

Zero-Carbon Hydrogen: An Essential Climate Mitigation Option

Nuclear Energy's Potential Role

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ENERGY OPTIONS
NETWORK

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SUMMARY

The world needs more zero-carbon energy solutions to displace carbon emissions from oil, natural gas and coal use. Economically-competitive, zero-carbon hydrogen — as direct hydrogen fuel or liquid fuel feedstock, primarily ammonia — offers tremendous promise toward eliminating emissions from fossil fuels.¹ A wide range of energy technologies may be able to produce the vast amounts of needed zero-carbon hydrogen. These include nuclear fission, photovoltaics (PV), wind, natural gas with carbon capture and sequestration (CCS), fusion energy and SuperHot geothermal energy (SHGE).²

Zero-carbon hydrogen industries are not starting from square one:

- A solid foundation exists in the *fossil fuel-based* hydrogen industry, which has tripled in size since 1975.
- Substantial public policy, research, development and commercialization of hydrogen fuels activity is already underway. Japan is the clear leader in moving to zero-carbon hydrogen fuels, but they are not alone. There are also many other examples of useful hydrogen energy activity throughout the world, including in United Kingdom (UK), European Union (EU), China, South Korea and California.

- In the mid-twentieth century, several initiatives began exploring technologies for producing hydrogen from nuclear energy. While this work did not lead to commercial deployment, it produced a body of knowledge about technology options, which are now available to support expanding nuclear hydrogen production.

While several competing technologies can potentially produce zero-carbon hydrogen at large scale, future hydrogen demand could transform nuclear fission — given the very large size of and relatively immediate need for these hydrogen markets. Extensive work has explored plausibly optimal paths to nuclear production of hydrogen by significantly reducing nuclear costs and deployment times.³ Nuclear energy produces both electricity and heat and operates at very high capacity factors, making it well suited to large-scale production of low-cost, zero-carbon hydrogen. At Energy Options Network's (EON's) projected costs, assuming much expanded hydrogen markets and optimal development of very large-scale hydrogen projects, nuclear hydrogen production appears *potentially* competitive with other currently available zero-carbon hydrogen production systems, including methane reforming of natural gas with CCS — today's low-cost option.

Economically-competitive, zero-carbon hydrogen — as direct hydrogen fuel or liquid fuel feedstock, primarily ammonia — offers tremendous promise toward eliminating emissions from fossil fuels.



▲ Japanese Prime Minister Shinzo Abe driving Toyota's hydrogen fuel cell Mirai.

Credit: The Asahi Shimbun / Contributor

Large zero-carbon hydrogen markets would greatly expand global nuclear industry opportunities, which today focus on producing electricity. This focus constrains nuclear development to national, “siloed” power markets that are too small to support development of optimal nuclear technology designs and deployment methods. Some of these power markets are also located in countries like the US, where natural gas costs are very low and/or the significant deployment of subsidized intermittent renewables generation has degraded nuclear power economics. However, future zero-carbon hydrogen market opportunities will dwarf today's nuclear power market prospects. For example, 360-650 GWe of nuclear capacity would be needed to supply 50 to 100% of projected marine shipping fuel demand in 2050 — equaling or doubling today's global installed nuclear capacity. For broader potential hydrogen markets, supplying only modest shares of end-use energy with nuclear hydrogen, global installed

capacity would be much greater. Supplying 25% of global oil and 10% of global natural gas demand by 2050 would require development of 4000 to 6000 GW of nuclear capacity, a factor of ten greater than exists today.

As nuclear's share of hydrogen production expands, competition will likely expand through innovative development of competitive zero-carbon hydrogen production technologies, like fusion energy and SHGE.

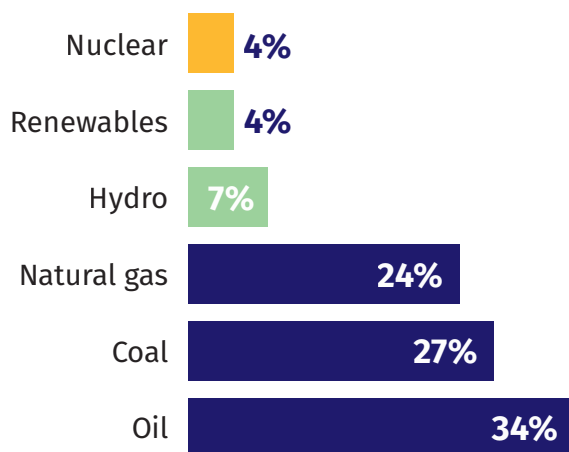
Establishing extensive production and application of zero-carbon hydrogen will require significant transformation of public policy, energy business structures, energy systems infrastructure, end-use energy application technologies and expansion of global hydrogen markets, together with the clearing of obstacles that stand in the way of hydrogen market growth. This transformation will likely take several decades.

