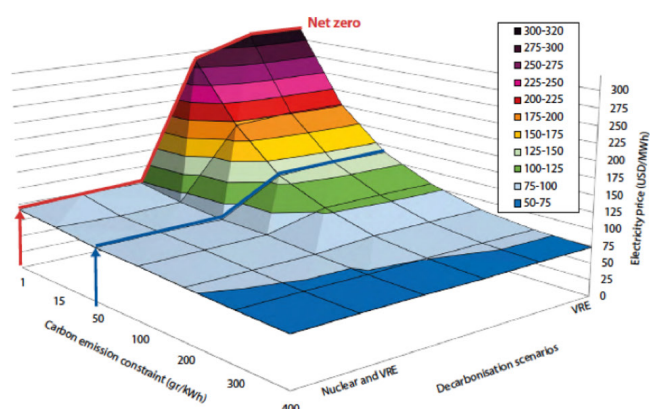


Figure 76: Full system electricity cost in function of % Variable Renewable Energy (VRE) versus nuclear and in function of carbon emission constraint<sup>112</sup>

Many industrial plants and hubs consume from hundreds of megawatts to several gigawatts of energy 24 hours a day, 7 days a week, 365 days per year. To manage the increasing costs imposed upon them when using carbon emitting technologies, industry is driven to move away from carbon-based energy sources and to invest in new or updated plants that run on low carbon heat electricity, hydrogen and/or other molecules.

However, an increasing share of variable renewable energy (VRE) sources on the public electricity grid in certain parts of the world is becoming an increasing barrier to fund investments to decarbonize existing plants or to build new low carbon plants. An increasing share of VREs in these grids pushes full system costs and market prices to non-competitive levels on a global scale and increases energy supply and market price instability. The non-competitiveness of key cost drivers on a global scale and the wide uncertainty about their future evolution becomes barriers for industries on those grids to obtain final investment decisions to decarbonise their existing plant or to build a new low carbon plant.

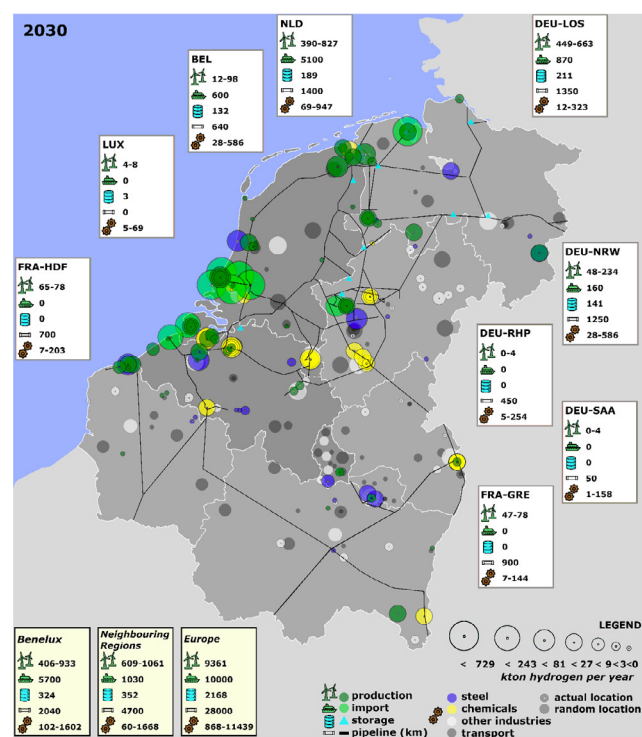


Figure 77: Illustration of industrial hydrogen demand concentration in industry plants and hubs<sup>113</sup>

<sup>111</sup>: OECD NEA, 2018.

<sup>112</sup>: Nestor Sepulveda, MIT, 2016 updated by OECD NEA, 2023

<sup>113</sup>: WaterstofNet study for Benelux Union, 2023: [https://www.benelux.int/wp-content/uploads/2023/04/Final-Report-Benelux-H2-Project\\_FINAL.pdf](https://www.benelux.int/wp-content/uploads/2023/04/Final-Report-Benelux-H2-Project_FINAL.pdf)

Hence more and more industries consider producing their own low carbon energy via investments in low carbon power plants in return for Power Purchase Agreements (PPAs)<sup>114</sup>, giving them a long-term stable supply and competitive and predictable cost of their low carbon energy needs. Low carbon renewable energy, however, depends on and uses the public grid, generating important indirect costs, to reach the low carbon industry plant. Moreover, in several areas of the planet the production capacity of renewables only covers a fraction of the total low carbon needs. In Europe this is estimated to be only 20% by 2030. Hence several industries and industry hubs are now considering producing their own low carbon energy, heat, electricity, hydrogen and other molecules on site by means of Small Modular Reactor heat.

Small Modular Reactors (SMRs)<sup>115</sup> are nuclear power plants that produce between tens and hundreds of megawatts of power for 90% or more of the time in the form of low carbon heat. With that low carbon heat, electricity, industrial heat, hydrogen and other molecules can be produced on site. By sizing the SMRs and the heat, electricity, hydrogen and other molecules infrastructure to meet the new low carbon industry plant or hub energy demand, the investors in the SMR mitigate their long-term commercial risk. In return for their long-term demand and optional co-investment in the SMRs and energy transformation infrastructures, new low carbon industry plants 1. have access to a long term predictable stable supply of energy at a long-term competitive cost, 2. can isolate their business case from the unpredictable and costly public grid and 3. so make their business case for a new low carbon industry plant fundable again. Sure, they will need to forge partnerships with experienced nuclear power plant operators and hydrogen and other molecule operators.

### **About this Annex**

*This paper was written by Chris Lefrère, WaterstofNet and Participant of the IEA TCP Hydrogen Task #44, under the supervision of Gilles Rodriguez, CEA and Manager of Task #44, and offered for review to the Participants of Task #44. It is neither a recommendation nor a position paper but is giving an overview of proven and innovative developing funding options for hydrogen produced with nuclear energy investments.*

---

<sup>114</sup>: <https://ppp.worldbank.org/public-private-partnership/sector/energy/energy-power-agreements/power-purchase-agreements>

<sup>115</sup>: <https://www.iaea.org/topics/small-modular-reactors>

## ANNEX 4

# The Euratom TANDEM project to pave the way of nuclear SMR integration into hybrid energy systems contributing to net-zero emissions: The two district heating scenarios

*This Annex is extracted from the TANDEM study which covers a wider scope of investigation than it is presented hereafter.*

The TANDEM<sup>116</sup> ("Small Modular Reactor for a European safe and Decarbonized Energy Mix") Euratom project ran from 2022 to 2025 to promote multi-purpose SMRs integrated into hybrid energy systems as reliable, resilient, and affordable clean energy options in Europe for electricity, heat and hydrogen production. The project focuses primarily on light-water SMR technologies for near-term deployment in Europe by 2030's, but also aims to support the deployment of Advanced Modular Reactors (AMRs) of Generation IV by 2050. The intrinsic key feature of the TANDEM project is the development of an integrated vision of the low-carbon energy mix on a local spatial scale (e.g., an urban area or an industrial area).

## Goals and stakes of the SMR integration into Hybrid Energy Systems (HES)

Nuclear energy, supported by SMR deployment, has a strong role to play in the energy transition. The main benefit of SMRs, compared with large reactors, relies on their hybridization with energy conversion systems and their integration into Hybrid Energy System at a local spatial scale.

Increasing the share of variable renewable energy sources, mainly wind and solar, with a view to decarbonizing energy, will lead to a need for energy flexibility to compensate for their intermittency and to ensure the electrical grid stability. Part of the required energy flexibility can be managed using batteries and tariff incentives offered by electricity suppliers. However, the use of nuclear energy, as a low-carbon and dispatchable production capacity can better offer to compensate these intermittencies. SMRs can be connected directly to a national electrical grid or inserted into microgrids. The latter solution can accelerate industry electrification and the construction of new energy infrastructure to meet rising electricity demand. Moreover, nuclear thermal energy can be used for many industrial processes consuming heat, and for hydrogen production too.

---

<sup>116</sup>: <https://tandemproject.eu/>

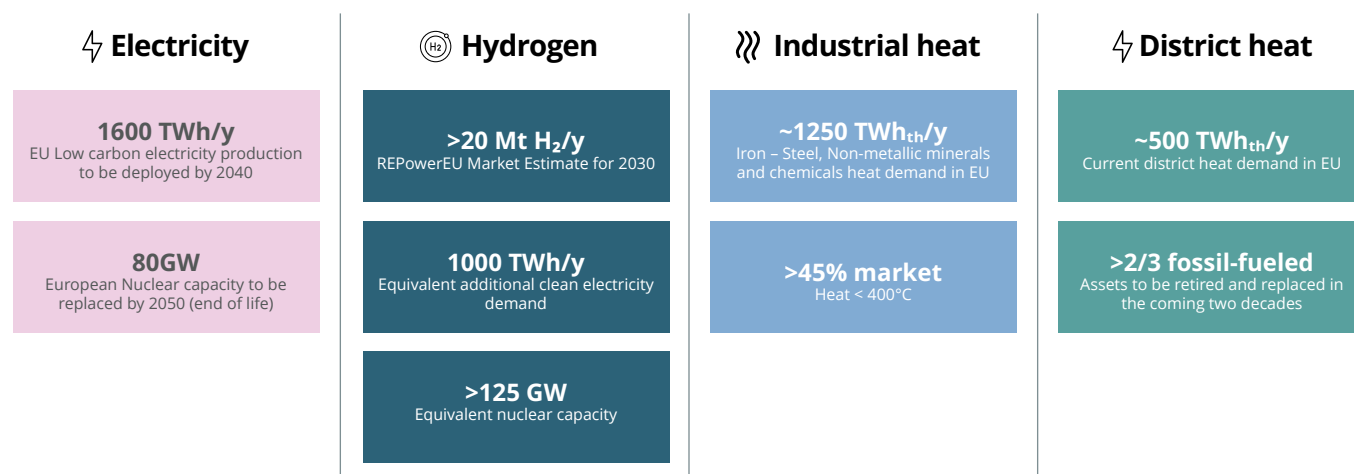


Figure 78: Energy market needs in EU

The overall demand for low-carbon electricity, heat and hydrogen is projected to be huge in the EU by 2050. Conventional hydrogen production methods (mainly steam methane reforming) accounted for 95.7% of total hydrogen production capacity in 2020. Concurrently, the hydrogen demand in the EU was estimated to be around 8.7 Mt the same year. The biggest share of hydrogen demand came from refineries (50% of total H<sub>2</sub> use ~4.4 Mt), followed by the ammonia industry (29% ~2.5 Mt).

