Nuclear-Hydrogen Digest

Nuclear Energy in the Hydrogen Economy

HYDROGEN INITIATIVE
AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

CLEAN ENERGY MINISTERIAL
Accelerating the Global Clean Energy Transition

NICE Future
Nuclear Innovation: Clean Energy Future
An Initiative of the Clean Energy Ministerial

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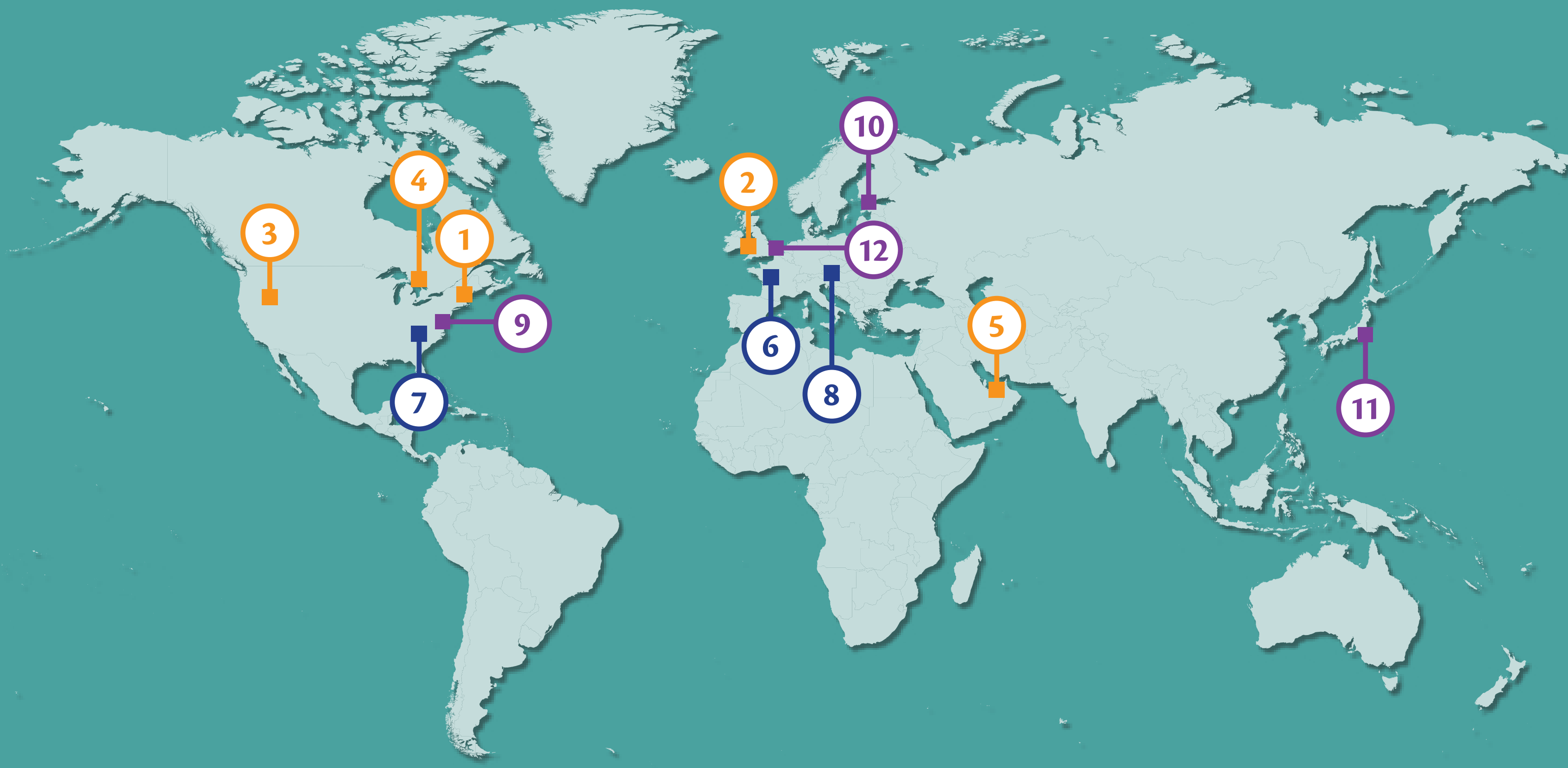

The Nuclear-Hydrogen Digest highlights initiatives from around the world.

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Kathryn Huff

Assistant Secretary for Nuclear Energy, U.S. Department of Energy

NUCLEAR ENERGY TO ACCELERATE THE HYDROGEN ECONOMY

In the "City of Steel", Pittsburgh, Pennsylvania, U.S. Secretary of Energy Jennifer Granholm has convened the Global Clean Energy Action Forum (GCEAF), possibly the world's largest and most impactful global clean energy event to date. We have brought together governments from more than 30 countries with nearly 6,000 global experts at a historic moment. We are rolling up our sleeves to bring new solutions that accelerate clean energy use, advance energy security, grow our economies, and save our planet from the consequences of climate change.

One of the most promising solutions being examined under the Nuclear Innovation: Clean Energy (NICE Future) initiative is hydrogen production from nuclear power. Hydrogen production will allow nuclear energy to expand beyond the grid into the industrial and transportation sectors. Because of their high capacity factors, nuclear plants can produce clean hydrogen at a very low cost. The clean hydrogen produced from nuclear plants can be used to decarbonize the very large existing industrial hydrogen markets or for new industrial uses and transportation fuels.

Hydrogen production also enables energy storage at nuclear plants. Hydrogen production levels can be quickly controlled to balance high electricity demand from the grid or low electricity supply from the natural fluctuations of variable renewable energy sources, providing the resilience needed for expanding the capacity of renewable energy sources without relying on backup energy from CO_2-emitting fossil energy sources or resource-intense batteries. Hydrogen can also be stored and converted back to electricity with advanced gas turbines.

In the United States, hydrogen is very much part of our future vision, and we are acting today to bring that vision into a reality. We are currently funding multiple nuclear-coupled hydrogen demonstration projects, at least one of the Clean Hydrogen Hubs will be powered by nuclear energy, and up to USD 3 per kg of produced hydrogen will be provided through tax credits.

Nuclear energy already accounts for about a third of the world's zero-emission electricity production and I am confident that hydrogen from nuclear, together with nuclear's applications beyond the grid, will help lift up quality of life for people around the world.

William D. Magwood, IV

Director-General of the OECD Nuclear Energy Agency (NEA)

TIME TO ACT FOR A CLEAN HYDROGEN FUTURE

Hydrogen is the most common element in the universe. Its potential as an energy source has been contemplated by mankind since Jules Verne famously prophetised in 1875 the advent of hydrogen as a fuel to replace coal in his novel *The Mysterious Island*. In the 1970s, in a context of growing resource depletion, environmental concerns and energy security challenges, countries began to envisage a significant role for hydrogen as an energy vector. At the time, nuclear energy was already considered a key solution to unlock the hydrogen economy.

Today, the potential role of hydrogen to decarbonize hard-to-abate sectors such as heavy transport and industrial applications is once again at the center of energy policy discussions. Leveraging decades of research and development and public-private partnerships, countries are entering a critical period to turn the vision of the hydrogen economy into reality.

Delivering low-carbon hydrogen at scale will require taking advantage of all low-carbon sources of energy. Nuclear power is the second largest source of low-carbon electricity worldwide and therefore has a key role to play. As of 2022, 13 countries representing 80% of global installed nuclear capacity have climate strategies identifying nuclear energy as a competitive source of energy to produce low-carbon hydrogen.

This decade must be one of climate action for the world to be on track to meet the objectives of the Paris Agreement. A new energy paradigm is emerging that will require massive production of clean electricity, heat and hydrogen. For several decades, nuclear has been a competitive, reliable and dispatchable source of electricity. Building on this solid track record, nuclear energy has the potential to play a vital role in future low-carbon energy mixes where it will deliver a range of new products and services, including large scale production of low-carbon hydrogen.

Kirsty Gogan

Co-founders, TerraPraxis

Eric Ingersoll

Co-founders, TerraPraxis

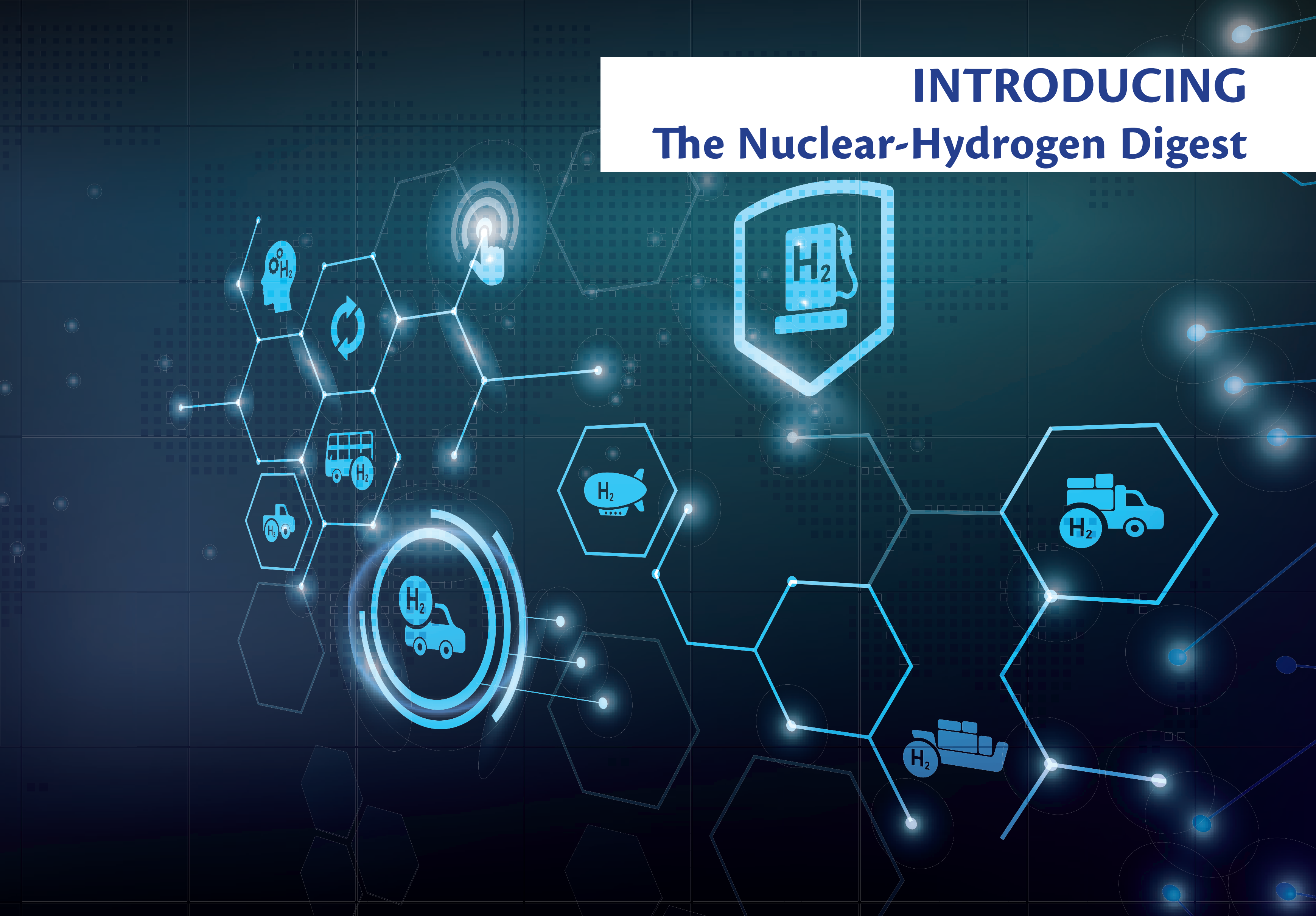
MISSING LINK TO A LIVABLE CLIMATE

Given the scale and urgency of the required clean transition combined with the needed growth of the global energy system, all zero-carbon hydrogen production options should be pursued. The potential of advanced heat sources to power the production of large-scale, very low-cost hydrogen (less than USD 1/kg) and hydrogen-based fuels could transform global prospects for near-term decarbonization and prosperity. Our landmark report, *Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals*, sets out a pathway to decarbonize a substantial portion of the global energy system, for which there is currently no viable alternative.