INTRODUCTION

The world clearly needs more zero-carbon energy solutions to significantly reduce future carbon emissions. Figure 1 shows fossil energy continues to dominate global energy production. Oil and natural gas produce about two-thirds of global carbon emissions and coal emissions over a quarter. And significant increases in future global energy demand are certain. Few zero-carbon technologies are available today to **rapidly** displace oil and gas use at scale, particularly for mobility and industrial energy demand. Zero-carbon energy solutions need to be available to replace fossil fuels in all sectors.

Zero-carbon hydrogen could significantly contribute to eliminating future oil and gas use, as well as some carbon emissions from coal. Very large amounts of zero-carbon hydrogen will be

Figure 1. Shares of Primary Global Energy by Fuel Consumption (2018)



Source: BP Statistical Review of World Energy 2019⁴

The world clearly needs more zero-carbon energy solutions to significantly reduce future carbon emissions.

needed as direct fuel (hydrogen) or as feedstock to produce ammonia. Ammonia has thermal properties similar to propane, is easy to compress into liquid form for transportation and storage, and has an energy density that is competitive with carbon-based fossil fuels.⁵

This report explores possible ranges of zero-carbon hydrogen production likely needed to support decarbonization of the global energy system, how zero-carbon hydrogen can be produced and how future zero-carbon hydrogen demand could enable significant expansion of nuclear fission deployment, along with other competing zero-carbon hydrogen production technologies.⁶

In-depth treatment of key report topics and analysis are presented in the following appendices, which can be found in the full report at EON's website:

energyoptionsnetwork.org

- **Appendix A: EXPLORING THE POTENTIAL SIZE OF FUTURE ZERO-CARBON HYDROGEN MARKETS** explores a range of possible future US and global zero-carbon hydrogen market scenarios — some looking out as far as 2100. This analysis used EON's global energy model and shows these markets could be much larger than today's global power markets.

- **Appendix B: OPTIMAL NUCLEAR HYDROGEN PRODUCTION** describes the extensive nuclear hydrogen production technology R&D that has established a solid technology foundation for future optimal nuclear energy hydrogen production.
- **Appendix C: LARGE NUCLEAR FACTORIES FOR HYDROGEN PRODUCTION** explores plausible very large-scale nuclear hydrogen production facilities, their production systems and potential cost ranges.
- **Appendix D: FUTURE DEMAND FOR ZERO-CARBON HYDROGEN CAN CREATE LARGE FAVORABLE MARKETS FOR NUCLEAR FISSION** explores how future large scale zero-carbon markets could support development and deployment of optimal nuclear hydrogen production systems.
- **Appendix E: EON'S GLOBAL ENERGY MODEL** describes the model and the full analysis conducted for this project.



ZERO-CARBON HYDROGEN TO ADDRESS CLIMATE CHANGE

Zero-carbon hydrogen can be produced today at large scale by several energy technology processes that emit no greenhouse gases, including nuclear fission. Two recent overviews of future zero-carbon fuels prospects, applications and pathways are presented in the Clean Air Task Force report *Fuels Without Carbon*⁷ and in the International Energy Agency's (IEA's) recent *Future of Hydrogen Report*.⁸ These reports detail the crucial role hydrogen-based zero-carbon fuels can play in decarbonizing the power, transportation, industrial and building sectors and the contributions they can make to climate change mitigation.

Establishing extensive production and application of zero-carbon hydrogen will require significant transformation of public policy, energy business structures, energy systems infrastructure, energy production, application technologies and global hydrogen markets expansion. These transformations must initially be driven by strong public policy until zero-hydrogen energy production and application systems become competitive with fossil energy systems, and obstacles constraining deployment of zero-carbon hydrogen production technologies are removed. This transition to widespread use of hydrogen fuels will likely take several decades — even if events “go well.”