The REPowerEU plan<sup>117</sup>, introduced by the European Commission in 2022, sets a target of 20 Mt of renewable hydrogen used by 2030 (half of which to be produced in the EU). Refineries, production of synthetic fuels and petrochemicals industries are planned to take a big share of this hydrogen demand but also other uses are now considered: production of industrial heat (3.6 Mt H<sub>2</sub> in 2030), transport (2.3 Mt H<sub>2</sub>), blast furnaces (1.5 Mt H<sub>2</sub>) and blending of hydrogen with natural gas (1.3 Mt H<sub>2</sub>). Producing 20 Mt H<sub>2</sub>/year, assuming power consumption of 55 kWh/kg H<sub>2</sub>, typical for low-temperature water electrolysis, implies using the equivalent electrical energy generated by 75 large EPR2 reactors (1670 MWe each) or 315 SMRs (400 MWe each). The deployment of large reactors and SMRs is complementary in the EU, since both types of reactors can be operated in cogeneration mode. The choice of nuclear plant size depends on the spatial scale envisaged for the energy use and the amount of needed energy.

## Assessment of the integration of SMRs into HES

The hybridization of SMRs with the development of an integrated vision of the energy system at a local scale requires addressing new R&D topics focused on:

- Economic viability of HES and their environmental impact,
- Nuclear safety addressing the coupling of SMRs with the rest of the HES, and in particular energy conversion applications and heat networks.

The development of a nuclear hybrid energy system follows a stepwise approach shown in Figure 3. Each level of the pyramid requires the development and implementation of dedicated tools and methodologies. The TANDEM Euratom project has developed tools and methodologies to assess HES feasibility, and implemented them on demonstrative study cases to contribute to meet net-zero emissions. To achieve this objective, the project has defined two hybrid energy system configurations to be studied, based on best-estimate projections of energy

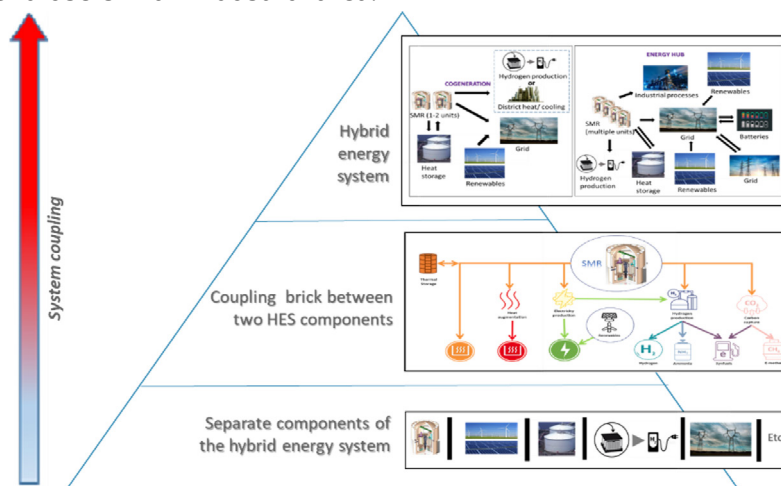
<sup>117</sup>: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN>

scenarios, consistent with the European policy of energy market evolution by 2050:

- A district heating configuration: this hybrid energy system is envisaged for district heating and power supply for a large urban area;
- An energy hub configuration: a HES concept where multiple energy carriers – heat, electricity and hydrogen can be converted, stored, and supplied for end-users in an industrial area.

The layouts of the hybrid energy system configurations are only intended to identify the key components to be considered in these systems, such as Combined Cycle Gas Turbines (CCGTs), district heating networks, hydrogen production with High Temperature Steam Electrolysers (HTSE) and Low Temperature Electrolysers (LTE).

Figure 79: Stepwise approach for the development of HES at local scale



Three different energy scenarios, progressively implementing low-carbon energy production solutions, have been considered in the decarbonisation studies:

- Business-as-usual: SMRs have not yet been introduced in HES. Only fossil fuel plants (corresponding to CCGT) and renewables provide energy. Hydrogen in the energy hub is produced by the conventional method (Steam Methane Gas Reforming);
- Start of SMR deployment in EU: half energy production by CCGT has been replaced by SMR production, for both configurations. Hydrogen in the energy hub is produced by electrolysis;
- Net-zero emissions: the main CCGT production has been replaced by low-carbon energy sources. Different options have been tested, in particular the replacement of all CCGTs by SMRs. Hydrogen in the energy hub is produced by electrolysis.

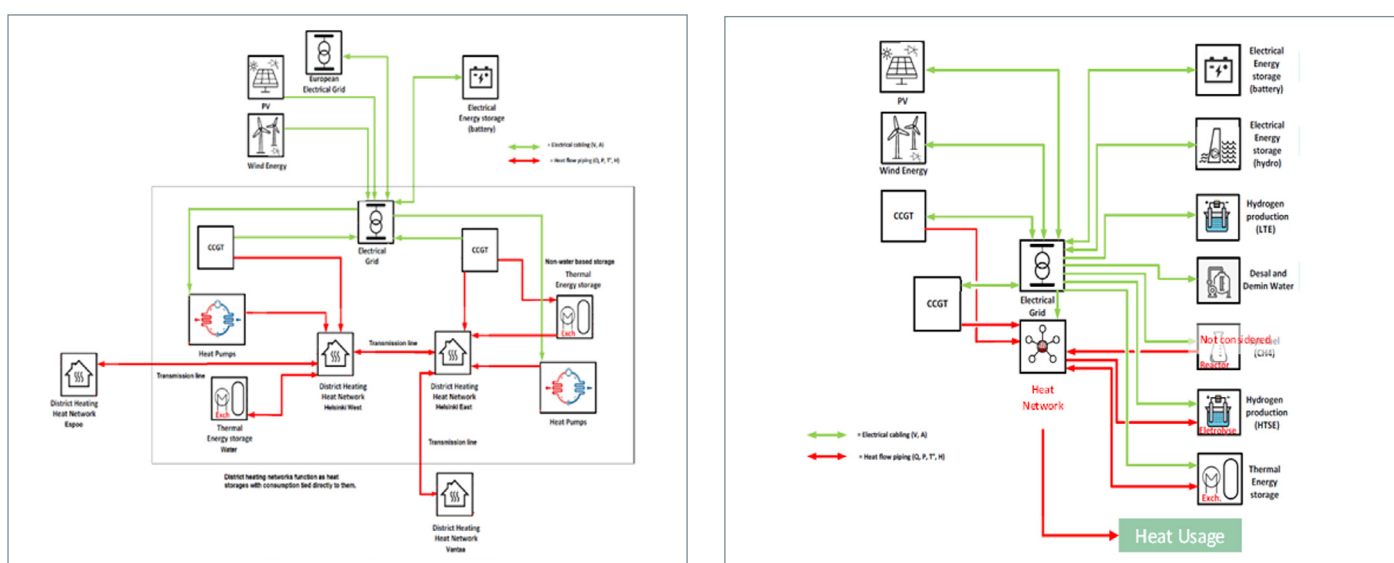


Figure 80: Conceptual layout of the hybrid energy systems configured by TANDEM: on the left, District Heating Configuration; on the right, Energy Hub Configuration (business-as-usual energy scenario)

The TANDEM project has defined three study cases to assess the economic viability of HES integrating SMRs to supply electricity, heat and hydrogen. An illustration of the assessment, relying on a process of techno-economic optimization under environmental constraints, is provided in this section.

## Description of the study cases

The three study cases have been derived from the two hybrid energy system configurations presented in the upper figure. These cases have been set up with a demonstration objective, as R&D studies for the needs of the TANDEM project, and are not intended to define future plans for energy decarbonization in the area under consideration, nor the construction of nuclear power sources.

The choice of heating solutions depends on the specific regional context (natural resources, geography, climate, energy markets and policies, industry) in which district heating is used. District heating is of particular interest in Northern and Central Europe. Two study cases of the district heating configuration have been characterized in TANDEM: the Northern European case and the Central European case. The Northern European case concerns a district heating system in the metropolitan area of Helsinki, in Finland, which includes the large cities of Espoo (population of 293,000) and Vantaa (population of 237,000). This district heating system needs to be decarbonized. Each city has separate companies responsible for district heating production: Helen Ltd. in Helsinki, Fortum Ltd. in Espoo, and Vantaa Energia Ltd. in Vantaa. The district heating networks of Espoo and Vantaa are connected to the Helsinki district heating network with limited transfer capacity. At present, district heating supply in Helsinki and Espoo relies on natural gas, biomass and increasing quantities of heat pumps, the first two posing long-term problems. In Vantaa, municipal waste plays a significant role in the energy production.

The aim of the Central European case study is to propose i) possible ways to replace existing coal heat sources by low-emission energy sources and reduce polluting emissions, and ii) the assessment of the hydrogen production potential for industrial applications – with the establishment of a “Hydrogen valley” on a selected model case in the Moravian-Silesian region in the Czech Republic. In fact, this region is highly industrialized with high CO<sub>2</sub> emissions. The most significant carbon-emitters are mainly large stationary sources, such as iron and steel industry, coal power plants and heating plants. In the entire Moravian-Silesian region, over 214,000 households are supplied with heat from district heating. In total, there are 1238.9 km of heating networks in the area, including:

- 137.9 km for steam distribution (max. 240°C, max. 1.8 MPa),
- 429.5 km for hot water (max. 180°C, max. 2.5 MPa),
- 671.5 km for warm water (max. 110°C, max. 1.6 MPa).