While it sounds daunting to achieve the scale of production needed, the scalability and power density of advanced heat sources are a major benefit. By moving to a manufacturing model with modular designs, it is possible to deliver hundreds of units in multiple markets around the world each year to produce abundant clean hydrogen-based synthetic fuels. To achieve global market penetration at the speed and scale required by the climate emergency, these drop-in substitute fuels must be delivered at prices that can outcompete fossil fuels within 10 years, and at a scale that can displace the 100 million barrels of oil that are currently consumed around the world each day.

Governments and industry are already collaborating to demonstrate hydrogen projects at existing nuclear plants, as well as supporting and leading national and international efforts to accelerate cost-effective commercialization of innovative technologies, delivery and deployment models. Seizing this opportunity to massively scale affordable clean energy, combined with aggressive renewables deployment, can help address the immediate global energy crisis, and gives us a fighting chance of achieving the Paris goals of limiting warming to 1.5°C in the very limited time available.

INTRODUCING
The Nuclear-Hydrogen Digest



A WINDOW INTO HOW NUCLEAR ENERGY IS ENABLING THE CLEAN HYDROGEN ECONOMY

Nuclear electricity can be harnessed to produce clean hydrogen at a competitive price. The next generation of nuclear plants have the potential for cogeneration: providing both emissions-free, baseload electricity to grids and continuous high quality heat for industry. Cogeneration of heat and power from nuclear plants can be exploited easily and reliably, to maximize production of clean hydrogen for an in-depth decarbonization of major sectors of the economy.

Showcased here, from multiple stakeholders around the globe, are examples of leading nuclear produced hydrogen initiatives which can be used to power hard-to-electrify sectors such as transport and heavy industry. Nuclear hydrogen is no longer a vision, but an actionable way to support the clean hydrogen economy.

HYDROGEN 101

Nearly all hydrogen today is produced using fossil fuels. Clean electricity or clean high temperature heat are needed to produce clean hydrogen.

Nuclear energy can produce hydrogen without carbon emissions:

- Today, non-emitting electricity can be used to produce hydrogen from electrolysis.
- In the coming years, innovations in Small Modular Reactors (SMRs) and other advanced nuclear technologies will offer continuous high temperatures to produce hydrogen more efficiently than with electrolysis alone.

The Nuclear-Hydrogen Digest highlights solutions being designed today, to create pathways to unlock massive increases in reliable and cost effective production of low-carbon hydrogen.

Large nuclear power plants can produce grid power as well as hydrogen continuously, ensuring security of supply all year round. SMRs can dedicate both heat and electricity to hydrogen production in remote locations. Dedicated shipyards with numerous reactor modules, maintenance and refueling facilities onsite could produce hydrogen to be then transported by sea around the world.

The examples on the following pages give insights into how nuclear produced hydrogen solutions like these are being developed and can be implemented globally, starting right now.

KEY TAKEAWAYS

Catch the wave of innovation in nuclear-hydrogen

Ambitious nuclear-hydrogen projects from around the world are featured here through a collection of stories from international organizations, civil society, industry, utilities and laboratories.

All available low-carbon solutions are needed to address the immense scale of the decarbonization challenge

Clean energy capacity today is insufficient to decarbonize the global electricity sector. Hydrogen production must also be ramped up by several orders of magnitude to support decarbonization of the industry and transport sectors. If expanded, nuclear energy can be harnessed to address both these gaps.

Nuclear energy is a leading option to achieve deep decarbonization of economies around the world by 2050 and beyond

Clean electricity alone is not enough. The stories in this book are a glimpse of the many opportunities nuclear offers to decarbonize electricity, heat, hydrogen production, as well as other synthetic fuels in the future.

The Nuclear-Hydrogen Digest is a window into how nuclear energy can enable a clean hydrogen economy. It highlights opportunities for stronger partnerships across energy sub-sectors at the Clean Energy Ministerial, with technology solutions that are being applied across industries and around the world.

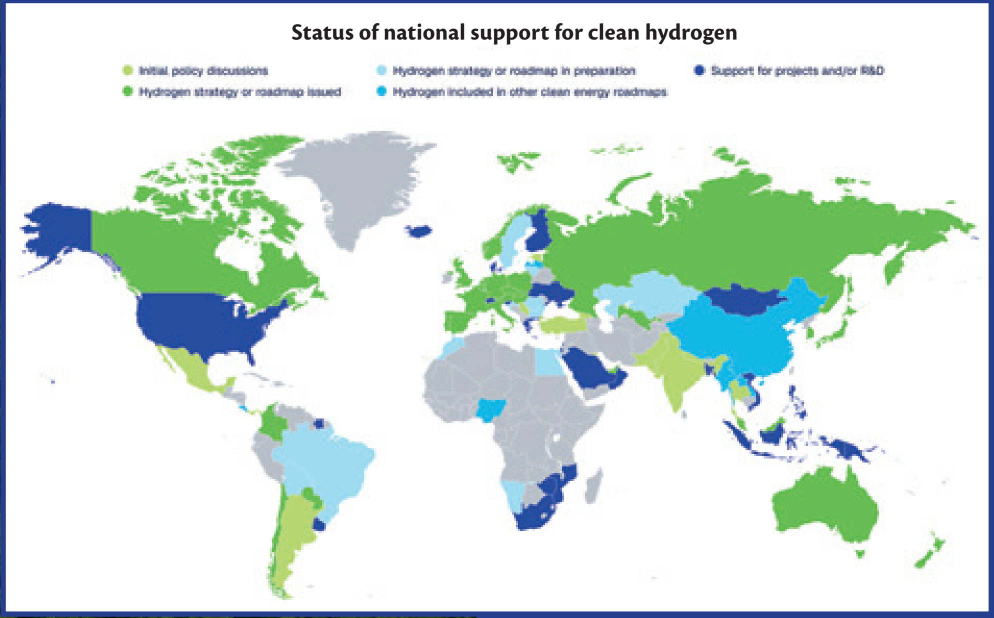
I – From vision to action

The moment for action is now. Showcased here are current activities by an NGO, a government, a national laboratory and utilities, who have all recognized nuclear energy as an essential tool for producing hydrogen. They are acting today to use nuclear-hydrogen to achieve net zero.

Hydrogen production from carbon-free nuclear energy

Overview of current policies and recommendations for government actions

80 countries provided support for clean hydrogen production – either through the issuance, development or consideration of hydrogen strategies, policies, or roadmaps, or by providing some support for clean hydrogen projects or research & development.



CLEAN AIR TASK FORCE

Nuclear Hydrogen Initiative

NUCLEAR ENERGY OFFERS MANY PATHWAYS FOR CLEAN HYDROGEN PRODUCTION

CATF is a non-traditional, fact-based environmental organization that builds momentum for solutions based on scientific evidence, intellectual integrity, and pragmatism. We know that the climate crisis is too complex a challenge, and the stakes are too high for us to limit the tools at our disposal. In line with that ethos, our mission is to push the technology and policy changes needed to achieve a zero-emissions, high-energy planet at an affordable cost. That is why we began convening working groups to investigate the opportunities and challenges associated with linking two promising technologies: hydrogen and advanced nuclear energy.

Clean hydrogen has increasingly emerged as one promising pathway to net-zero emissions, with the potential not only to store energy but also to decarbonize hard-to-abate energy sectors, such as transportation, power, industry, and buildings. Until now, approximately 80 countries – several of which have established nuclear infrastructure and operate nuclear reactors – have provided some support for clean hydrogen production, either through issuance, development, or consideration of hydrogen strategies, policies, or roadmaps, or by providing some support for clean hydrogen projects or research and development.

In the transition to a hydrogen economy, many forecasts of expected demand – even in the most conservative estimates – include clean hydrogen production increases of 2.5 to 7 times current capacity. Given potential exponential demand growth, all paths to produce clean hydrogen need to be explored. A zero-carbon production pathway is thus paramount to achieving hydrogen's true decarbonization potential. Nuclear energy has emerged as one such pathway. As such, some of the countries alluded to above have either expressly included nuclear hydrogen production in their roadmaps and strategies or have issued technology-neutral policy documents supporting nuclear hydrogen production because of its zero-carbon attributes.

Nuclear energy is a powerful hydrogen production method, adding benefits other energy sources don't. Nuclear plants are zero-carbon, operate at capacity factors above 90%, require minimal land compared to renewable energy, and allow several different clean hydrogen production techniques. First, zero-carbon electricity from existing nuclear plants can provide reliable power to Low Temperature Electrolysis (LTE). Nuclear plants can also produce heat alongside clean electricity, enabling them to pair with the more efficient High Temperature Electrolysis (HTE). And advanced reactors operating at very high temperatures can use the thermochemical water splitting process to produce clean hydrogen even more efficiently. The unique characteristics of nuclear energy allow it to pair with these low-cost, high-efficiency production processes, thereby boosting clean hydrogen's economic competitiveness. In this way, nuclear energy can be a catalyst for a global clean hydrogen market.

This fact prompted the formation of the Nuclear Hydrogen Initiative (NHI), a coalition of partners born out of CATF's initial working groups and aimed at advancing nuclear hydrogen as a critical climate solution. While NHI participants are encouraged to see jurisdictions and government leadership – with the support of the private sector – debate, develop, and issue hydrogen strategies, policies, and roadmaps while seeking to decarbonize hard-to-abate energy sectors, it became clear over the course of the NHI's working group discussions that a more robust and technology-inclusive approach is required to accelerate and sustain the transformation of these energy sectors.