ZERO-CARBON HYDROGEN TODAY

Zero-carbon hydrogen markets are already emerging in some parts of the world. Policy-driven activities have created early global zero-carbon hydrogen markets that will expand as the world mobilizes to address climate change effectively. In some cases, applications are beginning with conventional hydrogen production processes that emit carbon, like methane reforming. These situations get hydrogen energy technology applications moving, expecting that affordable zero-carbon hydrogen sources will eventually follow. Several examples show the diversity of these current activities.⁹

Japan

Japan has established a significant national hydrogen fuels program and has indicated it intends to purchase large amounts of zero-carbon hydrogen fuel (both hydrogen gas and ammonia) in the near future. Japan's Ministry of Economy, Technology and Industry (METI) produced a comprehensive hydrogen strategy roadmap in 2017 and updated it in 2019.¹⁰ The roadmap's goal is to replace fossil fuel use in Japan with zero-carbon hydrogen. It includes ambitious hydrogen use targets in mobility, power generation, commercial and industrial sectors and sets significant cost reduction targets. Rapid expansion of hydrogen fuel cell use is anticipated in buildings and mobility applications, including cars (fuel cell vehicles (FCVs))¹¹, buses and other vehicles (e.g., forklifts, large trucks, tractors), along with associated hydrogen fuel infrastructure. **To achieve the ambitious national hydrogen strategy targets, the government is supporting regulatory reform, technology development assistance and private sector collaboration.**

Several power sector projects are exploring co-firing ammonia and coal in boilers and ammonia



▲ The Chugoku Electric Power, Mizushima Coal Power Station in Kurashiki, Okayama co-fires with ammonia.

and natural gas in combustion turbines.¹² Japan plans to broadly mix ammonia with coal at power plants and use ammonia in combustion turbines by around 2030. To eventually generate power solely through hydrogen fuels, Japan is supporting commercialization of combustion technologies with low NOx emissions combined with higher efficiency hydrogen fuels combustion.

Marine shipping is another important hydrogen fuel application target. In September 2019, the Japan Engine Corporation announced a partnership with the National Maritime Research Institute (NMRI) to begin developing engines fueled by hydrogen and ammonia.¹³ This builds on several years of ammonia engine development at NMRI as part of their Cross-Ministerial Strategic Innovation Promotion Program's (SIP) Energy Carriers initiative.¹⁴ The SIP program funded R&D focusing on "efficient and cost-effective technology for utilizing hydrogen" and included R&D for ammonia-fired gas turbines, ammonia co-firing



with fossil fuels, ammonia fueling for industrial furnaces, direct ammonia solid oxide fuel cells, and more efficient ammonia production methods.¹⁵

Toyota has recently introduced a “second generation” fuel cell car into the global FCV market.¹⁶

Japan is today the global leader in the transition to hydrogen fuels and has committed significant resources for several years to support developing the technology and infrastructure needed to broadly enable practical use of hydrogen fuels. With their nuclear power stations largely mothballed, Japan plans to import zero-carbon hydrogen and ammonia from outside Japan.

South Korea¹⁷

South Korea is another hydrogen fuels front runner, with significant action described in the *Hydrogen Economy Roadmap of Korea*¹⁸ and the *National Roadmap of Hydrogen Technology Development* in 2019. Targets include:

- Producing 6.2 million FCVs by 2040
- Replacing 40,000 buses and 80,000 taxis with hydrogen vehicles and deploying 80,000 hydrogen trucks by 2040

South Korea had 24 hydrogen refueling stations (HRS) in 2019 and plans to build 310 HRS by 2022 and 1200 HRS by 2040. Fuel cell power generation is also a priority, along with facilitating hydrogen fuels infrastructure development in four pilot cities. The objective in these pilot cities is to build the infrastructure necessary for hydrogen production, transport and distribution to utilize hydrogen for pilot city heating, transport and power generation.

DSME, one of the Korea’s largest shipbuilders, has spent years “preparing [for] the ammonia era... [and] is planning to expand [its] technology and business to ammonia engineering and systems for commercial ships.”¹⁹

UK and EU

The UK is actively exploring blending hydrogen into their natural gas distribution systems, with a long-term target of 100% hydrogen.²⁰

Germany plans to develop 400 hydrogen fueling stations by 2023, using the “H2 Mobility” framework launched by six European private companies in 2015.²¹ Hydrogen production demonstration projects have been conducted at about 30 wind and solar project sites.