The study case for the energy hub configuration is inspired from a harbour-like infrastructure. In Europe, there are several examples of industrialized harbours, which are responsible for a significant proportion of CO<sub>2</sub> emissions and are engaged in a process of decarbonization. To give an example, the port of Rotterdam is the first European port considering the Twenty-Foot Equivalent (TFE) criteria<sup>118</sup>, with 14.5 TFE in 2020, and it is responsible for about 20% of the national CO<sub>2</sub> emissions of the Netherlands. Furthermore, the French industrial port zones of Dunkirk and Fos-sur-Mer are also involved in a decarbonation process, betting on new hydrogen uses. They are the winners of the "low-carbon industrial zones" call for projects launched as part of the France 2030 plan<sup>119</sup>. The port of Dunkirk contributes to 21% of the French

<sup>118</sup>: It is a general unit of cargo capacity, often used for container ships and container ports

<sup>119</sup>: With a budget of €54 billion, France 2030 is an Investment Plan aiming to sustainably transform the key sectors of the French economy (energy, automotive, aeronautics or space) through research, innovation and industrial investment. 50% of France 2030's credits will be dedicated to emerging stakeholders with environmentally friendly innovations, and 50% to decarbonise the economy.

CO<sub>2</sub> emissions due to its industrial sector. It has been involved in the energy transition for years and, in 2018, the “Toile énergétique®”<sup>120</sup> of this region has been released. This “Toile énergétique®” is a representation of the energy ecosystem of the territory. It makes it possible to identify macroscopically the resources and energies imported, produced, converted and exchanged inside this territory and with other territories. Thanks to this representation, it is possible to get an idea of the global energy flows in the region. However, due to the difficulties of accessing detailed energy flow characteristics across several industrial plants in the European ports, which are required to define an energy hub configuration to be studied in the TANDEM project, it was decided to arbitrarily set constant loads of hydrogen and electricity<sup>121</sup> to be produced in the South of France for the definition of the study case.

The benefit of integrating SMRs in these three study cases has been analysed, starting from the current initial architecture of the study cases relying on a “business-as-usual” energy scenario, and replacing progressively fossil fuel plants by low-carbon energy sources, in particular SMRs and renewables, so as to decarbonize the system. The Backbone and PERSEE tools, developed by VTT and CEA, respectively, have been implemented to analyse the three study cases. They are based on a Mixed Integer Linear Programming (MILP) formalism meaning that the optimization problem is described thanks to an objective function, linear constraints and binary variables. The objective function can be the maximization of the Net Present Value, the minimization of the total costs or of CO<sub>2</sub> emissions for instance. This process leads to an assessment of an optimal sizing of HES components. Most of the techno-economic and environmental data used in the optimizations come from open literature (peer-reviewed papers, OECD/NEA and IAEA documents, etc.).

## Techno-economics assessment and environmental impact

The Northern European case was studied using the Backbone code, with a city-level model of the studied area. Thus, only units within the Helsinki metropolitan area were included in the model. Furthermore, the SMR investments were studied from the perspective of the district heating operator, focusing on satisfying the heat demand and selling electricity when the electricity prices exceed plant operating costs. As a simplification, the study case does not take into account the services rendered to the electricity grid by SMRs or their remuneration. Additionally, electricity balance is not modelled in the Northern European case. Instead, the model uses time series data of electricity price.

SMRs showed promise for decarbonizing the Helsinki metropolitan area. From the perspective of a district heating operator whose priority is to produce heat as a baseline, small heat only units like LDR-50 allow profitability to be found in the context of the Helsinki area. The high seasonal variability in energy demand and the relatively low electricity prices in the studied area posed challenges for profitability of the larger European SMR (E-SMR)<sup>122</sup>. The LDR-50, a 50 MWth heat-only boiler SMR, is exclusively designed for district heat generation. In contrast, E-SMR, with 540 MWth/170MWe total power, generates mostly electricity and was assumed to utilize 10% of its thermal energy to district heating, thus requiring a more favorable electricity market to be profitable, under the taken assumptions for key economic features.

For the Central European case, the optimisation calculations have shown the potential to decarbonize the production of district heating, electricity and hydrogen with the use of SMRs, LTE for hydrogen production and renewable

<sup>120</sup>: [https://www.wizodo.fr/photos\\_perso/agur/DocumentsPublications/Cahier\\_Toile-energie-MAI2018\\_OK.PDF](https://www.wizodo.fr/photos_perso/agur/DocumentsPublications/Cahier_Toile-energie-MAI2018_OK.PDF)

<sup>121</sup>: 72.3 kTons of hydrogen and 657 GWh of electricity per year, as a baseline, but which can easily be scaled up.

<sup>122</sup>: The E-SMR concept was characterized in the framework of the Euratom ELSMOR project (<http://www.elsmor.eu/>). The E-SMR data set is open-source and available at <https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1>

energy (solar and wind). Whereas in the business-as-usual energy scenario the hydrogen production emits at least 8 times more CO<sub>2</sub> than the EU Taxonomy threshold<sup>123</sup>, in the decarbonisation scenarios implementing SMRs, the required threshold for sustainable hydrogen production is reached with a large margin. Demonstrative results of the Central Europe case could be easily valorised for decarbonizing other similar territories, such as Silesian Voivodeship in Poland or Žilina self-governing region in the Slovak Republic.

The third study case for the energy hub configuration is inspired from a harbour-like infrastructure. It is presented in §7 of this document.

## Conclusions & Policy Briefs

The TANDEM project has provided methodologies and tools for the technical assessment of Hybrid Energy Systems (HES) and implemented them on demonstrative case studies of energy systems to be decarbonized. As a conclusion, it released policy briefs for policy-makers at different levels (European, national, local) and technical guidelines – for the industrial and R&D communities. They are summarized in §7 of this document<sup>124</sup>.

---

<sup>123</sup>: The EU Taxonomy threshold for sustainable hydrogen manufacturing corresponds to 3 kg CO<sub>2</sub> eq/kg H<sub>2</sub>

<sup>124</sup>: J. Johnson et al., “Policy briefs for policymakers and end-users”, TANDEM Deliverable WP5 – D5.1, 2025, [https://tandemproject.eu/wp-content/uploads/2025/06/D5\\_1\\_policy\\_briefs\\_for\\_policymakers\\_and\\_end\\_users\\_V1.pdf](https://tandemproject.eu/wp-content/uploads/2025/06/D5_1_policy_briefs_for_policymakers_and_end_users_V1.pdf)