In order to promote and enable a more robust array of clean hydrogen production methods, CATF and NHI make the following recommendations for developing the various strategies, policies, and roadmaps:

- *Make hydrogen plans technology neutral;*
- *Include nuclear technology in hydrogen policies and plans;*
- *Promote nuclear hydrogen research, development, and demonstration (RD&D);*
- *Set production incentives such as investment and production tax credits;*
- *Establish end-user incentives such as tax incentives for offtake of nuclear hydrogen;*
- *Leverage government procurement to drive market development.*

The UK's policy and innovation-led approach to nuclear-enabled hydrogen

Contribution from BEIS and NNL

NATIONAL NUCLEAR LABORATORY

Department for Business, Energy & Industrial Strategy

PROVIDING AN ENVIRONMENT WHERE THE NUCLEAR SECTOR COULD SUPPORT CARBON NEUTRALITY ACROSS THE WHOLE ENERGY SYSTEM

NEW POLICIES NEEDED TO REACH NET ZERO

The UK was the first large economy to legislate the target of net zero greenhouse gas emissions by 2050 and regularly reports on new policies to reach its carbon budgets. These policies influence the technologies that may emerge to reduce emissions. The UK government (HMG) has been clear that nuclear is an important part of the energy mix, providing opportunities for the nuclear sector to enter new markets and outlines the financial frameworks to ensure fair competition with other technologies to support net zero goals. HMG believes that nuclear could have a role in 'beyond the grid' applications, including hydrogen production. In the longer-term, this has the potential to reduce reliance on fossil fuels, improve energy security and increase resilience and reliability of energy systems around the world.

CREATING THE CONDITIONS FOR NUCLEAR ENABLED HYDROGEN AT COMMERCIAL SCALE

Nuclear technology is recognised in several current and emerging HMG publications on Net Zero. These include its hydrogen strategy and in future sustainable aviation fuel (SAF) production, where SAF could remove 10% of all UK aviation emissions by 2030. In the UK hydrogen strategy, nuclear enabled hydrogen is categorised as low-carbon electrolytic hydrogen, alongside renewable produced hydrogen. The strategy recognises the potential importance of nuclear for a diverse and secure future supply of hydrogen and identifies necessary deployment actions through the British Energy Security Strategy, amongst other policies, to support achieving this potential.

Nuclear is included as a heat source for industrial heat decarbonisation and to drive direct air capture systems and identified as an energy source for home heating. In shipping, decarbonisation of up to 50% prompts its inclusion in the maritime consultation. The nuclear sector is pursuing these opportunities with key stakeholders and is rapidly developing the required technologies.

In parallel, the UK's National Nuclear Laboratory, through its Hydrogen Programme, has been building a wider evidence base by modelling economic, whole energy systems and hydrogen production. This modelling has highlighted the potential for nuclear enabled hydrogen to be cost competitive or lower cost than other routes to low-carbon hydrogen. When this can be achieved, the market share for nuclear enabled hydrogen and sustainable fuels could be increased.

In the UK, the design of key policies to support low-carbon hydrogen production have been orientated to allow nuclear enabled projects to bid for - specifically the GBP 240m Net Zero Hydrogen Fund and Hydrogen Business Model. Other non-nuclear industry groups, for example the UK Hydrogen and Fuel Cell Association are also recognising this opportunity, particularly in hydrogen production.

For nuclear enabled hydrogen to emerge as a viable commercial proposition at scale, there are technology, market and economic aspects to overcome, including technology selections that balance efficiency against commercial readiness. However, for nations that choose nuclear technologies as part of their current or future energy mix, a combination of evidence-based policymaking and innovation funding frameworks, led by the technology, can be a key enabler to nuclear realising its potential in addressing the climate emergency.

> *For nuclear enabled hydrogen to emerge at scale in the future, a combination of the right policies, technology innovation programmes, and funding mechanisms need to run in parallel. The UK is providing an environment where the nuclear sector could support carbon neutrality across the whole energy system, including electricity generation.*

Idaho National Laboratory supports clean hydrogen production

Contribution from Idaho National Laboratory

Idaho National Laboratory

Development and Testing of Materials

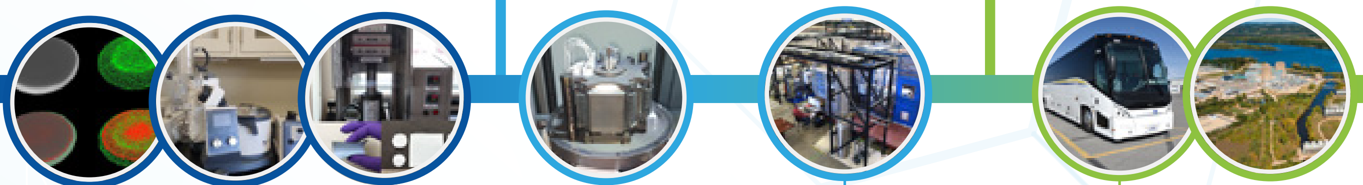
2008-2019

Integrated Systems Testing

2019-2022

Scale-up Demonstrations

2022-2025



- Materials Development-HydroGen
- Short Stack Testing 3-10 cells
- 5-20 kWe Stack Assembly Performance Testing
- Demonstrate technology through Pilot Plant, INL Motor Coach Fleet, and Industry Partners.

INL RESEARCHERS HELPING UTILITIES DEMONSTRATE TECHNOLOGY AT NUCLEAR POWER PLANTS

One approach to decarbonizing industrial and transportation sectors is to convert energy from carbon-free power plants into clean hydrogen.

Researchers at Idaho National Laboratory are working to produce clean hydrogen using electrolysis powered by nuclear energy. One approach – high-temperature electrolysis – can use heat and electricity from a nuclear power plant to split steam into hydrogen and oxygen and is more than 95% efficient.

DEVELOPING AND TESTING ELECTROLYSIS TECHNOLOGIES

For over 20 years, researchers at INL have helped industry combine electrolysis and nuclear energy by shepherding high-temperature electrolysis through a series of technological advancements, economic analyses and testing.

High-temperature electrolysis relies on stacks of cells fabricated from specialized metal oxides that conduct electrons and the ions of oxygen and hydrogen. These stacks are combined into modules that are sized to accommodate the energy output of a nuclear reactor power plant.

With support from the U.S. Department of Energy, INL researchers are testing commercial high-temperature electrolysis systems to prove their performance under real-world conditions. A test with a commercial 100 kW module is underway, and additional tests are planned for systems ranging from 5 kW to 250 kW. (A 100 kW system produces about 60 kilograms of hydrogen per day.)

INL researchers are also helping nuclear utilities conduct demonstration projects at their nuclear power plants. A low-temperature electrolysis test will be conducted at Constellation's Nine-Mile Point Nuclear Station in New York. Other demonstrations are scheduled for the Energy Harbor Davis-Besse Nuclear Power Station in Ohio and the Xcel Energy Prairie Island Nuclear Generating Plant in Minnesota where heat and electricity will be used for the first high-temperature electrolysis demonstration.

These projects are forerunners of DOE-supported regional hydrogen hubs that will use nuclear energy to produce large amounts of hydrogen for industrial and transportation applications. The hubs will require electrolysis companies to ramp up production.

As the amount of hydrogen produced by the regional hubs increases, the cost of clean hydrogen will likely decrease, making it competitive with conventional plants that convert natural gas into hydrogen.

The first Energy Earthshot, launched June 7, 2021 – Hydrogen Shot – seeks to reduce the cost of clean hydrogen by 80% to GBP 1 per 1 kilogram in 1 decade. INL is helping high-temperature electrolysis providers reach this target by developing and proving longer lasting cells and systems.

INL technical and economic assessments show that if 10 existing U.S. nuclear power plants incorporate hydrogen production in the next decade, they could produce 5 million metric tons of hydrogen a year – a 50% increase over current levels. This would set a course to significantly reduce greenhouse gas emissions using clean hydrogen.

About Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment. For more information, visit www.inl.gov.

BrucePower

Innovation at work

Exploring the feasibility of using optimized output for hydrogen production

Bruce Power nuclear-hydrogen feasibility study

FORMED IN 2001, BRUCE NUCLEAR POWER PLANT OPERATES EIGHT UNITS AND IS ONE OF THE LARGEST POWER PLANTS IN THE WORLD

Bruce Power announced "NZ-2050" which is the company's strategy for helping Canada achieve its stated goal of Net-Zero emissions by 2050. The strategy consists of five pillars, one of which specifically speaks to the goal to utilize nuclear power generation to produce clean fuels and electrify industrial processes and transportation with an historic opportunity to contribute to a national hydrogen and clean fuels strategy.

Building off this announcement in 2021, Bruce Power announced its commitment to achieve Net Zero greenhouse gas (GHG) emissions from its site operations by 2027. This makes Bruce Power the first nuclear operator in North America to announce such an ambitious commitment.

SUPPORTING ONTARIO'S LOW-CARBON HYDROGEN STRATEGY

In 2022, as one of the eight immediate actions included in Ontario's low-carbon hydrogen strategy, Bruce Power began a feasibility study to determine opportunities for hydrogen production using optimized energy production generated primarily at night by reactors at the Bruce Site. The project will be undertaken in collaboration with the renewable fuels manufacturer Greenfield Global, Hydrogen Optimized which has high-current unipolar water electrolysis systems technology and agricultural cooperative, and Hensall District Co-op, and is expected to be completed in early 2023.

The feasibility study is exploring multiple options in terms of electrolyser technology, size, and options to scale. The hydrogen produced from this project would be GHG emissions free.