German gas pipeline operators have presented a plan to create a 1,200-kilometer hydrogen transport system by 2030: H2 Startnetz. This hydrogen grid would initially connect zero-carbon renewables hydrogen production projects in Northern Germany with consumption centers. This project is a first step towards a theoretical 5,900 km hydrogen grid that would rely 90% on the existing natural gas pipeline network.²²

Policies and activities can facilitate expansion of zero-carbon hydrogen markets many times beyond today's hydrogen market.

The EU has defined “Premium Hydrogen” (i.e., hydrogen coming from renewable energy) and developed a “Premium Hydrogen” certification system roadmap. “Premium Hydrogen” will be used in steelmaking and oil refining processes under an initiative to reduce industrial sector carbon emissions.²³

A French automaker has developed an electric vehicle using hydrogen fuel cells to power the battery to increase driving range, selling about 200 units through the end of 2019. France plans to expand hydrogen fuel use while minimizing initial investment and anticipates broad deployment of hydrogen fueling stations in the second half of the 2020s.²⁴

China

In 2016, China released a roadmap for scaling up the number of FCVs, targeting deployment of one million FCVs and 1,000 hydrogen fueling stations by 2030. The 13th National People's Congress included language “promoting the construction of hydrogen facilities” in resulting government guidance documents, suggesting that hydrogen production and FCV use has become a national priority.

US

- California's hydrogen FCV program has moved commercial hydrogen fuel cell long-haul truck tractor offerings into the market,²⁵ and one long-haul FC truck tractor manufacturer has outlined a vision of establishing 700 hydrogen fuel truck stops throughout the US, covering a large fraction of today's long-haul trucking traffic.

- The Illinois-based Gas Technology Institute (GTI) is the leading US research, development and training organization focused on the natural gas distribution industry. GTI is currently testing all US natural gas transport and distribution infrastructure components for various hydrogen fraction blends with natural gas. GTI plans to develop standards for hydrogen use in existing gas infrastructure equipment to determine how much hydrogen can be blended into existing natural gas systems.
- The US DOE recently established a “H2@Scale” initiative, funding projects and National Laboratory activities to “accelerate the early-stage research, development and demonstrations to apply hydrogen technologies.”²⁶ In August, 2019, the DOE announced funding for a project with Exelon — the largest US nuclear power plant “fleet” owner — to produce, store and use hydrogen produced at an existing nuclear plant. And ARPA-e subsequently funded FirstEnergy Solutions, Xcel Energy and Arizona Public Service to demonstrate hydrogen production at existing nuclear facilities as well.²⁷

These efforts highlight global zero-carbon hydrogen fuels momentum and the range of applications underway. Combined with recently expanding climate NGO awareness of the need to develop large amounts of zero-carbon hydrogen fuels, these types of policies and activities can facilitate expansion of zero-CO₂ similar policies and activities can facilitate expansion of zero-carbon hydrogen markets many times beyond today's hydrogen market.

HOW MUCH ZERO-CARBON HYDROGEN COULD BE NEEDED TO ADDRESS CLIMATE CHANGE?

Looking well beyond 2050 and considering high energy growth scenarios to explore the zero-carbon hydrogen needed to support decarbonizing the global energy system is critical, as we should “plan for the worst and hope for the best” given what is at stake. EON used its global energy system model²⁸ to project future energy demand in 2050 and 2100, addressing both “mainstream” and possible “higher growth” scenarios to explore more challenging decarbonization challenges than are typically addressed by most forecasters.²⁹

The need to consider future growth in energy consumption is clear. The US EIA projects 2050 global energy demand of about 812 quads, a **40% increase** over 2015 energy consumption. EON’s High Growth 2050 case projects 1200 quads by 2050, about a **107% increase** from today’s levels. And EON’s 2100 base case of 2005 quads is about a **250% increase** from today’s levels.

Recognition is emerging that zero-carbon hydrogen-based fuels will be essential to displace much future fossil fuel use within this broad range of projected future energy demand levels. Although electrification is expected to help, it is clear that certain energy applications will require a zero-carbon gaseous or liquid fuel. Effective displacement of future fossil energy requires that sufficient technologies capable of providing affordable zero-carbon energy are available in *all potentially plausible energy futures*.