## ANNEX 5

# The six Generation IV Systems

## GFR

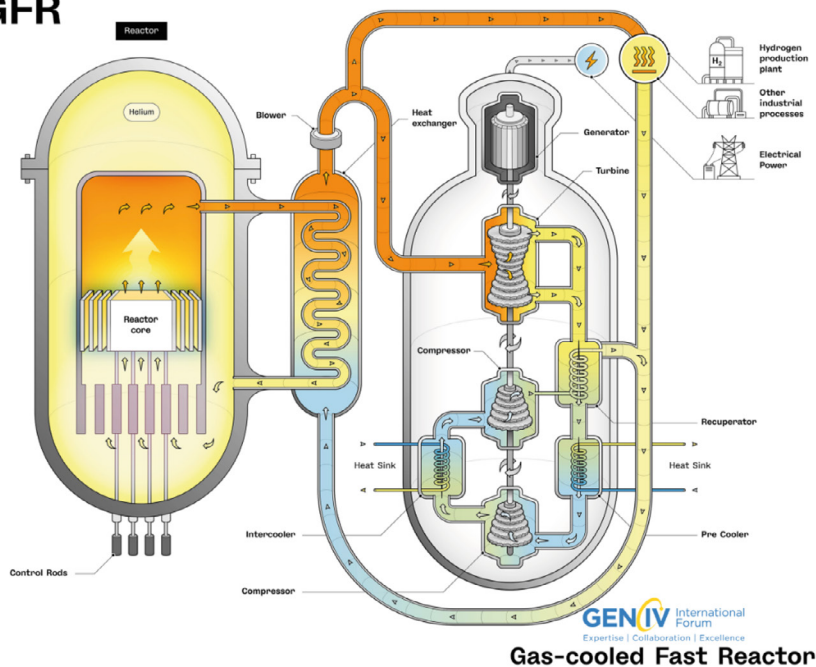


Figure 81: Gas Fast Reactor

## LFR

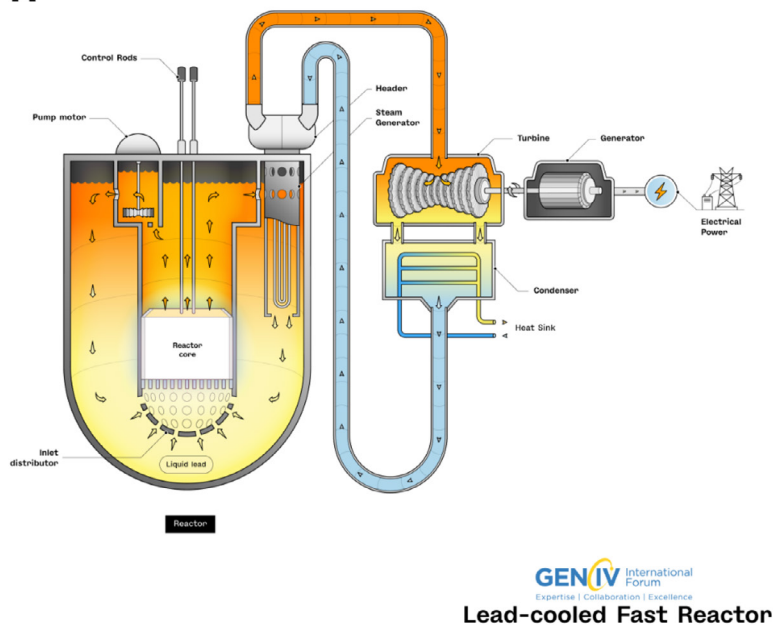


Figure 82: Lead Fast Reactor

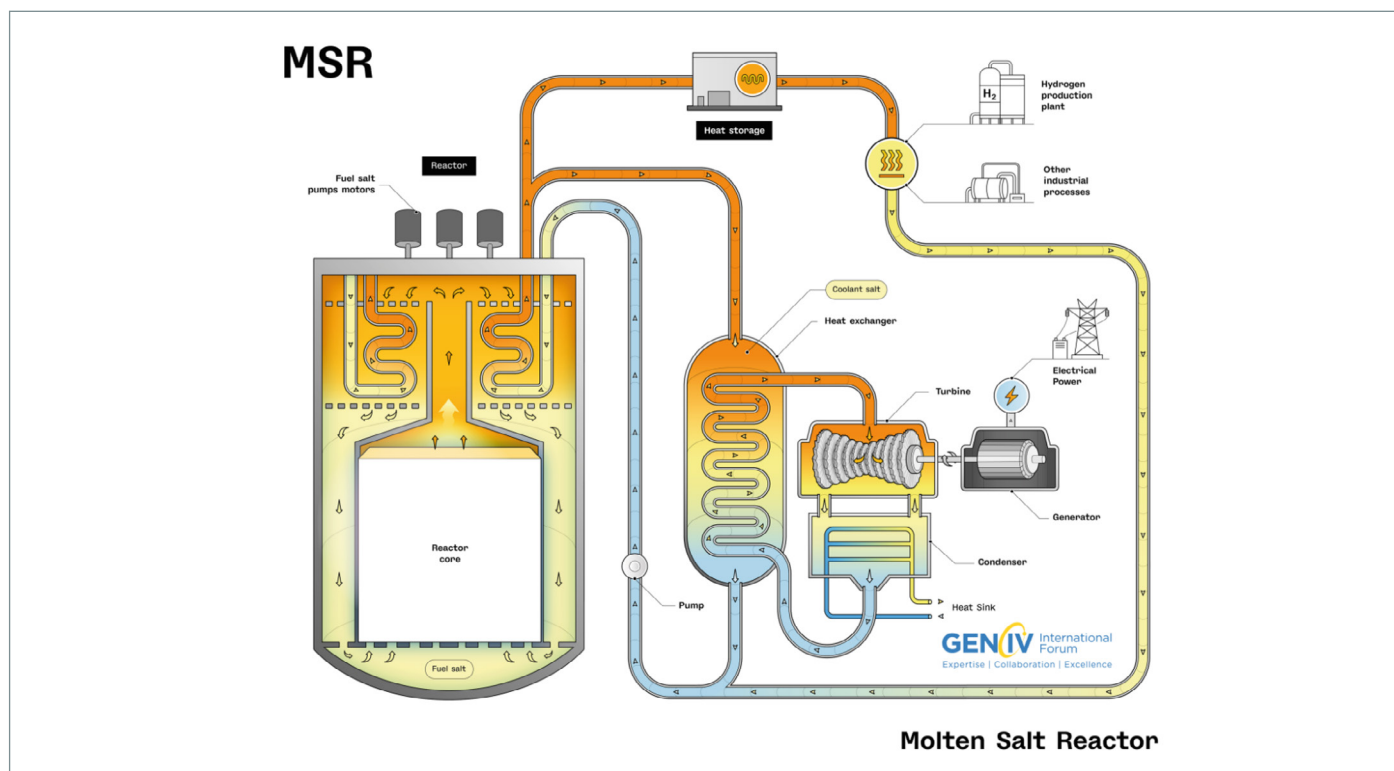


Figure 83: Molten Salt Reactor

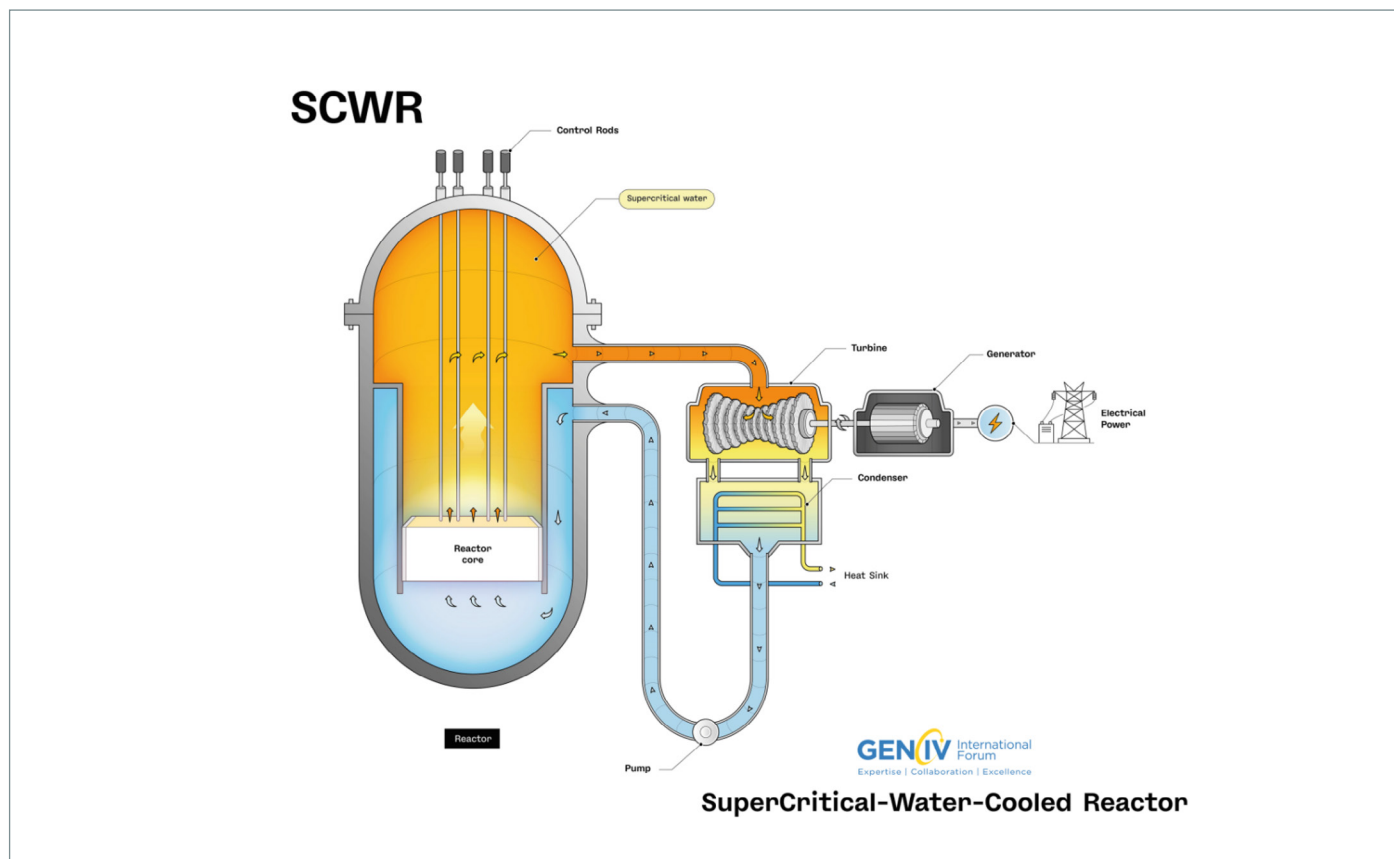


Figure 84: SuperCritical Water Reactor

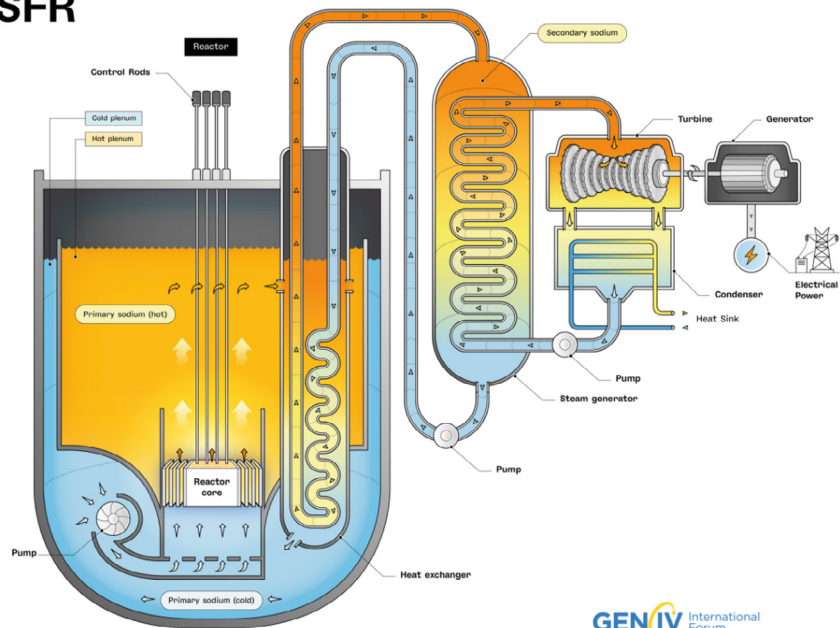
**SFR****Sodium-cooled Fast Reactor**

Figure 85: Sodium Fast Reactor

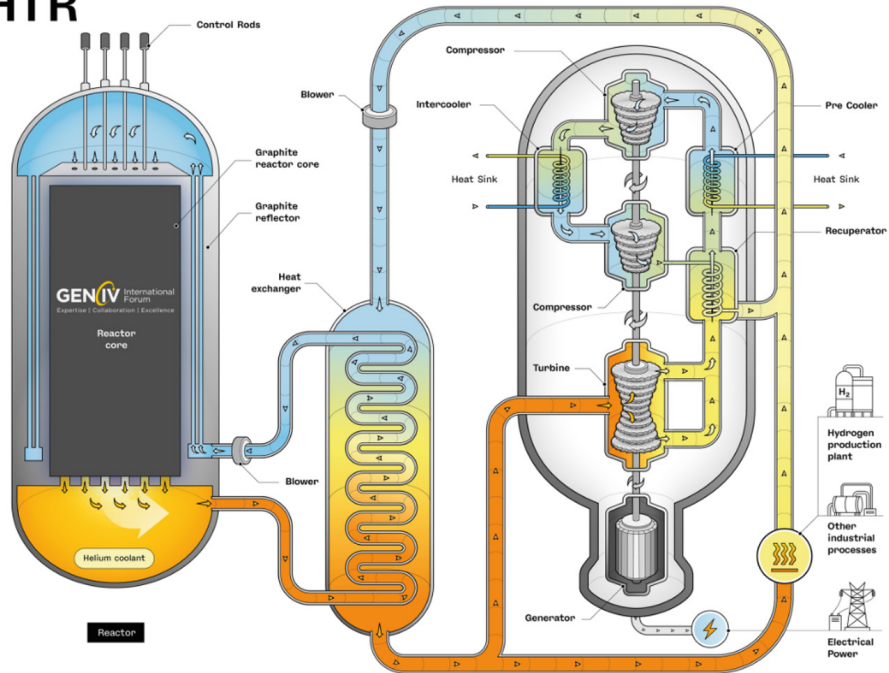
**VHTR****Very-High-Temperature Reactor**