PUSHING THE BOUNDARIES OF ENERGY INNOVATION

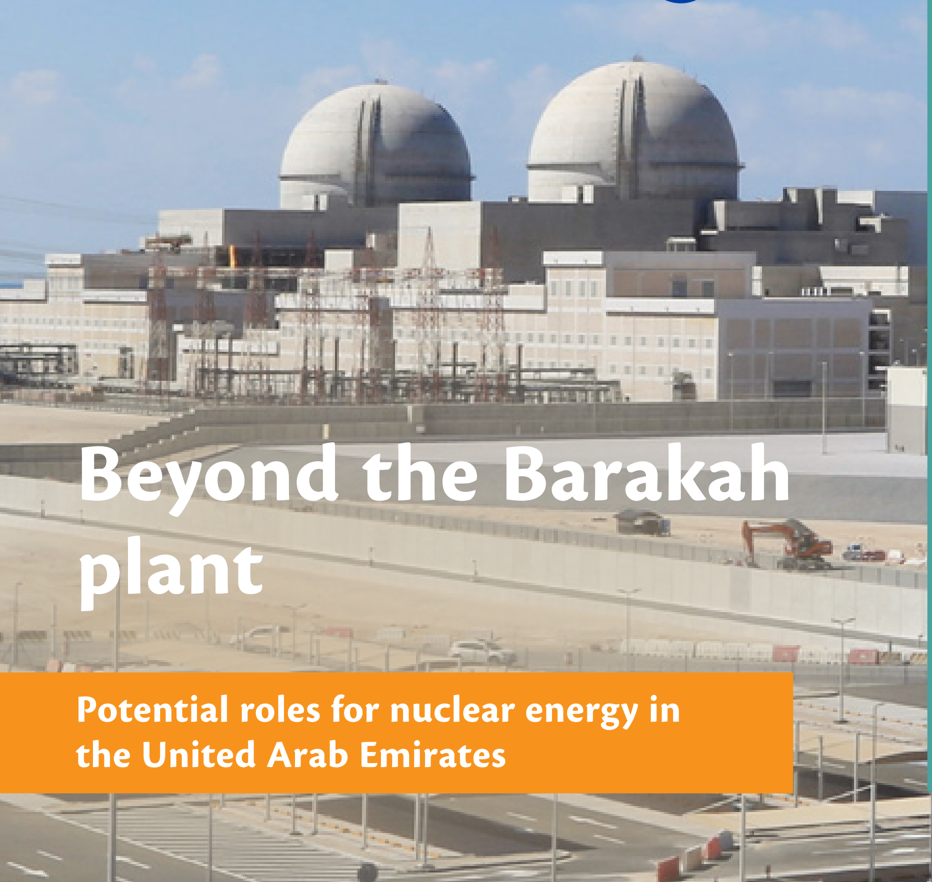
We look forward to working with partners across the industry to ensure that nuclear is not underutilized due to an exclusionary definition of 'green' hydrogen which could end up inhibiting or becoming a barrier to increased production despite the growing need for all types of hydrogen."

Bruce Power continues to push the boundaries when it comes to energy innovation. Our work with the Nuclear Innovation Institute is exploring opportunities for Bruce Power's assets to maximize the impact they'll have on Canada's clean energy future. This includes leading public policy initiatives under the Hydrogen Strategy for Canada through the Bruce Power Centre for New Nuclear & Net Zero Partnerships – which serves as the Task Force lead for Production Opportunities for hydrogen production from nuclear assets across Canada.

مؤسسة الإمارات للطاقة النووية
Emirates Nuclear Energy Corporation

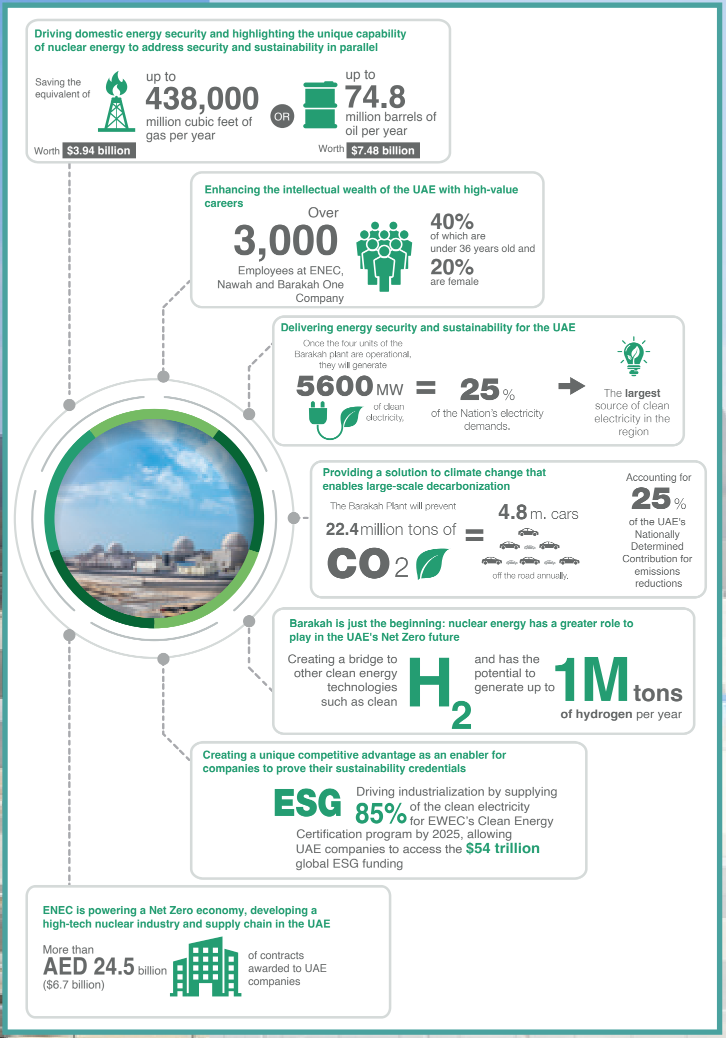
شركة براكة الأولى ش.م.خ
Barakah One Company PJSC

شركة نواة للطاقة
Nawah Energy Company



Beyond the Barakah plant

Potential roles for nuclear energy in the United Arab Emirates



CLEAN ELECTRICITY IS JUST THE START FOR THE UAE'S NEW NUCLEAR INDUSTRY

The UAE initiated its Peaceful Nuclear Energy Program in 2009 with the aim to deliver a clean, reliable and efficient source of electricity, while diversifying the nation's energy portfolio and securing a sustainable energy future.

Fast forward to today, and the Emirates Nuclear Energy Corporation (ENEC) has already delivered 50% of its flagship project – the Barakah Nuclear Energy Plant – a third reactor is now online, and the fourth and final reactor is in the final stages of commissioning. The Barakah plant offers a new model for nuclear energy development and implementation, delivered in a timely manner to the highest national and international standards and in partnership with responsible nations and global organizations since inception.

DELIVERING ENERGY SECURITY AND SUSTAINABILITY IN PARALLEL

Since the successful start of operation of Unit 1 in 2020, the Barakah Plant has had a transformational impact on the UAE's energy landscape, adding 1,400 MW of power capacity with each unit that comes on-line. Clean electricity is a major geopolitical asset, particularly in this period of global energy shortages and prices spikes, enabling the UAE's oil and gas industry to export more LNG. Through Barakah, the UAE is demonstrating the positive role nuclear energy plays in driving energy security and sustainability for nations that are keen to commit to the long-term vision and development process required.

Once fully operational by 2025, Barakah will provide up to 25% of UAE's energy demand and prevent the release of 22.4 million tons of CO_2 annually. This will free up about 440 billion cubic feet of natural gas which would otherwise be used for electricity production, worth almost USD 4 billion at today's prices. It is clearly providing energy security and driving rapid decarbonization of the nation's energy sector.

BEYOND THE BARAKAH PLANT

The Barakah Plant is only the beginning of the UAE Peaceful Nuclear Energy Program, with nuclear energy having a greater role to play in the nation's Net Zero future. ENEC's wider mission is to explore and incubate strategic investments in nuclear energy that support national growth and development goals. To promote this, ENEC established a research and development (R&D) program with various nuclear energy and non-energy research focus areas, from hydrogen and SMR development through to reactor longevity and materials studies. The production of carbon-neutral hydrogen from nuclear energy is one of the main research initiatives.

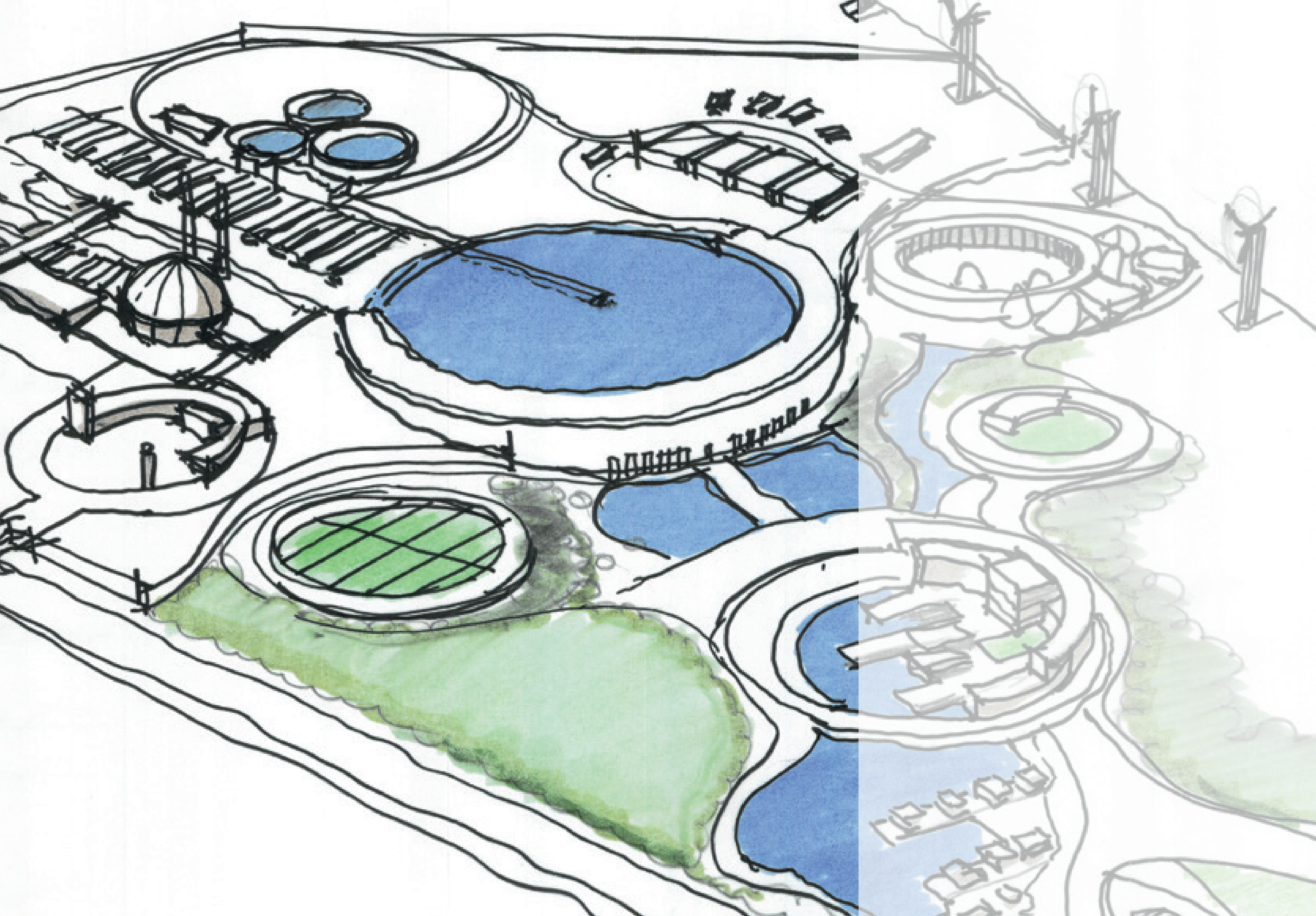
The Barakah Plant's four Units have the potential to generate up to one million tons of hydrogen each year, contributing significantly to the UAE's ambitions in the sector and its Net Zero by 2050 target. The International Energy Agency (IEA) projects that to achieve Net Zero, global demand for hydrogen needs to increase from 90 million tons today to over 200 million tons in 2030. Nuclear energy can ensure that this production happens with the lowest possible carbon footprint.