EON explored plausible, large future zero-carbon hydrogen demands to illustrate how much nuclear capacity would be needed to meet such projected hydrogen demands.³⁰ Four nuclear hydrogen production scenarios were assessed: 1) zero-carbon ammonia providing 50% of 2050 marine shipping fuel, 2) displacing 10% of natural gas by blending 10% hydrogen into the US natural gas infrastructure, 3) ammonia supplying 10% of global transportation fuel by 2040 and 4) hydrogen displacing 25% of global oil and 10% of global natural gas markets by 2050 and 2100. These scenarios are fully described in Appendix A. They show that if nuclear energy captures even a small portion of potential future zero-carbon hydrogen demand, it would dwarf today’s ~400 GWe of global nuclear power capacity – the result of six decades³¹ of nuclear power deployment.

- Supplying just 10% of global transportation energy with ammonia by 2040 would double current **global** hydrogen production.
- Displacing only 25% of the **global** oil market and 10% of global natural gas by 2050 with hydrogen would require ten times current hydrogen production. EON’s higher growth case would require about *15 times today’s hydrogen production*.

Table 1 illustrates how large this nuclear market could be through 2100.

Recognition is emerging that zero-carbon hydrogen-based fuels will be essential to displace much future fossil fuel use within this broad range of projected future energy demand levels.

Table 1. Estimated New Nuclear Capacity Needed to Displace Portions of Future Oil and Natural Gas Markets (GWe-equivalent)

Global Oil & Natural Gas Demand	2050		2100	
	Base Case	Higher Growth	Base Case	Higher Growth
Global oil demand	243 quads*	359 quads	599 quads	837 quads
Nuclear-enabled displacement % of oil demand	25%	25%	25%	25%
Nuclear-enabled displacement of oil demand	61 quads	90 quads	150 quads	209 quads
Global natural gas demand	218 quads	322 quads	539 quads	753 quads
Nuclear-enabled displacement % of NG demand	10%	10%	10%	10%
Nuclear-enabled displacement of NG demand	22 quads	32 quads	54 quads	75 quads
Total nuclear-enabled displacement of oil & NG	83 quads	122 quads	204 quads	284 quads
• in Gigajoules (GJ)	87 billion GJ	129 billion GJ	215 billion GJ	300 billion GJ
• in metric tons of hydrogen	0.73 billion t	1.07 billion t	1.79 billion t	2.50 billion t
• in Nm ³ of hydrogen	8 trillion Nm ³	12 trillion Nm ³	20 trillion Nm ³	28 trillion Nm ³
Estimated new nuclear capacity (GW) to displace 25% of global oil and 10% of global natural gas demand	3,972	5,871	9,800	13,686

*"Quads" refer to quadrillion Btus

Nuclear energy does not dominate hydrogen production in Table 1 scenarios. Given the substantial potential cost reductions and deployment efficiency benefits

these market scenarios would inevitably deliver, nuclear capacity needed to displace oil and natural gas use by 2050 and later could be much higher.

Nuclear capacity needed to displace oil and natural gas use by 2050 and later could be much higher.

WHAT TECHNOLOGIES COULD PRODUCE THE NEEDED ZERO-CARBON HYDROGEN?

Many technologies can produce zero-carbon hydrogen today: natural gas reforming combined with CCS, PV, wind, and nuclear fission. Promising pre-commercial technologies include fusion energy and SHGE. The emergence of large, zero-carbon hydrogen markets will accelerate commercialization of existing competing technologies and potentially draw additional technologies to commercial status.

Technology maturity, economics and current and potential deployment constraints vary widely across these potentially competing hydrogen production technologies. Potential hydrogen production

deployment constraints that could impact some zero-carbon hydrogen technologies include, but are not limited to: current technology status (commercial, very early stage, etc.), locational requirements, safety licensing systems, significant early stage R&D costs and timing and business model/structure evolution. Thus, formulating reliable technology development and commercial deployment timelines today remains challenging. However, it is safe to say that many technologies with the potential for very large-scale hydrogen production will take significant time to reach commercial deployment.



NUCLEAR HYDROGEN PRODUCTION

To produce a significant fraction of future global energy demand, nuclear energy will require: 1) deployment of nuclear generation at a much larger scale than occurs today, 2) significant reduction of nuclear plant life-cycle costs (including capital costs of \$1000/kWe or less) and 3) significant scale-up of thermochemical or electricity-based hydrogen production processes.

Accomplishing this will require transformative nuclear plant designs, advanced manufacturing approaches and innovative deployment models. And while dramatic scale-up of nuclear fission faces challenges, core nuclear fission technology is quite mature. Recent work has mapped out pathways to improve and expand the role of nuclear fission, recognizing the demands and markets that fission could meet beyond electric power generation opportunities.³²

Nuclear fission has a key hydrogen production advantage over intermittent generation alternatives

like PV and wind; nuclear's ability to run at a very high annual generation capacity means the necessary hydrogen production capital equipment would also operate at very high annual capacities. This is not possible for intermittent generation absent significant additional energy storage and associated costs.