Figure 86: Very High Temperature Reactor

## ANNEX 6

# “H<sub>2-be</sub> or H<sub>not-2-be</sub>” – Decarbonation of industrial uses in Europe

This Annex is extracted from a specific study carried out by TerraWater, member of Task #44.

For any innovative process, such as hydrogen production from nuclear, to succeed, it needs to convince its ecosystem to invest the necessary resources to secure their development for as long as their time-to-market requires, which often means on the long term. These investments are of financing nature of course, but not only: time allocated to education and training, public authorities support, regulators consideration, industry confidence and support for the establishment of new industrial lines, public acceptance etc. all things that many other innovative products and services compete for as well.

Convincing these investors to care often means one thing: secure market niches that will guarantee a minimum outlet to the product, independently of what the future industrial landscape will look like.

We propose to evaluate the need for hydrogen in two very different categories of energy systems, that each reflects existing though opposed philosophies of what an energy landscape at country level could look like, as a way to assess its future attractiveness.

The most relevant industrial uses for hydrogen as an energy vector can vary depending on the local energy context of the country where the project is planned. The variability lies in the strong competition between the superior intrinsic efficiency of direct electrification versus the flexibility that hydrogen can provide, thanks to its ability to decouple energy production from energy consumption through storage.

Direct electrification provides a 30% (high temperature) to 70% (low temperature) gain over the use of gas as heating fuel, and up to a 50 - 80% gain when the primary electricity needed to produce the hydrogen is added to the equation. However, though it is a very efficient energy carrier, it is also a rigid one because of its difficulty to be stored – even more problematic when the fastest growing technologies expected to produce it – namely photovoltaic and wind power – don't provide firm power while industries put high value in a steady supply.

Two extreme cases can thus be distinguished:

1. In electric systems where a strong base of electricity production can provide a reliable flow of power, direct electrification allows to make the most efficient use of the energy produced and keep prices low by skipping the energy hungry step of hydrogen production. This reasoning also applies to grids with an important share of nuclear power, but also those with massive reservoir hydropower capacities to buffer the renewable output (Norway, South America, etc.), or arid/desertic areas where a few hours of battery storage are enough to firm large solar farms (Saharan and sub-Saharan Africa, Persian Gulf, etc.). In this case, hydrogen requirements as a vector may dwindle to the lowest levels.
2. In electric systems facing very high production volatility, a trade-off between efficiency and flexibility must be found. Indeed, as industries need baseload power, direct electrification would require a very large amount of backup dispatchable electricity production to fill the supply gaps left by renewables. At such scale, in absence of fossil fuel and no batteries being able to scale up to the required level, this backup electricity would have to be generated by burning hydrogen, whose production would itself and in addition require three and half times

the amount of electricity. Such a scheme quickly becomes unsustainable by its sheer size and overcapacity as soon as the backup electricity to be generated exceeds a few percent of total generation.

This situation is expected to be encountered in systems based on a very high share of intermittent power with strong seasonal mismatch (inadequate balancing of solar and wind) and lacking natural large reservoir hydropower assets. In this case, hydrogen requirements as vector may rise to the highest levels. But the important losses caused by the water electrolysis will still induce a huge consumption penalty at system scale. This is what can be seen on the following figures that show two possible outcomes for a scenario with 100% renewables based on Germany data. Despite being slightly less power hungry, the first case (hydrogen path) remains extremely energy-intensive, in such ways that its sustainability and feasibility appear questionable.

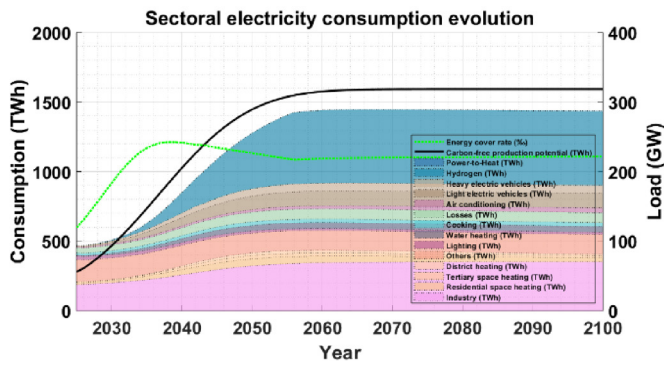


Figure 87: Germany scenario's sectoral electricity consumption with green-hydrogen based of industrial

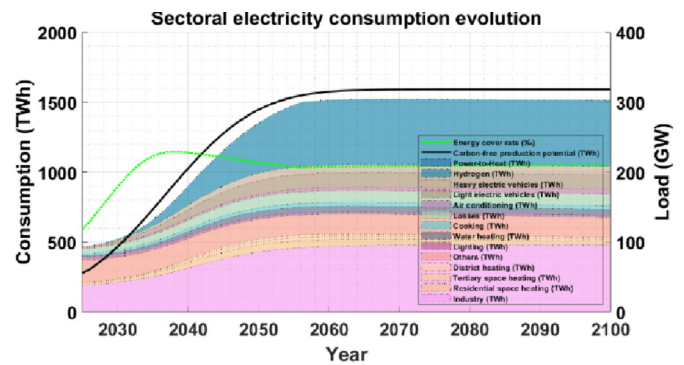


Figure 88: Germany scenario's sectoral electricity consumption with direct electrification of industrial

Which category an industrial process falls within is a matter of whether the efficiency difference between hydrogen and direct electrification lies below a certain threshold, dependent on the location. This threshold – marking the point where one option shows lower system-level energy requirements as compared to the other – can be estimated following relatively simple assumptions. For a constant industrial load, the use of hydrogen becomes more interesting when the following equation is satisfied:

$$\tau_E \geq \frac{\left( \frac{1}{\eta_{\text{Electrolysis}} \cdot \eta_{\text{H}_2\text{storage}}} - \eta_{\text{H}_2\text{Useful}} \right) \cdot \eta_{\text{GasTurbine}}}{\left( \frac{1}{\eta_{\text{Electrolysis}} \cdot \eta_{\text{H}_2\text{storage}}} - \eta_{\text{GasTurbine}} \right) \cdot \eta_{\text{Useful}}}$$

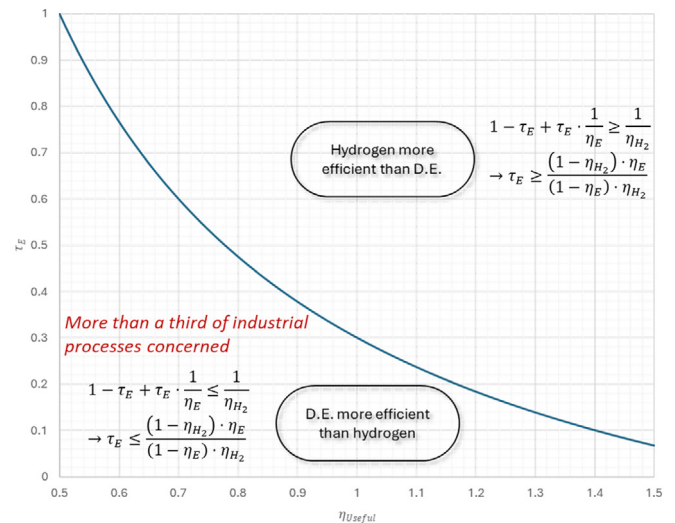


Figure 89: Hydrogen vs Direct Electrification

The upper Figure leads to the following conclusion: **direct electrification requires less energy at system level whenever backup electricity production provides less than 30% of the electricity used for the industrial process**. In most efficient and integrated energy systems, the amount of electricity coming from hydrogen fired power station should stay well below 10%, making direct electrification more interesting over a broad range of efficiency ratios, and so, in a large panel of countries. If the firmness of decarbonation policies is considered granted and hence price and availability of fossil fuels do not weigh in as an alternative, the importance of location hence becomes paramount.

This importance can additionally be exacerbated by the level of (in)stability of the country energy landscape depending on how much political weight energy issues carry culturally. As recent history has shown, country energy choices can shift and reverse in a handful of years. Above all, this competition between electricity and hydrogen only exists if substituting one with the other is an available and desirable option all other considerations included (subsidies, market behaviors etc.). Innovative hydrogen production technologies thus must absolutely seek captive uses of hydrogen where it is required as a bonded chemical reagent, where it is not substitutable. If nuclear-based hydrogen production technologies want to rely on sustainable in-time, high guarantee, likely high-profitability markets on which to base their argumentation for development, they should give priority to these captive uses: ammonia for fertilizers, aviation E-fuels... The market for hydrogen as a molecule not being correlated to that of hydrogen as a vector, the superiority of nuclear-based hydrogen can then be assessed simply thanks to the respective competitiveness level of energy sources available to produce hydrogen, which in 100% low carbon energy systems nuclear should often dominate (i.e. except in context with high shares of hydro or geothermal).