ENEC's R&D Program is in the process of developing a roadmap for market and feasibility studies to assess the economics and technologies for establishing viable nuclear-generated hydrogen capabilities. The R&D program also targets the development of large-scale synthetic fuels production from nuclear energy which support the decarbonization of various industrial sectors.

POWERING SUSTAINABLE GROWTH

The UAE advocates the development of low-carbon hydrogen production as it supports diversifying the energy mix for the country and is key in reducing carbon emissions of hard-to-abate industrial sectors. It is a key enabler in UAE's Net Zero Strategy 2050, in line with the 2015 Paris Agreement for emissions reductions. These plans envision targeted applications in oil refining and ammonia, industrial heat and steel, power storage, heavy road transport, marine shipping, and sustainable aviation fuel. In addition, it supports UAE's goals for low-carbon export products to maintain its sustainable economic growth.

The Barakah plant is an excellent example for other nations looking to use nuclear energy to generate significant baseload electricity 24/7 while in parallel decarbonizing the power sector, then working as a catalyst for other clean energy forms like hydrogen. Throughout, ENEC has been able to generate thousands of high-quality jobs for UAE Nationals that will continue throughout the next six decades and beyond: a true powerhouse of sustainable growth. ■

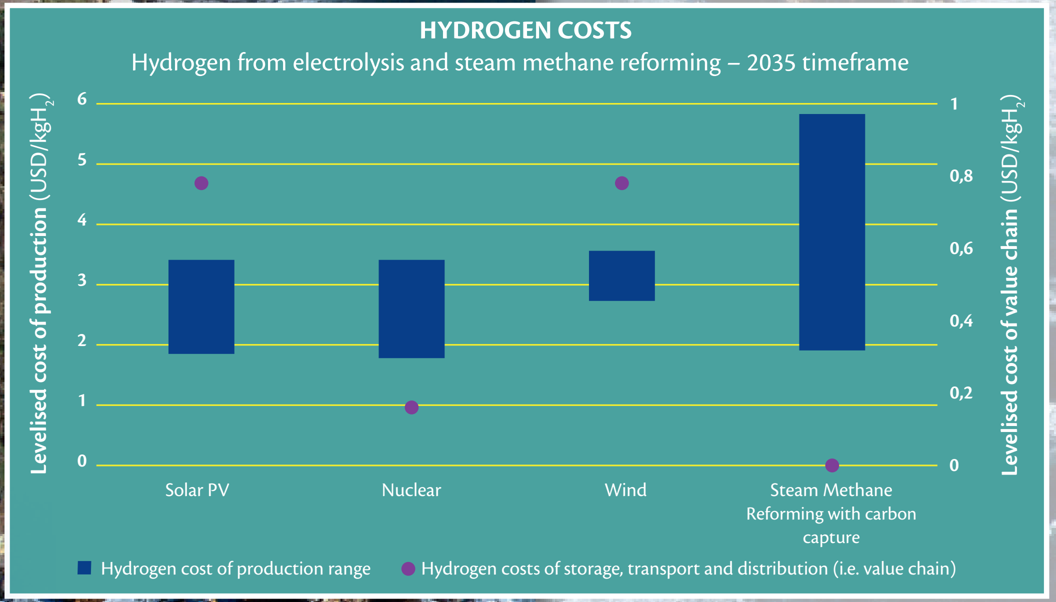


II – Competitive production and delivery of low-carbon hydrogen

It's economical. These features demonstrate the affordability of nuclear-hydrogen from production to market. Nuclear energy is competitive for the production and delivery of hydrogen and it shows.

The Role of Nuclear Power in the Hydrogen Economy: Cost and Competitiveness

A new report by the Nuclear Energy Agency



NEA
NUCLEAR ENERGY AGENCY

CLEAN HYDROGEN WILL PLAY AN ESSENTIAL ROLE IN DECARBONISATION STRATEGIES

By 2035: the world will require millions of tons of clean hydrogen. But hydrogen can only fully contribute to deep decarbonisation if:

- it is produced from low-carbon energy sources;
- there is enough low-carbon electricity generation to produce it after meeting other priorities such as the direct electrification of the transport sector.

In the short term (by 2030): hydrogen can be produced through a process called "water electrolysis" which, as its name implies, requires inputs of water and electricity. Hydrogen from water electrolysis is only low-carbon if it uses electricity from wind, solar PV, hydropower or nuclear power.

In the medium term: new innovations are expected that will also allow hydrogen to be produced in different and more efficient ways, including from fossil fuels coupled with carbon capture, and advanced nuclear technologies such as next generation Small Modular Reactors. These advanced nuclear technologies will use significantly higher temperatures (>700°C) to produce hydrogen efficiently through thermo-chemical processes that will require inputs of water and heat.

For hydrogen to contribute to deep decarbonisation, it must be produced from either renewables or nuclear energy. Hydrogen produced from Steam Methane Reforming – *even if coupled with carbon capture* – may never contribute to deep decarbonisation because it requires methane as an input, which is 25-85 times more potent than carbon dioxide as a greenhouse gas.

3 KEY REASONS TO SUPPORT NUCLEAR-PRODUCED HYDROGEN

A newly published OECD NEA (2022) report details the economics of hydrogen production and delivery from water electrolysis in the 2035 timeframe. It finds:

- **Nuclear is a competitive energy source to produce low-carbon hydrogen at large scale.** In fact, amortized reactors in long term operation can unlock the cheapest production costs, less than USD 2 per kilogram. The cost of hydrogen from new nuclear reactors is similar to the cost of hydrogen from variable renewables (solar and wind) in most places around the world.
- **Nuclear can provide hydrogen and energy to industrial hubs at low costs.** Nuclear steadiness and power density allows it to deliver a large-scale, unremitting flow of low-carbon hydrogen and heat. Nuclear creates opportunities to optimize hydrogen delivery infrastructure costs and to leverage co-location with otherwise hard-to-abate industrial activities.
- **Nuclear has low grid and system level costs.** Meeting Net Zero decarbonisation goals, including increased hydrogen production, using only variable renewables would require unprecedented amounts of generation capacity. The OECD NEA (2022) report shows that including nuclear in the generation mix reduces the total capacity requirements at the system's level and optimises the grid-level cost of the global power system.

THE PATH TO NET-ZERO BY 2050 REQUIRES IMMEDIATE ACTION AND SYSTEMS LEVEL THINKING

Low-carbon hydrogen still faces many challenges and requires research, development and at-scale demonstration using nuclear and other sources of clean power.

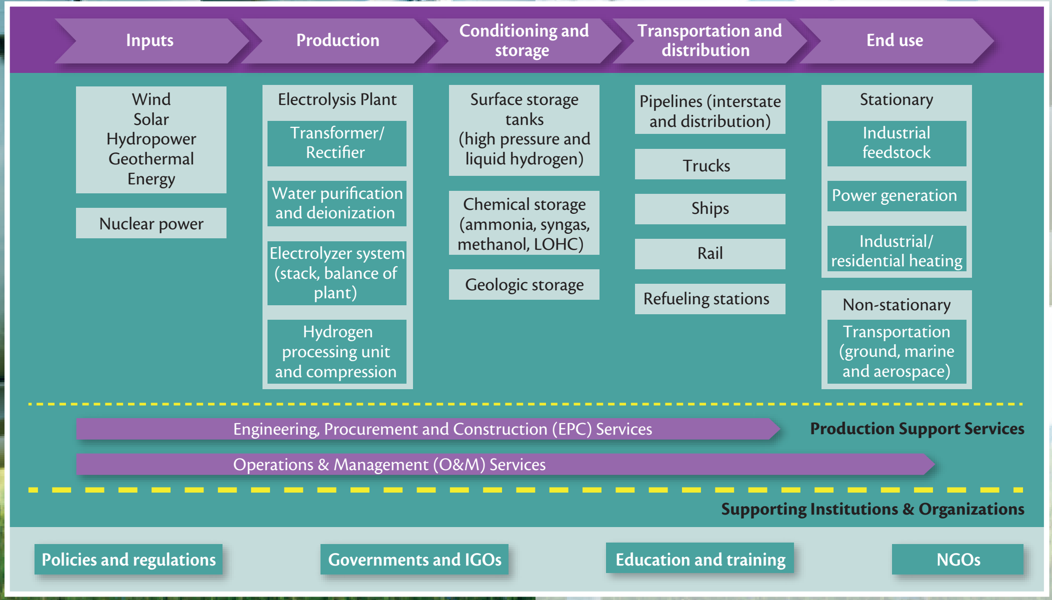
Future energy systems will be more complex, relying on various sources of clean power and clean heat to meet growing and diverse needs across all sectors of the economy. Systems level thinking is needed to ensure that integrated and hybrid energy systems combine variable (e.g. solar and wind) and firm sources (e.g. hydro and nuclear) of energy to provide heat and power when and where it's needed. Systems level thinking is also required to optimize the overall costs of the energy system.

The latest OECD NEA report "The Role of Nuclear Power in the Hydrogen Economy: Cost and Competitiveness" details the role of nuclear in the hydrogen economy and how it can unlock the production at large scale of competitive low-carbon hydrogen.

The green hydrogen value chain in the southeast United States

E4 Carolinas®

A report by E4 Carolinas



Source: Authors

NUCLEAR POWER PLANTS IN SOUTHEAST US COULD DOUBLE THE POTENTIAL FOR LOW-CARBON HYDROGEN

E4 Carolinas is an association of over 150 companies and affiliated organizations in North and South Carolina with the mission to grow the energy economy in the region.

In 2021, E4 Carolinas was approached by the Southeast Hydrogen Energy Alliance (SHEA) and the Battelle Savannah River Alliance (BSRA) to develop a study that maps the hydrogen and green hydrogen global value chains, identifies the companies active in each segment of the value chain in the region, reviews global green hydrogen projects, and makes recommendations about how green hydrogen could be developed further in the ten-state region comprising the Southeast United States. The study, initially intended to only cover renewable energy sources, expanded to include nuclear power due to the recognition that the region's nuclear fleet could double the amount of clean, no-carbon hydrogen produced.