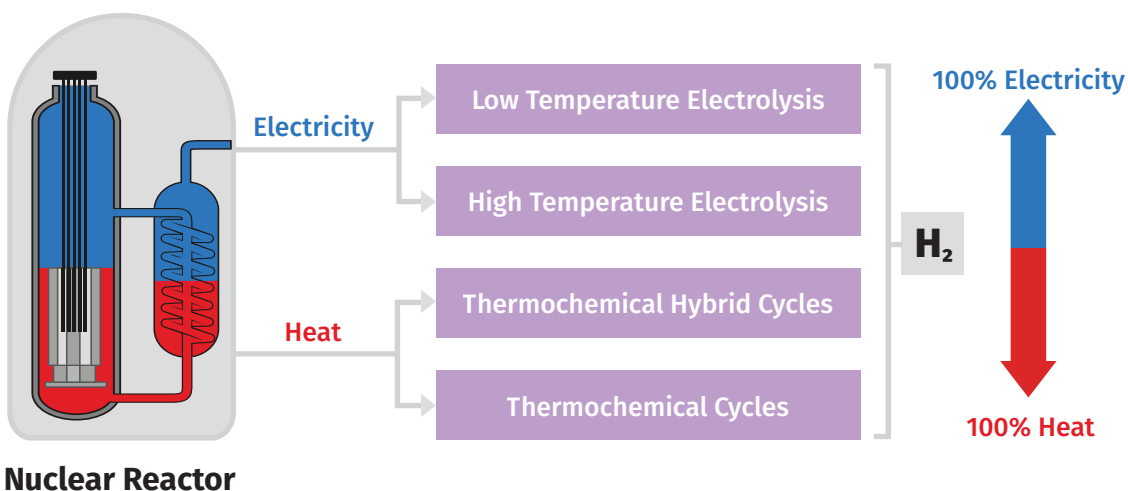
Nuclear fission is thus potentially well positioned for transformation and significant future deployment as zero-carbon hydrogen markets expand.

Nuclear Hydrogen Production Process Options

Figure 2 shows process technology options for generating hydrogen with nuclear power, ranging from those using only electricity to those using only heat.³³

An inherent advantage over technologies that only produce electricity (like wind and PV) is nuclear's

Figure 2. Options for Nuclear Reactor Coupling to Hydrogen Production (Sink, DOE 2004)



An inherent advantage over technologies that only produce electricity (like wind and PV) is nuclear's capacity to produce both electricity and heat, affording it the ability to take advantage of all hydrogen production technology options.

capacity to produce both electricity and heat, affording it the ability to take advantage of all hydrogen production technology options.

Starting with low-temperature electrolysis (LTE) at the top, advanced reactors that operate at higher temperatures than light water reactors (LWRs) could be used to improve the thermal energy to hydrogen efficiency of the current commercially-available electrolysis processes from about 28-30%³⁴ to as high as 35-38%.³⁵ This path is a mid-term opportunity to improving the efficiency of nuclear hydrogen production. Moving down these options are processes that combine electricity and process heat and processes that use only heat and improve hydrogen production efficiency.

Nuclear reactor hydrogen production has a rich history. Significant progress developing hydrogen production pathway processes evolved from the 1960's through the mid 2000's. While the rate of hydrogen production processes development declined as the nuclear industry lost momentum, interest in promoting and further deploying hydrogen production technology has resumed, primarily due to ever-increasing climate change concerns. This renewed interest in hydrogen production processes development coincides with recent interest and investment in advanced reactor development.

Optimal Nuclear Development Pathways

Broadly speaking, two paths can drive nuclear energy systems cost reduction and deployment at scale. The first is to move the factory to the project so manufacturing and assembly of nuclear heat and power generating capacity is co-located and

integrated into the overall project. This is not just having more components of the plant manufactured and then delivered to a conventional construction project. This means organizing the site as part of the factory. The second approach is to move the entire project to a highly-productive manufacturing environment, most likely a shipyard, which also enables ocean delivery of a completed plant.