## ANNEX 7

# The HyNE prospective analysis

To complement the graph presented in **Insert 13** (repeated below), the following table completes the prospective analysis.

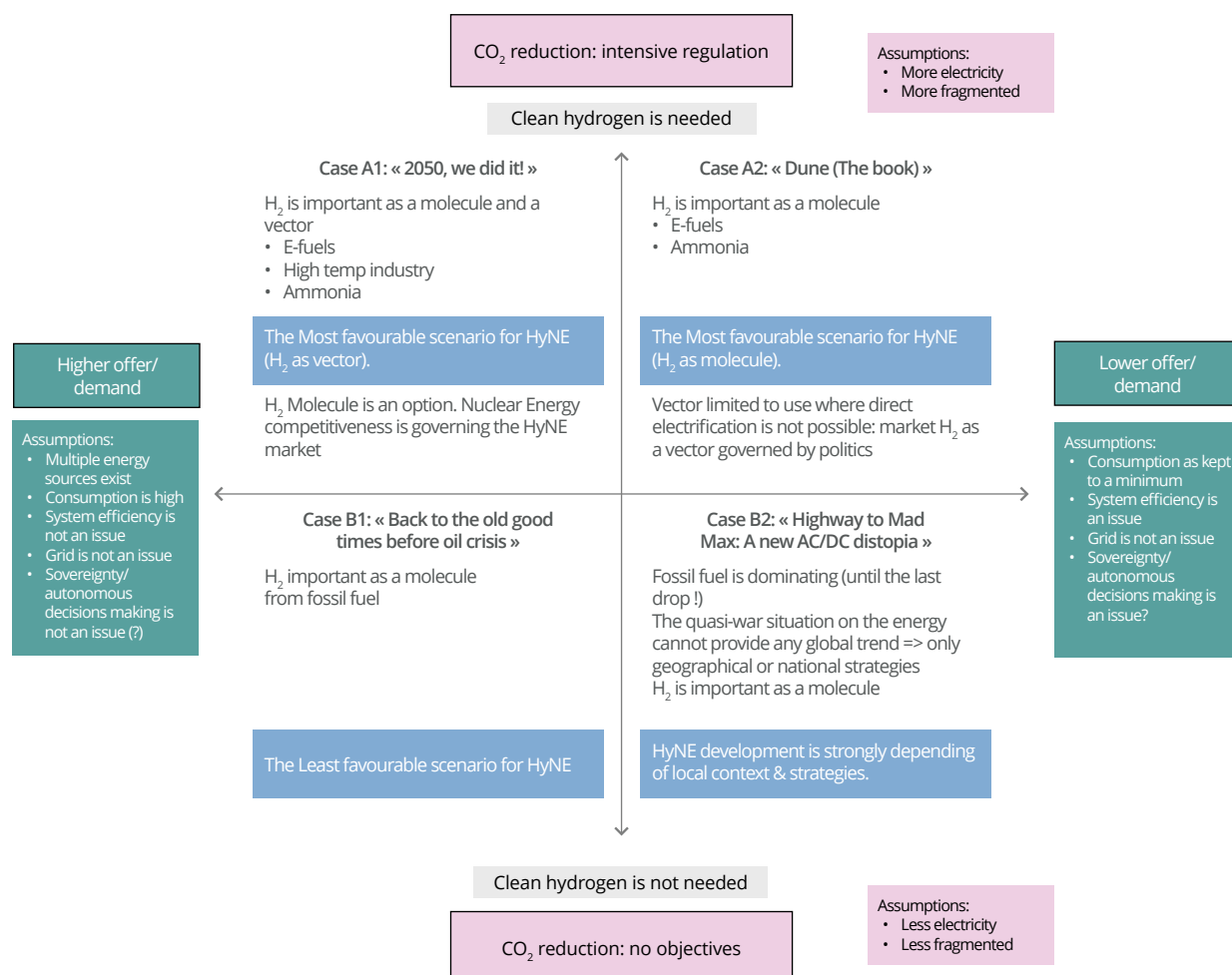


Figure 90: Synthesis of the prospective analysis for HyNE in four different world scenarios

Table 4: The matrix of solutions to produce hydrogen with nuclear energy and the preselected cases

| "2050 We did it!"                                                                                                                                                                                                                                                                                                                         | "Dune"                                                                                                                                                                                                                                                                                                                                |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Assumptions: cheap clean energy not evenly distributed in time and space.</p> <p><b>Market characteristics</b></p> <ul style="list-style-type: none"> <li>• The supply of fossil-free power production is extensive and cheap.</li> <li>• E-fuels/SAF is produced in high amount and to costs that outperform fossil fuels.</li> </ul> | <p>Assumptions: Policy/incentives drives the market.</p> <p><b>Market characteristics</b></p> <ul style="list-style-type: none"> <li>• There is a lack of fossil free power production.</li> <li>• E-fuels/SAF do not outperform fossil fuel.</li> <li>• Oil is still important.</li> <li>• Efficiency is a key parameter.</li> </ul> |

- Oil is no longer the black gold, conflicts move towards other countries, wealth moves to actors/ countries strong in end products (B2C).
- The need for storage and hydrogen as a vector increase.
- Flexibility is important, the one that can adopt and use high amounts of power when prices are negative wins.
- Energy efficiency not important.

#### Business characteristics

- Low profits for power producing companies. High capex costs are challenging.
- Traditional energy actors seek to understand and take control of more of the value chain.
- Steel, cement, chemical industry decarbonised. Industry follows lowest cost for electricity. Production is governed progressively more by electricity prices rather than on demand.

#### Consumer characteristics

- Low cost and clean electricity give incentives to use more power, which means more consumption.
- Consumption cannot be evenly distributed during the day/month/year unless balancing mechanisms, storages are present.
- Storage/balancing mechanisms will be present.

#### HyNE

- Nuclear important.
- Hydrogen as a vector not important.
- Hydrogen as part of an end product could be important.

#### Business characteristics

- Electricity is expensive and only used where there is a high total efficiency.
- Profit can be found in each step of the value chain.

#### Consumer characteristic

- Consumption is expensive, likely less consumption.

#### HyNE

- Nuclear important.
- Hydrogen as a vector not important.
- Hydrogen as part of an end product could be important.

### "Back to the good old days before oil crisis"

#### Market characteristics

- There is a lack of fossil free power production.
- E-fuels/SAF could outperform fossil fuel.
- Oil is not important.
- Efficiency is not important.

### "Mad Max"

#### Market characteristics

- There is a lack of fossil free power production.
- E-fuels/SAF does not outperform fossil fuel.
- Oil is still important.
- Efficiency is a key parameter.

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>Business characteristics</b></p> <ul style="list-style-type: none"> <li>• Electricity is expensive and only used where there is a high total efficiency.</li> <li>• Profit can be found in each step of the value chain.</li> </ul> <p><b>Consumer characteristic</b></p> <ul style="list-style-type: none"> <li>• Likely consumption increased.</li> </ul> <p><b>HyNE</b></p> <ul style="list-style-type: none"> <li>• Nuclear not important</li> <li>• Hydrogen as a vector not important.</li> <li>• Hydrogen as part of an end product not important.</li> </ul> | <p><b>Business characteristics</b></p> <ul style="list-style-type: none"> <li>• Electricity is expensive and only used where there is a high total efficiency.</li> <li>• Profit can be found in each step of the value chain.</li> </ul> <p><b>Consumer characteristic</b></p> <ul style="list-style-type: none"> <li>• Consumption is expensive, likely consumption decreases.</li> </ul> <p><b>HyNE</b></p> <ul style="list-style-type: none"> <li>• Nuclear important.</li> <li>• Hydrogen as a vector not important.</li> <li>• Hydrogen as part of an end product could be important.</li> </ul> |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

## ANNEX 8

## e-reputation all along the Task #44 duration

The e-reputation<sup>125</sup> action of Task #44 was launched on February 2023 (point-0) until end Q1 2026. This study was not limited to Task #44, but also focused on the Hydrogen TCP and on the topic of nuclear energy as a whole.

### Press

The Task's specific work didn't get standalone media attention, so public perception tends to be shaped by broader discourse on hydrogen economics and nuclear's role in energy transitions. The Task #44 has been mentioned only once in the French press.

« La 'tâche 44' de l'Agence internationale de l'énergie (AIE) s'intitule HyNE, pour HYdrogen from Nuclear Energy. Cette agence regroupe beaucoup de pays européens, en particulier ceux qui ont une industrie nucléaire importante », Le Point n°2690, p. 26, 22 février 2024.

[https://www.lepoint.fr/sciences-nature/la-revolution-hydrogene-va-t-elle-faire-pschitt-26-02-2024-2553407\\_1924.php](https://www.lepoint.fr/sciences-nature/la-revolution-hydrogene-va-t-elle-faire-pschitt-26-02-2024-2553407_1924.php)

### Website traffic monitoring

The following graph produced with [SE ranking](#) shows the traffic since January 2023 on the [ieahydrogen.org](#) domain. Analysis of traffic on the task's website was not possible because the task does not have its own website but is part of the hydrogen TCP website (ieahydrogen domain). The tools used for this study did not allow the analysis of a subdomain of a website.