KEY FINDINGS FROM THE REPORT

- Potential hydrogen production in the Southeast is significant for PV solar, hydroelectric power, nuclear, and, to a lesser extent, offshore wind. Approximately 564 billion kilograms of hydrogen, equivalent to 28 billion MWh, could be produced. As a reference, the United States generated approximately 4.1 billion MWh of electricity in 2021 (EIA).
- If 15% of the existing Southeast renewable capacity were used for hydrogen production, about 3,500 MW of hydrogen could be produced. This amount could be roughly doubled if a similar amount of existing nuclear capacity were devoted to hydrogen production.
- Hydrogen is a complex production system comprised of inputs, production, conditioning and storage, transportation & distribution, and end-use (see Figure).

The review of the Southeast's footprint in the green hydrogen value chain found that the Southeast has a capable base of companies in the hydrogen and green hydrogen industry. The Southeast is particularly well-endowed with large integrated industrial equipment manufacturing and engineering service companies (Siemens Energy, Toshiba, Mitsubishi, Cummins, GE, ABB) that also participate in global markets. Global lead firms from Germany, Japan, and the UK are well-represented in the Southeast. Less well-represented in the region are firms with headquarters locations in France and Scandinavian countries despite their strong position in global markets. The Southeast also hosts important supporting organizations including research universities conducting primary research on hydrogen and hydrogen-related industrial feedstock and that help develop the industry's workforce.

The review of green hydrogen projects from around the world found that green hydrogen projects can be classified by their predominant use-case: transportation, industry, electric power generation, and exports. Industrial use (29%), electric power generation (28%), and transportation (27%) applications represent 84% of use-cases globally, whereas exports represent 16% of global project use-cases. In the United States, the intended use cases for green hydrogen projects are transportation (36%), electric power generation (34%), industry (21%), with the balance (9%) focused on exports. Demand aggregation and greening existing hydrogen demand from dedicated off-takers is a demonstrably important pathway for developing economically viable green hydrogen projects.

GOVERNMENTS PLAY A VITAL ROLE IN THE DEVELOPMENT OF GREEN HYDROGEN PROJECTS

The review of green hydrogen projects around the world demonstrates three ways in which governments are important actors in the development of hydrogen projects: (1) as convenor of private and public interests around specific opportunities; (2) as the source of policies, including production subsidies, carbon taxes, and consumption credits, and other regulations which incentivize the development of green hydrogen projects, and (3) use their direct purchasing and contracting power to promote innovation and achieve environmental goals.

Accelerating commercial deployment of nuclear hydrogen

The IAEA Roadmap Initiative

IAEA
International Atomic Energy Agency
Atoms For Peace

LEVERAGING THE POWER OF INTERNATIONAL PARTNERSHIPS TO ADVANCE CLEAN HYDROGEN PRODUCTION

To accelerate the emerging clean hydrogen economy, the IAEA has launched an initiative to develop roadmaps for the commercial deployment of hydrogen production using nuclear energy. The initiative is part of the Agency's broader efforts to support Member States in making informed energy decisions by better understanding the technical and economic case for using nuclear energy to produce hydrogen.

THE ROADMAP INITIATIVE

The roadmap initiative is bringing together decision makers, designers, project managers and operators to share the latest advances in national strategies and technologies and to identify technical readiness for different technologies of hydrogen production using nuclear energy. The initiative will culminate in a publication providing guidelines for countries for evaluating, planning and strategizing the development of nuclear hydrogen projects. The publication will feature an overview of hydrogen's role in meeting net zero goals; technologies best suited for nuclear hydrogen production, including the current fleet and advanced reactors; safety and regulatory aspects; stakeholder engagement; economic and related considerations for commercial deployment; and examples of national roadmaps for commercial deployment of nuclear hydrogen production.

BUILDING ON EXISTING IAEA RESOURCES

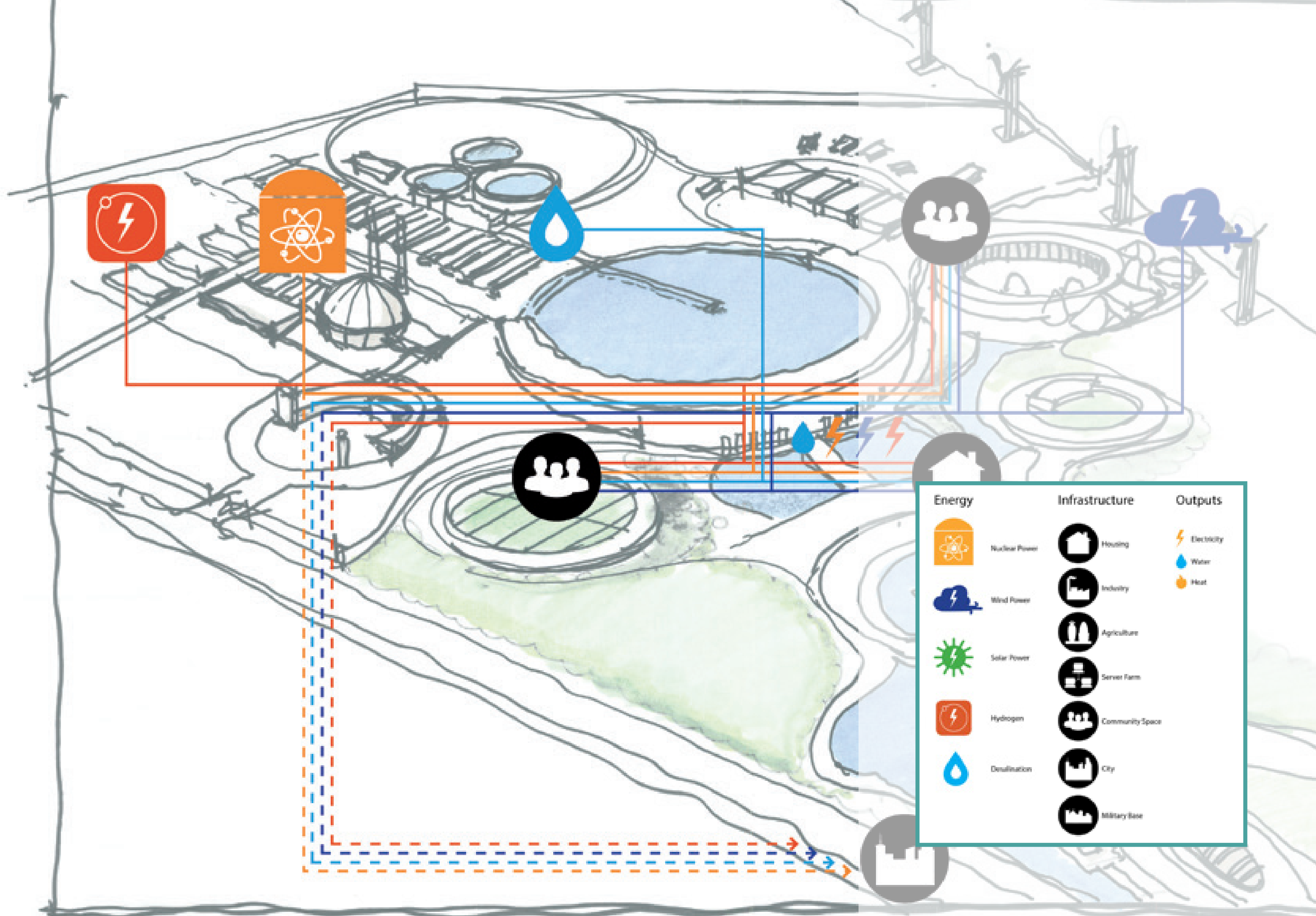
The roadmap initiative will build on an array of existing IAEA resources on the topic, including publications and software tools to help assesses the economics of nuclear hydrogen production using different technologies. The IAEA is also finalizing additional publications to support Member States in the commercial deployment of nuclear hydrogen, including *Building the Business Case for Hydrogen Production with Operating Nuclear Power Plants and Vendor* and *User Requirements and Responsibilities in Nuclear Cogeneration Projects*. The Agency has also led a Coordinated Research Project (CRP) on Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-term Deployment and is the initial stages of a follow-up CRP on Role of Nuclear Cogeneration within the Context of Sustainable Development.

ENERGY MODELLING FOR HYDROGEN PRODUCTION PLANNING

The IAEA roadmap will be supported by IAEA energy modelling tools including MESSAGE, which models the energy transition for Member States, as well as FRAMES, which is being developed to quantify the value that nuclear brings to low-carbon energy systems, including by producing hydrogen. A recent FRAMES analysis found that when natural gas prices rise above USD 20 per million British thermal units (BTUs), which is about 50% less than recent prices in the European Union, the optimal method of hydrogen production is electrolysis powered by a mix of nuclear and renewables.

INTERNATIONAL PARTICIPATION IN THE ROADMAP INITIATIVE

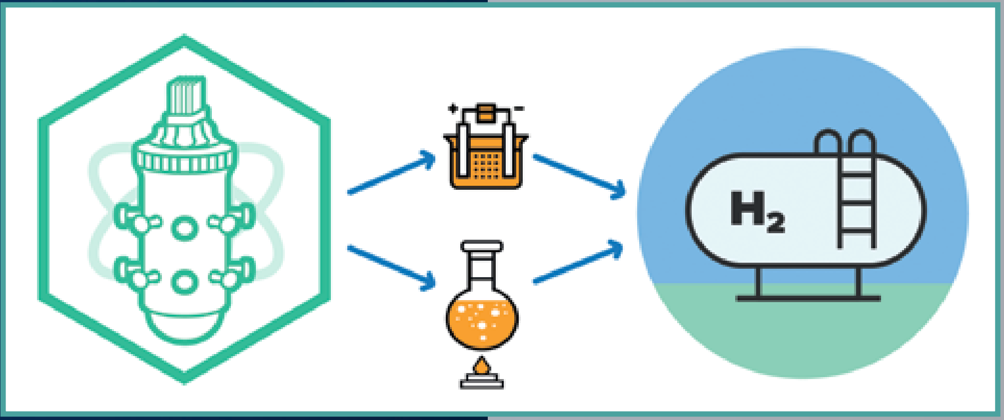
Some 28 countries and four international organizations have so far joined the IAEA roadmap initiative to share experience and know-how on their nuclear hydrogen plans or projects. "The key to success for nuclear-produced hydrogen will be finding the right opportunities that combine a strong business case and nuclear electricity and heat from existing or new nuclear power plants with applications that offer significant decarbonizing potential," Ian Castillo of Canadian Nuclear Laboratories said at the initiative's kick-off meeting at the IAEA in Vienna in May 2022. ■



Energy
Nuclear Power
Wind Power
Solar Power
Hydrogen
Desalination
Infrastructure
Housing
Industry
Agriculture
Server Farm
Community Space
City
Military Base
Outputs
Electricity
Water
Heat

III – The next wave of innovation in nuclear-produced hydrogen

The future is better with nuclear energy. Highlighted here are a collection of innovations in nuclear and hydrogen in development. They demonstrate the breadth of opportunities nuclear energy could provide in a clean hydrogen economy.