The first concept could be realized through a large, centralized "oil refinery" model for nuclear hydrogen fuels production, capturing economies of scale and deployment scalability. Nuclear capacity would be deployed at 10's of gigawatts at a refinery-scale site, with extensive integration of site infrastructure. The second concept draws on the experience in shipbuilding and offshore oil and gas industries for design: fabrication and deployment. Both **are radical departures from today's industrial, business and technology model** that define cost outcomes and schedules for today's "build-at-site, one-plant-at-a-time approach," with very little advanced manufacturing, design standardization or offsite modular fabrication.³⁶

Emerging large, zero-carbon hydrogen fuels market demand could remove key current nuclear deployment constraints by:

- Enabling development of very large (relative to current nuclear power stations) nuclear hydrogen fuels production complexes in locations with existing nuclear infrastructure³⁷ combined with global export of produced fuels.
- Creating nuclear complexes that are much larger than today's largest nuclear power stations, which could capture substantial cost reductions and significantly accelerate deployment.

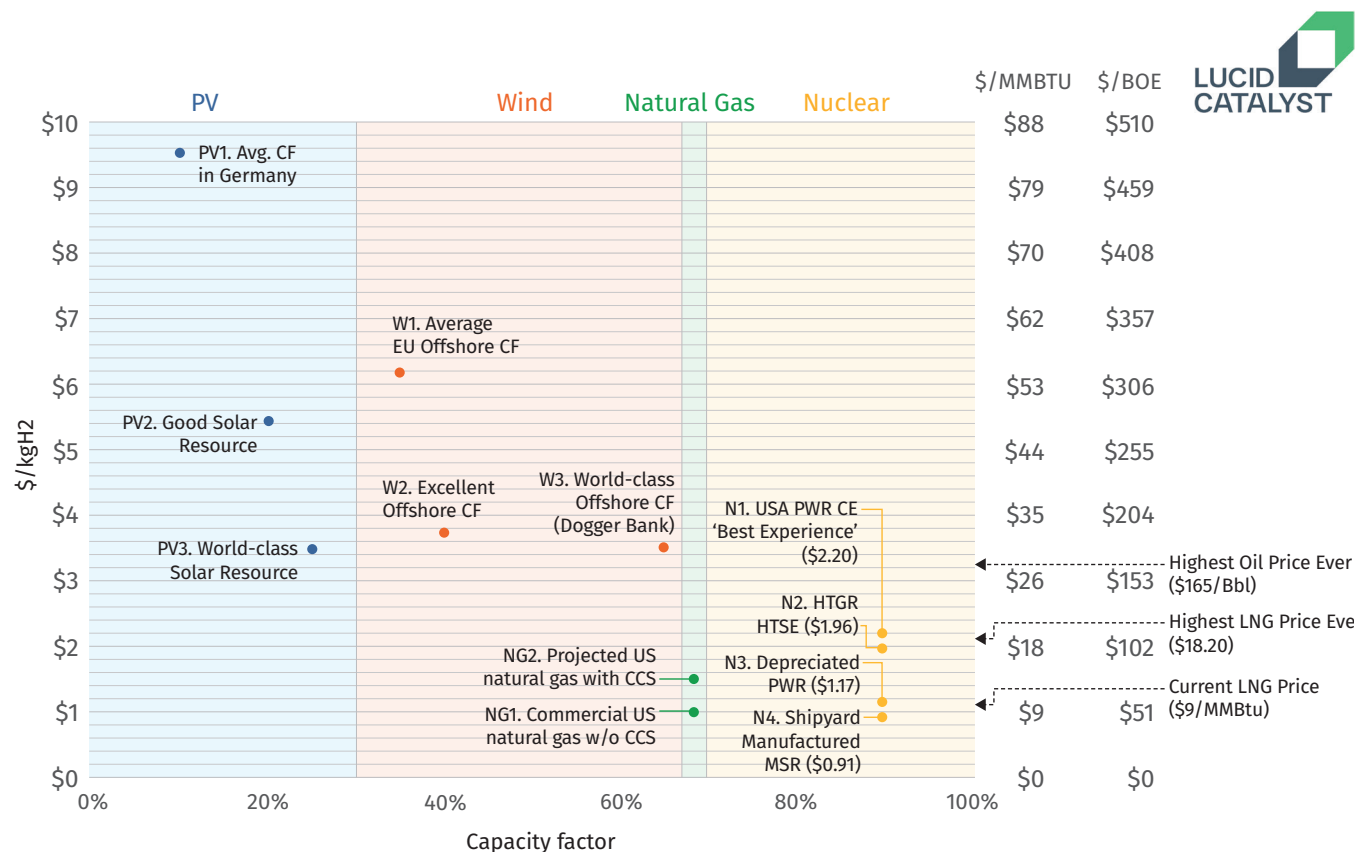
ESTIMATED NUCLEAR HYDROGEN PRODUCTION COSTS