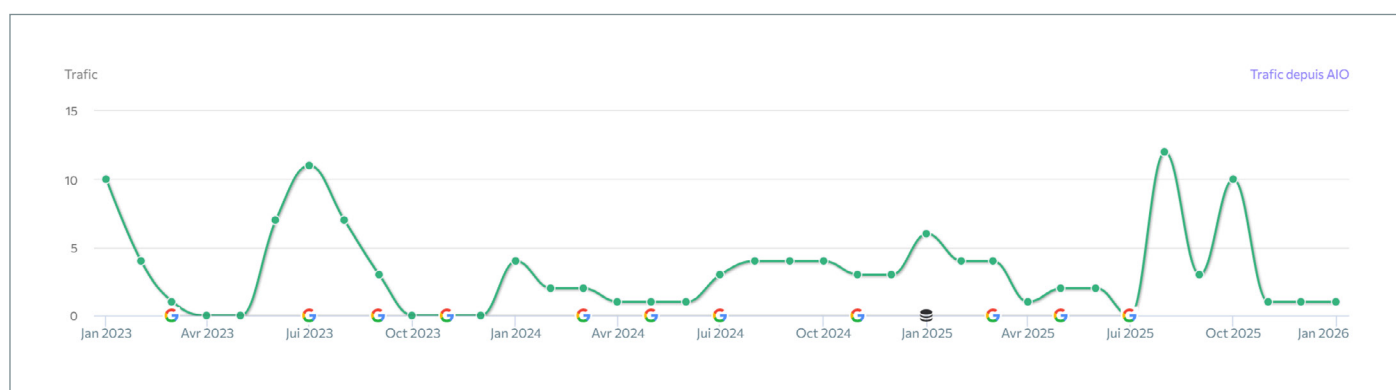


Figure 91: Traffic since January 2023 on the [ieahydrogen.org](#) domain (Y axis is read in hundred)

The notable increases in traffic to [ieahydrogen.org](#) in July 2023, August 2025, and November 2025 coincide with several key developments in the low-carbon hydrogen landscape. In July 2023, the IEA published the Global Hydrogen Review 2023, an annual analysis of hydrogen markets, demand, and low-emission production that attracted broad stakeholder interest. In August 2025, attention was growing in advance of the Global Hydrogen Review 2025,

<sup>125</sup>: e-reputation means the digital image of a person, a company or a product on the Internet. This asset is essential for the company. On average, at least 25% of a company's value is linked to its reputation, according to a study by the World Economic Forum.

accompanied by preparatory announcements and sector events highlighting hydrogen innovation and policy progress. Finally, in November 2025, the Hydrogen TCP celebrated its 100<sup>th</sup> Executive Committee (ExCo) Meeting, marking a major institutional milestone, and the EU Hydrogen Research and Innovation Days brought hydrogen research and innovation into sharp focus in Brussels. These high-visibility reports and events help explain the traffic peaks, even though specific Task #44 outputs may not have been individually published at those exact times.

## Internet

The following graph shows search trends for the search terms “nuclear hydrogen” (in blue) and “hydrogen from nuclear energy” (in red) from February 2023 to present. The Google search traffic trends for the queries “**nuclear hydrogen**” and “**hydrogen from nuclear energy**” appear to correlate with the spikes in visitor traffic observed on the Hydrogen TCP website.

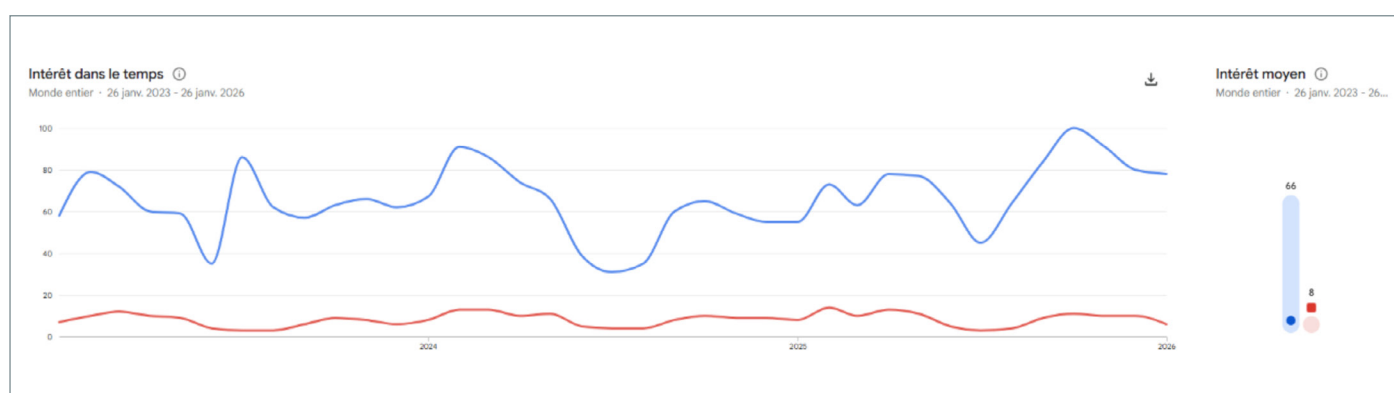


Figure 92: Search trends for the search terms “nuclear hydrogen” (in blue) and “hydrogen from nuclear energy” (in red) from February 2023 to present (Y axis is read in hundred)

## Social media: LinkedIn Posts

HyNE seems to have a fairly low presence on LinkedIn. Members of Task #44 are quite active and post regularly on the network. Since February 2023, we counted a little over 30 posts on LinkedIn about Task #44. The search was performed on the basis of the use of the following terms: Task #44, IEA, nuclear hydrogen, IEA Hydrogen TCP.

Gilles Rodriguez, IEA Hydrogen TCP and Rami El-Emam are the accounts that have posted the most on this initiative. The other posts come mainly from members of the task force.

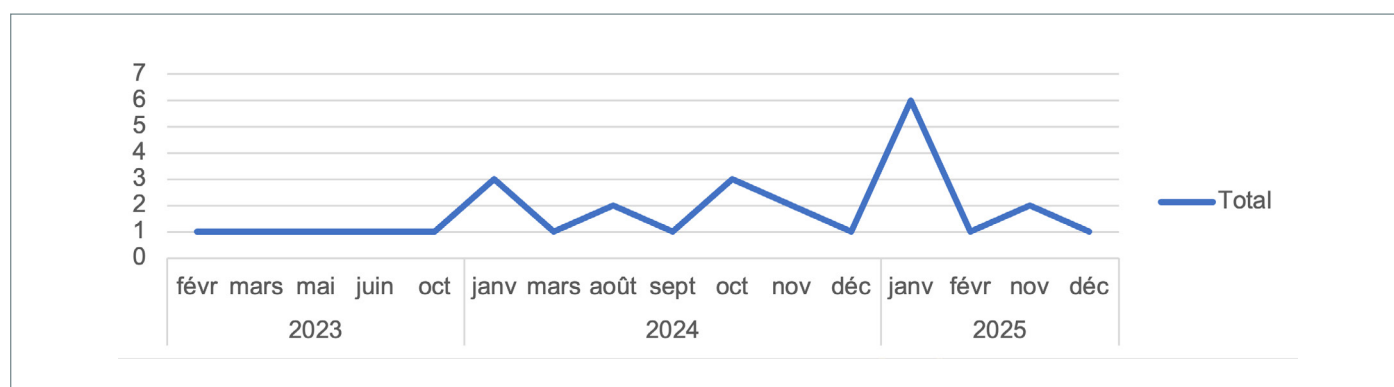


Figure 93: Number of LinkedIn posts from January 2023 to December 2025 (Y axis is read in hundred)

## Publications and conferences

Task #44 has been cited or has been mentioned in many presentations and reports. These internal meetings, international conferences and reports are listed here.

### Internal meetings / 2022

New Tasks perspective – Nuclear Hydrogen, IEA – Technology Collaboration Program, March 29<sup>th</sup>, April 14<sup>th</sup> & 20<sup>th</sup>, 2022, Gilles Rodriguez (CEA, DES/IRESNE/DER), <https://cea.talkspirit.com/#/l/drives/xvowj4?clip=all&parent=63e10f4fc309f13b7a0160de&type=drive>

### Internal meetings / 2023

First in-person meeting of Task #44 : Hydrogen from Nuclear Energy, IEA – Task #44, Marseille (France), April 25-27<sup>th</sup>, 2023, [https://www.ieahydrogen.org/blog\\_post/first-in-person-meeting-of-task-44-hydrogen-from-nuclear-energy-in-marseille-from-april-25th-to-27th/](https://www.ieahydrogen.org/blog_post/first-in-person-meeting-of-task-44-hydrogen-from-nuclear-energy-in-marseille-from-april-25th-to-27th/)

Task #44 Update. HyNE: Hydrogen from Nuclear Energy, IEA - 93<sup>rd</sup> ExCo Meeting Casablanca (Morocco), June, 29<sup>th</sup>, 2023, Gilles Rodriguez (CEA, DES/IRESNE/DER), <https://cea.talkspirit.com/#/l/document/648b26028d7577327756d5df?type=slide>

### Internal meeting / 2024

- Task #44 Report. HyNE: Hydrogen from Nuclear Energy, IEA – 97<sup>th</sup> ExCo Meeting, Vienna (Austria), March 20<sup>th</sup>, 2024, Gilles Rodriguez (CEA, DES/IRESNE/DER)
- Second in-person meeting of Task #44, IEA – INL, Idaho Falls (USA), January 22-25<sup>th</sup>, 2024
- Third in-person meeting of Task #44, Co-embedded G4SR5, Ottawa (Canada), October 1-4<sup>th</sup>, 2024
- Fourth in-person meeting of Task #44, Co-embedded “Codes & Standards for hydrogen systems coupled with nuclear energy” hosted by Walter Tosto, Chieti Scalo (Italy), 28-30<sup>th</sup> October, 2024

### Internal meeting / 2025

- Fifth in-person meeting of Task #44, Co-embedded Second Nuclear and Hydrogen Workshop, Paris (France), January 21-23<sup>rd</sup>, 2025.

## Conferences and webinars

This section lists the various presentations delivered over the past three years by HyNE members at international conferences.