Advanced nuclear reactors for hydrogen production

The industry perspective from the Nuclear Energy Institute

ADVANCED REACTORS CAN UNLOCK LARGE SCALE PRODUCTION OF LOW-CARBON HYDROGEN

UNLOCKING GREATER PRODUCTION EFFICIENCIES

As the world moves forward with establishing clean hydrogen markets from existing technologies, it is crucial that investments in promising new technologies remain robust. Advanced nuclear reactor designs offer the option to utilize advanced methods of hydrogen production that have greater efficiencies and potentially lower costs.

- Currently, the most readily available method for producing low-carbon hydrogen is low-temperature electrolysis. With the majority of the current fleet of nuclear reactors operating globally producing outlet heat of around 300°C, they are well suited to utilize the established low-temperature electrolysis technologies with conversion efficiencies around 60% and some high-temperature electrolysis technologies.
- While low-temperature electrolysis is capable of creating large amounts of hydrogen and is available today, new technologies offer the potential for higher efficiencies and lower costs. High-temperature electrolysis can reach efficiencies of around 80%, while thermochemical processes can achieve higher total process efficiencies by circumventing the need for input electricity and associated thermodynamic losses.
- Several advanced reactor designs under development currently can generate outlet temperatures ranging from 500°C to 1000°C. At these higher temperatures, new methods for generating hydrogen, such as high-temperature electrolysis and thermochemical processes, are unlocked.

ADVANCED REACTORS BEING DEMONSTRATED NOW

In October 2020, the Department of Energy announced TerraPower and X-energy as the winners of the Advanced Reactor Demonstration Program. The program provides a total of USD 3.2 billion in funding for the companies to demonstrate their advanced reactor designs before 2030.

- TerraPower's Natrium and MCFR reactors use a sodium-cooled fast reactor and molten salt reactor design, respectively. These designs are well suited to "help decarbonize energy-intensive industries. Industrial processes, like producing hydrogen, petrochemicals and steel, require high-temperature heat" that TerraPower reactors can provide.
- X-energy takes a different approach, using a high-temperature, gas-cooled reactor design in their Xe-100 reactor. This is a versatile design and the "high-temperature helium gas can also be used in energy-intensive processes that currently rely on fossil fuels, such as hydrogen production and petroleum refining."

As advanced reactor designs like those being developed by TerraPower and X-energy reach full scale commercialization, new methods of hydrogen production can begin to be deployed.

REALIZING THE OPPORTUNITY

There is a massive opportunity for advanced reactors to produce large amounts of hydrogen using more efficient hydrogen production technologies for significant emissions reductions in sectors that are hard to decarbonize. These advanced reactors are being demonstrated now and, in order to take full advantage of the benefits offered by these designs, high-temperature electrolysis and thermochemical processes must be ready when these reactors are being deployed commercially. Continued support for both advanced reactors and advanced hydrogen production technologies is critical for creating a low-carbon future.

Small modular reactor for a European safe and decarbonized energy mix (TANDEM)

A large consortium studies the future of nuclear in Europe

VTT

TANDEM

SMALL MODULAR REACTOR FOR DECARBONISED ENERGY

SMALL MODULAR REACTORS OPENS A MULTITUDE OF NEW OPPORTUNITIES FOR NUCLEAR

Smaller and more varied than currently operating nuclear reactors, SMRs may be well suited to operate flexibly in tandem with storage systems and other energy sources such as variable renewable energy sources. SMRs could also offer new opportunities on non-electrical applications, including district heating, industrial heat, and hydrogen production. Clean hydrogen can be produced with low temperature electrolysis that only uses electricity from SMRs, or with high temperature electrolysis using both steam and electricity from SMRs. In both cases, the hydrogen production facility can benefit from the co-located dispatchable clean energy source. These illustrate some ways that the SMRs can be used with other energy sources, storage systems and energy conversion applications, and how they can be integrated into hybrid energy systems.

SMALL MODULAR REACTORS PROVIDE WIDE ENERGY SERVICES

The assessment of SMRs roles in hybrid energy systems, ensuring electricity, heat, or hydrogen production to support a wide array of energy demands is being investigated in Europe. SMRs would provide a dispatchable low-carbon source of electricity and heat. TANDEM is a new European project starting in September 2022 that investigates SMR potential in future clean energy systems. It aims to better inform the role of SMRs in future integrated energy systems that will connect multiple sources of low-carbon energy altogether. TANDEM is research consortium funded by EURATOM Research and Training program and convenes leading European organizations.

The technical and economic feasibility of SMRs integration into integrated systems rely on three main topics addressed in the TANDEM project:

- Safety: The safety of SMRs integrated into a hybrid system requires an extension of the current safety approach of existing nuclear power plants.
- Flexibility: The flexibility of SMRs to help manage renewable intermittency, grid stability and resilience.
- Economics: The economic viability of SMRs within future energy markets, including electricity, hydrogen and heat markets.

SMALL MODULAR REACTORS' POTENTIAL FOR DECARBONIZATION

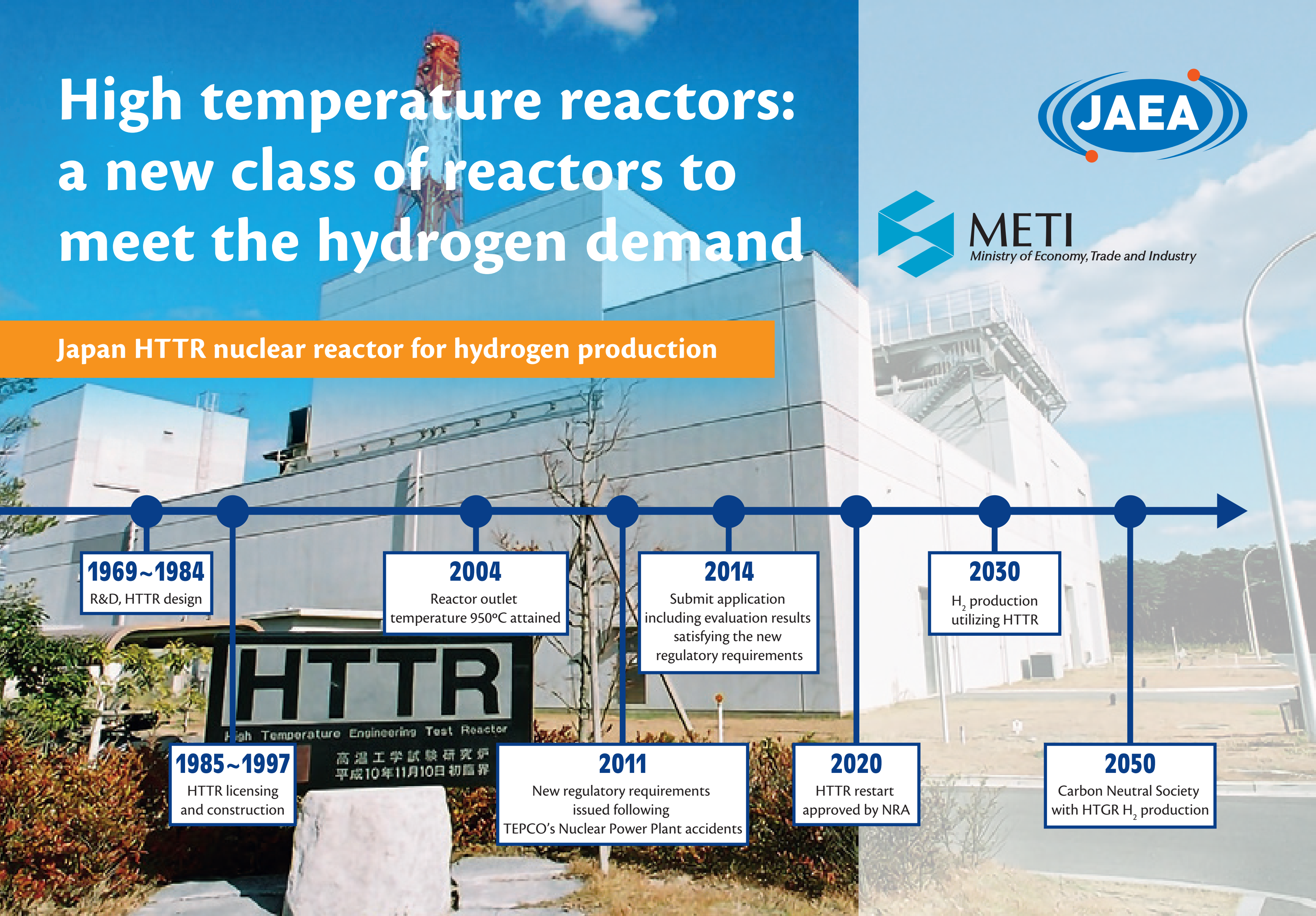
These opportunities for SMRs have the potential to significantly contribute to the European and worldwide energy decarbonization. SMRs have the capacity to be a reliable, resilient, and affordable clean energy option, providing electricity, heat, hydrogen and support a wide range of energy needs. The integration of nuclear reactors, and in particular small modular reactors, into hybrid energy systems is a new R&D topic to be investigate for points of view of safety, design, flexibility, and societal acceptance. The aim of the TANDEM project is to highlight the potential role of small modular reactors in the development of the future European decarbonized energy mix and build an open and long-term community that will ensure expertise in the domain and support the wide acceptance of small modular reactors at different levels.

High temperature reactors: a new class of reactors to meet the hydrogen demand

JAEA

METI
Ministry of Economy, Trade and Industry

Japan HTTR nuclear reactor for hydrogen production



1969~1984
R&D, HTTR design

1985~1997
HTTR licensing and construction

2004
Reactor outlet temperature 950ºC attained

2011
New regulatory requirements issued following TEPCO's Nuclear Power Plant accidents

2014
Submit application including evaluation results satisfying the new regulatory requirements

2020
HTTR restart approved by NRA

2030
H_2 production utilizing HTTR

2050
Carbon Neutral Society with HTGR H_2 production

HTGR WILL CONTRIBUTE TO CARBON NEUTRALITY VIA UNIQUE HIGH-TEMPERATURE HEAT WITH EXCELLENT SAFETY

FROM R&D TO DEMONSTRATION

Since 1969, Japan has continued efforts to demonstrate the potential of high temperature gas-cooled reactors (HTGRs) to meet future energy needs, moving from research and development to demonstration and licensing of the first demonstration unit, the High Temperature Engineering Test Reactor (HTTR). Now, after a period of HTTR inactivity, Japan is looking to this technology to advance the country's energy transition. The HTTR was approved to restart in 2020 and is expected to produce hydrogen at scale by 2030.