### 2023

- The role of hydrogen from nuclear energy to support clean energy transitions, IAEA, Webinar “Hydrogen Production with Operating Nuclear Power Plants the Business Case”, March 23<sup>rd</sup>, 2023, [https://www.iaea.org/sites/default/files/24/01/hydrogen\\_production\\_v2.pdf](https://www.iaea.org/sites/default/files/24/01/hydrogen_production_v2.pdf)
- Hydrogen production with Nuclear Energy: the CEA approach through the IEA/Hydrogen frame and CEA studies on coupling a PWR SMR with HTSE, Hybrid Consultancy Meeting on Advances on High Temperature Water Splitting Processes with Emphasis on HTSE for Near Term Deployment of Nuclear Hydrogen Production,

Vienna (Austria), March 28-30<sup>th</sup>, 2023, Gilles Rodriguez (CEA, DES/IRESNE/DER), <https://cea.talkspirit.com/#//document/654e24ef3eb4e95f6309ede3?type=slide>

- Les SMR au service de la decarbonation : Du réacteur purement calogène aux systèmes intégrés dédiés à la production de molécules d'intérêt, Conférence SFEN Rhône Ain Loire, Lyon, June 13<sup>th</sup> 2023, Philippe Amphoux et Clément Liegeard (CEA, DES/IRESNE/DER/SESI), [https://sfenral.fr/images/Reunions\\_Debats/2023-06-14\\_IDNES.pdf](https://sfenral.fr/images/Reunions_Debats/2023-06-14_IDNES.pdf)
- Hydrogen from Nuclear Power: Technology Perspectives, Webinar Nuclear Europe – 12 September 2023, <https://www.youtube.com/watch?v=R4iWBcP--aM>
- Hydrogen high temperature process coupled with nuclear reactor. A tentative historical review initiated by the IEA/ H<sub>2</sub> TCP TASK #44, IAEA, Technical Meeting on Advances in High Temperature Processes for Hydrogen Production with Nuclear Energy, September 5-8<sup>th</sup>, 2023, Vienna (Austria), Gilles Rodriguez (CEA, DES/IRESNE/DER), <https://nucleus.iaea.org/sites/smr/SitePages/Event-details.aspx?EventID=EVT2103544>
- HyNE: hydrogen from nuclear energy. A new task from the IEA / Hydrogen Technology Cooperative Program, IAEA Second international Conference on Climate Change and the Role of Nuclear Power: Atoms4NetZero, Vienna (Austria), October 9-13<sup>th</sup>, 2023, Gilles Rodriguez (CEA, DES/IRESNE/DER), [https://www-pub.iaea.org/MTCD/publications/PDF/PUB2118\\_web.pdf](https://www-pub.iaea.org/MTCD/publications/PDF/PUB2118_web.pdf)

## 2024

- IEA Hydrogen Technology Collaboration Program Task #44 – Hydrogen from Nuclear Energy, Workshop on Non-electric and Hybrid Applications of Nuclear Energy (NEANH 2024 Workshop), Busan (Korea), 26 April 2024, Pierre Serre-Combe on behalf of Gilles Rodriguez (CEA, DES/IRESNE/DER) <https://www.gen-4.org/resources/events/workshop-non-electric-and-hybrid-applications-nuclear-energy-neanh-2024-workshop>
- Workshop on Gen-IV SMRs: Agenda and Introduction of Speakers, IAEA Interregional Workshop on Advances in Design of Generation-IV SMRs Beijing, 3-7 June 2024, Rami El-Emam (Ontario Tech), <https://conferences.iaea.org/event/391/contributions/32267/attachments/16808/28349/2024-06-03-Agenda-and-Intro.pdf>
- Activities supporting the transition of Advanced Reactors from R&D to deployment, Nuclear Innovation Conference 2024, 5-6 June 2024, Brent Wilhelm (NEA), <https://nic2024.eu/wp-content/uploads/2024/06/Brent-Wilhelm-NEA.pdf>
- Hydrogen production from nuclear energy, TANDEM workshop “Non-electric applications of SMRs, hybrid energy systems and their components”, September 18, 2024, Gilles Rodriguez (CEA, DES/IRESNE/DER/SESI), [https://enen.eu/wp-content/uploads/2022/09/Rodriguez\\_presentation\\_H2.pdf](https://enen.eu/wp-content/uploads/2022/09/Rodriguez_presentation_H2.pdf)
- The Fifth Generation IV and Small Reactor Conference (G4SR-5) / GIF Workshop Hydrogen Production Using Nuclear Energy – Safety Considerations, Ottawa (Canada), October 1-4<sup>th</sup>, 2024, Gilles Rodriguez (CEA, DES/IRESNE/DER) and Rami El-Emam (Ontario Tech), [https://www.linkedin.com/posts/elemam\\_ontariotech-cea-safety-activity-7247618061178978304-Kum5?utm\\_source=share&utm\\_medium=member\\_desktop&rcm=ACoAADoRfBAB\\_6zlzqL38QtTf7KmwbEfYm\\_pntE](https://www.linkedin.com/posts/elemam_ontariotech-cea-safety-activity-7247618061178978304-Kum5?utm_source=share&utm_medium=member_desktop&rcm=ACoAADoRfBAB_6zlzqL38QtTf7KmwbEfYm_pntE)  
<https://www.cns-snc.ca/news/g4sr-5-august-2024-update-1-act-now-early-bird-registration-deadline-is-august-24-2/>  
<https://www.gen-4.org/resources/events/workshop-hydrogen-production-using-nuclear-energy-safety-considerations>
- Codes & Standards for Hydrogen Production from Nuclear Energy, Chieti (Italy), October 28-30<sup>th</sup>, 2024, Gilles Rodriguez (CEA, DES/IRESNE/DER), [https://www.linkedin.com/posts/walter-tosto-s%2Ep%2Ea%2E\\_aidic-confimiabruzzo-waltertosto-activity-7257757643866316800-7kwA?utm\\_source=share&utm\\_medium=member\\_desktop&rcm=ACoAADoRfBAB\\_6zlzqL38QtTf7KmwbEfYm\\_pntE](https://www.linkedin.com/posts/walter-tosto-s%2Ep%2Ea%2E_aidic-confimiabruzzo-waltertosto-activity-7257757643866316800-7kwA?utm_source=share&utm_medium=member_desktop&rcm=ACoAADoRfBAB_6zlzqL38QtTf7KmwbEfYm_pntE)

## 2025

- 2<sup>nd</sup> “Hydrogen production from Nuclear Energy and its value chain” working session, January 21-23, 2025 in Paris, France. A Joint IEA - HyNE Task #44, GIF, and NEA initiative. <https://www.linkedin.com/posts/abbott-risk-consulting>

[netzeroneedsnuclear-engineeringconsultancy-activity-7291129605535539200-ZGg2?utm\\_source=share&utm\\_medium=member\\_desktop&rcm=ACoAADoRfBAB\\_6zlzqL38QtTf7KmwBefYm\\_pntE](https://www.gen-4.org/sites/default/files/2024-08/2024%20SIAP%20Special%20Session%20on%20NEANH%20Presentations.pdf)

- Overview Of Non-electric Applications of Nuclear Heat (NEANH), GIF Senior Industrial Advisory Panel, Special Session on Non-Electric Applications of Nuclear Heat, Ottawa (Canada), February 28, 2025, Ramesh Sadhankar (Natural Resources Canada), <https://www.gen-4.org/sites/default/files/2024-08/2024%20SIAP%20Special%20Session%20on%20NEANH%20Presentations.pdf>

## 2026

- 3<sup>rd</sup> Nuclear and Hydrogen Workshop, January, 20-22<sup>nd</sup> 2026, Toronto (Canada), Ontario Tech, [https://www.linkedin.com/posts/les-jacobs-9bb267267\\_annual-international-workshop-on-hydrogen-ugcPost-7420221875357810688-OYRI?utm\\_source=share&utm\\_medium=member\\_desktop&rcm=ACoAADoRfBAB\\_6zlzqL38QtTf7KmwBefYm\\_pntE](https://www.linkedin.com/posts/les-jacobs-9bb267267_annual-international-workshop-on-hydrogen-ugcPost-7420221875357810688-OYRI?utm_source=share&utm_medium=member_desktop&rcm=ACoAADoRfBAB_6zlzqL38QtTf7KmwBefYm_pntE)

## Reports

HyNE – Task #44 is mentioned in two reports, first in a NEA report and the second in a TANDEM report.

- MANDATE OF THE WORKING GROUP ON HYDROGEN VALUE CHAINS (H<sub>2</sub>-VAL): 2023-2025, committee for technical and economic studies on nuclear energy development and fuel cycle, NEA/NCD (2023) 9/REV1, Nuclear Energy Agency, [https://ceiden.com/wp-content/uploads/2023/10/NEA-NDC20239-REV1.en\\_.pdf](https://ceiden.com/wp-content/uploads/2023/10/NEA-NDC20239-REV1.en_.pdf)
- TANDEM: D7.4–Intermediate SAC recommendations report, WP7–Task 7.2, March 5<sup>th</sup>, 2024, Claire Vaglio-Gaudard (CEA), <https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5098d7a32&appId=PPGMS>  
*"- the presentation of TANDEM during a joint meeting of GIF/NEANH TF, GIF/VHTR HP PMB, IEA H<sub>2</sub> TCP/Task #44, OECD/NEA on hydrogen production with nuclear energy, at Idaho Falls, USA, January 22-25, 2024."*

## Working group

- Working Group on Hydrogen Value Chains (H<sub>2</sub>-VAL), [https://www.oecd-nea.org/tools/mandates/index/id/12443/lang/en\\_gb](https://www.oecd-nea.org/tools/mandates/index/id/12443/lang/en_gb)

## Conclusion

The project's online visibility remains relatively limited at this stage, making it difficult to fully assess its broader impact. A more accurate evaluation will only be possible once the final Task #44 report is published and its findings are more widely disseminated. That said, Task #44 members have demonstrated strong personal engagement across numerous major international initiatives, including OECD, the IAEA, and the NEA. They have also maintained an active presence at specialized congresses and conferences dedicated to hydrogen production from nuclear energy. These contributions suggest that, while public visibility may currently be modest, the Task's influence within expert and institutional circles is both real and growing. There is up to now no signal of negative impact of this communication (opponents, vehement criticism). Although there was a deficit of Task #44 communication and scientific publications during its existence, the production of this current final report may balance this situation and provide the biggest impact.



# Task #44: **H**ydrogen from **N**uclear **E**nergy

**HyNE** 2023-2026