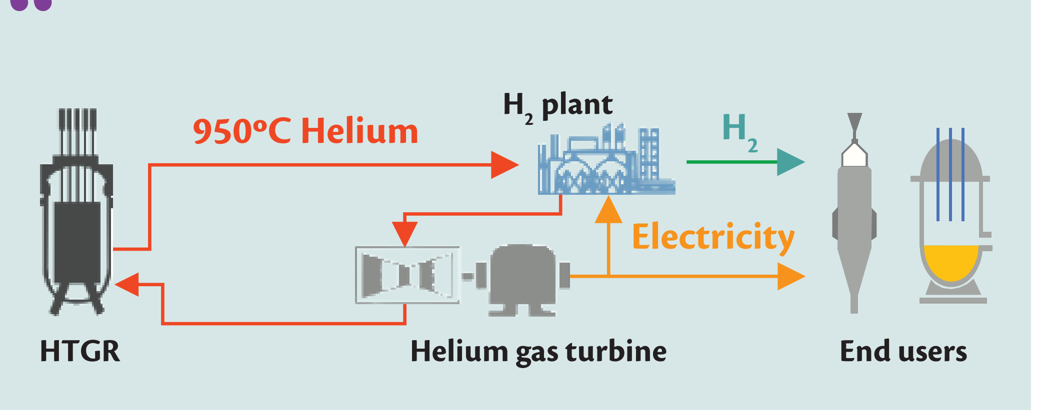
HTGRs can provide output temperatures three times hotter than traditional light water reactors. Thanks to this feature, HTGRs are expected to aid the decarbonization of industry on multiple fronts: Producing high-efficiency, low-carbon hydrogen via thermal decomposition of water; Providing low-carbon heat for hard-to-abate industries that require high temperatures, such as steel manufacturing; Generating high-efficiency, low-carbon electricity.

WALKAWAY SAFETY

HTGRs have excellent safety features, including those offered by the coated fuel particles (CFPs) utilized in the HTTR. These small black balls, less than 1 mm in diameter, are wrapped in a thin, heat-resistant ceramic layer composed of silicon carbide and carbon. Even at temperatures exceeding 1000°C, this coating will remain intact, ensuring that the fuel inside remains protected. These precautions, combined with the high heat capacity of the graphite moderator and helium coolant, provides HTGRs with a high degree of "passive" safety.

HTGRS TO SUPPORT NET ZERO GOALS BY 2050

HTGRs are expected to play an important role in attaining carbon neutrality by 2050 by enabling the decarbonization of otherwise hard-to-abate industrial sectors. One HTGR can produce 80,000 tons of hydrogen per year, with an expected production cost of 1 USD/kg in 2050 for a combined use of power generation and heat supply. Japan's HTTR is a leader in demonstrating the important role that nuclear energy can play in a future global hydrogen economy.



Clean synthetic fuels gigafactory

A report by TerraPraxis

TERRA PRAXIS

ENERGY INNOVATION FOR A PROSPEROUS PLANET

Powered 100% by philanthropy, TerraPraxis is a non-profit organization that innovates and incubates scalable solutions for a livable planet and human prosperity.

Climate change is an energy problem. We believe that when the true challenges of achieving a clean, affordable, and reliable energy transition by 2050 start to bite, the more necessary zero-carbon advanced heat sources (advanced fission, fusion, or super-hot rock geothermal) will be to protect people and the planet, particularly for the difficult-to-decarbonize sectors of industrial heat, coal, and heavy transport. TerraPraxis has been anticipating this demand and has been designing transformative strategies to achieve the urgency, scale, and low costs required (for coal plant conversion, flexible co-generation, clean hydrogen, and clean synthetic fuels production).

TerraPraxis' flagship programs – Repowering Coal and Clean Synthetic Fuels – could accelerate the reduction of global carbon emissions by repurposing trillions of dollars of existing infrastructure to supply clean, affordable, and reliable energy to billions of people.

THE MISSING LINK TO A LIVABLE CLIMATE

The world can still meet the Paris goals of 1.5-2°C if sufficient, low-cost, clean hydrogen is produced to replace oil and gas in shipping, aviation and industry, according to a major new report, co-authored by *TerraPraxis: Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals.*

TerraPraxis' report introduces an innovative climate solution for a 'Hydrogen Gigafactory' to produce abundant clean hydrogen-based synthetic fuels at prices that can outcompete fossil fuels within 10 years, and at a scale that can displace the 100 million barrels of oil that are currently consumed around the world each day.

Hydrogen-based synthetic fuels produced via Gigafactories can enable rapid affordable decarbonization of carbon-intensive sectors such as shipping, aviation and industry that are difficult to electrify, and for which there are currently no viable alternative solutions. Oil and gas use in these sectors is currently projected to represent more than half of energy consumption until mid-century, creating a high risk of a 3-4°C trajectory of warming by 2100.

WHAT IS A GIGAFACTORY?

The Hydrogen/Synfuels Gigafactory is a fully integrated facility that manufactures advanced heat sources and other needed components that are then installed and operated on the same site for highly efficient, low-cost and large-scale production of hydrogen and clean synthetic fuels. The combination of low specific capital cost and low operational costs to produce emissions-free heat and power enables the Gigafactory to produce two million Tonnes of hydrogen per year for less than USD 1/kg on a site of less than 4 km^2.

The hydrogen can be fed directly into existing gas networks or used for other applications such as conversion to ammonia. The Gigafactory could produce 5.5 million tonnes of ammonia or 50 million barrels of synthetic hydrocarbon fuel per year. The Gigafactory can be sited on former coastal refinery and industrial sites, creating high-paying jobs, often to depressed industrial areas. To give a sense of the scale, just twelve Gigafactories placed on existing former refinery sites in the UK could supply the country's current oil and gas demand.

Since publishing this report in September 2020, TerraPraxis has been leading engagement with a wide range of stakeholders around the world – including governments, large liquid fuels users, major oil producers, policy makers and NGOs – to make the Gigafactory a reality.

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The “Nuclear-Hydrogen Digest: The Role of Nuclear Energy in a Hydrogen Economy” report, was authored by experts from around the world representing many different organizations. The views expressed in the report are the views of the authors and do not necessarily represent a statement of the views of the Clean Energy Ministerial, or its member countries, the Nuclear Innovation: Clean Energy Future (NICE Future) initiative or its Flexible Nuclear Campaign (FNC) for Nuclear Renewables Integration and its Campaign to Research the Impacts on Social Equity and Economic Empowerment (RISE3), the Hydrogen Initiative, or its participants or any of their sponsoring governments or organizations or partners, the Joint Institute for Strategic Energy Analysis, the National Renewable Energy Laboratory nor the TANDEM consortium. No warranty is expressed or implied, no legal liability or responsibility assumed for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, and no representation made that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring.

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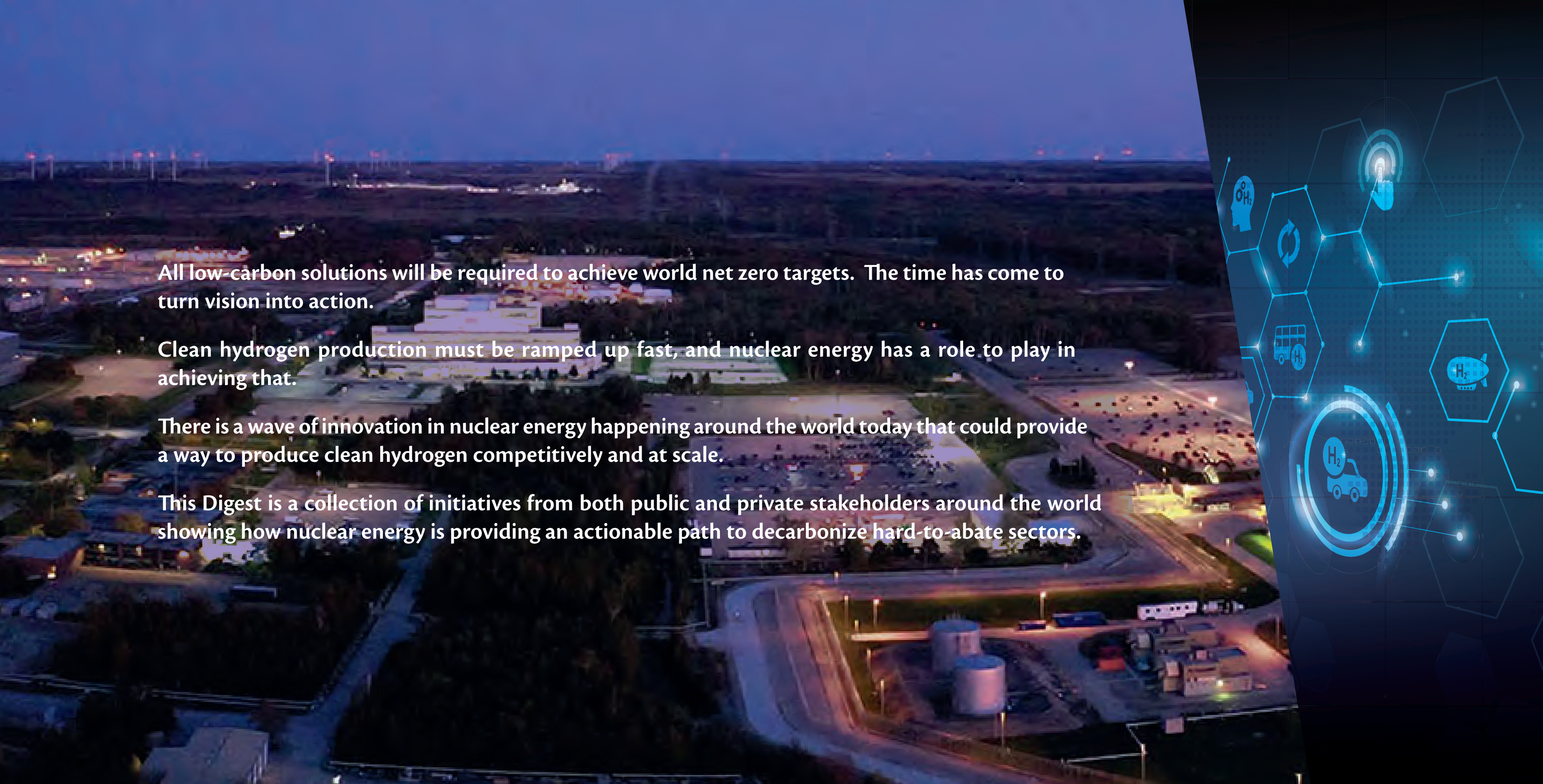

All low-carbon solutions will be required to achieve world net zero targets. The time has come to turn vision into action.

Clean hydrogen production must be ramped up fast, and nuclear energy has a role to play in achieving that.

There is a wave of innovation in nuclear energy happening around the world today that could provide a way to produce clean hydrogen competitively and at scale.

This Digest is a collection of initiatives from both public and private stakeholders around the world showing how nuclear energy is providing an actionable path to decarbonize hard-to-abate sectors.