Several analyses have explored potential future zero-carbon hydrogen production costs from nuclear, PV and wind energy.³⁸ EON's project team reviewed these studies and combined some key results with modeling of different projected nuclear reactor and hydrogen production pathways — **assuming very large-scale future hydrogen markets**. These are presented in Figure 3. **Possible achievable future costs** range from about **\$2/kg** to as low as about **\$1/kg** for shipyard manufactured nuclear technology. These projected costs could compete with current fossil based zero-carbon hydrogen production technologies but will face

increasing competition over time from other evolving energy technologies.³⁹

In contrast, commercial production of hydrogen from natural gas with methane reforming today produces hydrogen very cheaply at about \$1/kg. Hydrogen from such projects combined with CCS for about a 90% carbon emissions reduction is projected by the International Energy Agency (IEA) to cost about \$1.50/kg.⁴⁰ Commercially promising natural gas reforming technology being developed by GTI,⁴¹ Haldor Topsøe A/S⁴² and others could further reduce near-term, natural gas-based hydrogen production costs. And

Figure 3. Estimated Hydrogen Production Costs by Generation type (2018 USD)



	Data Point	Description (Source)
PV 1	Avg. Solar Resource in Germany	CF:11% (1); \$1,100/kW (2); \$840/kWe electrolyzer (3)
PV 2	Good Solar Resource	CF: 20% (2); \$1,100/kW (2); \$840/kWe electrolyzer (3)
PV 3	Excellent Solar Resource	CF: 25% (2); \$850/kW (2); \$840/kWe electrolyzer (3)
Wind 1	Avg. EU offshore resource	CF: 37% (4); \$3,000/kW; \$840/kWe electrolyzer (3)
Wind 2	Good onshore resource	CF: 41% (2); \$1,555/kW (2); \$840/kW electrolyzer (3)
Wind 3	World-class resource (Dogger Bank)	CF: 63% (5); \$3,100/kW (6); \$500/kWe electrolyzer*
NG 1	US natural gas w/o CCS	(9) USD 500–900 per kilowatt hydrogen (kWh ₂)
NG 2	US natural gas w/CCS	(9) USD 900–1,600/ per kilowatt hydrogen (kWh ₂)
N1	USA PWR	CF: 90%; \$3,900/kWe (7)*: \$500 electrolyzer**
N2	High Temperature Steam Electrolysis for HTGR	CF: 90%; This figure is sourced from a detailed Techno economic analysis of High Temperature Steam Electrolysis for NGNP (600MWt) HTGR (8). The analysis assumes \$60/MWh for electricity. LucidCatalyst modified this assumption to \$35/MWh.
N3	Fully depreciated US PWR	CF: 90%; \$3,900/kWe (7)*: \$500 electrolyzer**
N4	Shipyard manufactured MSR	CF: 95%; \$800/kWe*, HTSE electrolyzer \$425/kWe**
F1	** Assumes HTSE is made in highly productive shipyard manufacturing environment, thus lowering cost.	(9) More information on the underlying assumptions is available at www.iea.org/hydrogen2019
F2	Projected US natural gas H ₂ production – with CCS (~90% CO ₂ reduction)	(9) More information on the underlying assumptions is available at www.iea.org/hydrogen2019

See full table in Appendix B, Figure B4

large-scale hydrogen production at very large gas reserves using innovative reforming technology and local CCS could *potentially* produce very low-cost, near zero-carbon hydrogen. So considerable technology competition for producing low-cost zero/low-carbon hydrogen will exist as zero-carbon hydrogen markets evolve. Further, as these markets grow significantly, they will likely draw additional competing technologies like SHGE and fusion energy into the market.

Considerable technology competition for producing low-cost zero/low-carbon hydrogen will exist as zero-carbon hydrogen markets evolve.



▲ Today, conversions of existing industrial boilers support operation with hydrogen fuels.

Credit: Bosch Industriekessel GmbH

CAN FUTURE HYDROGEN MARKETS HELP TRANSFORM NUCLEAR FISSION?

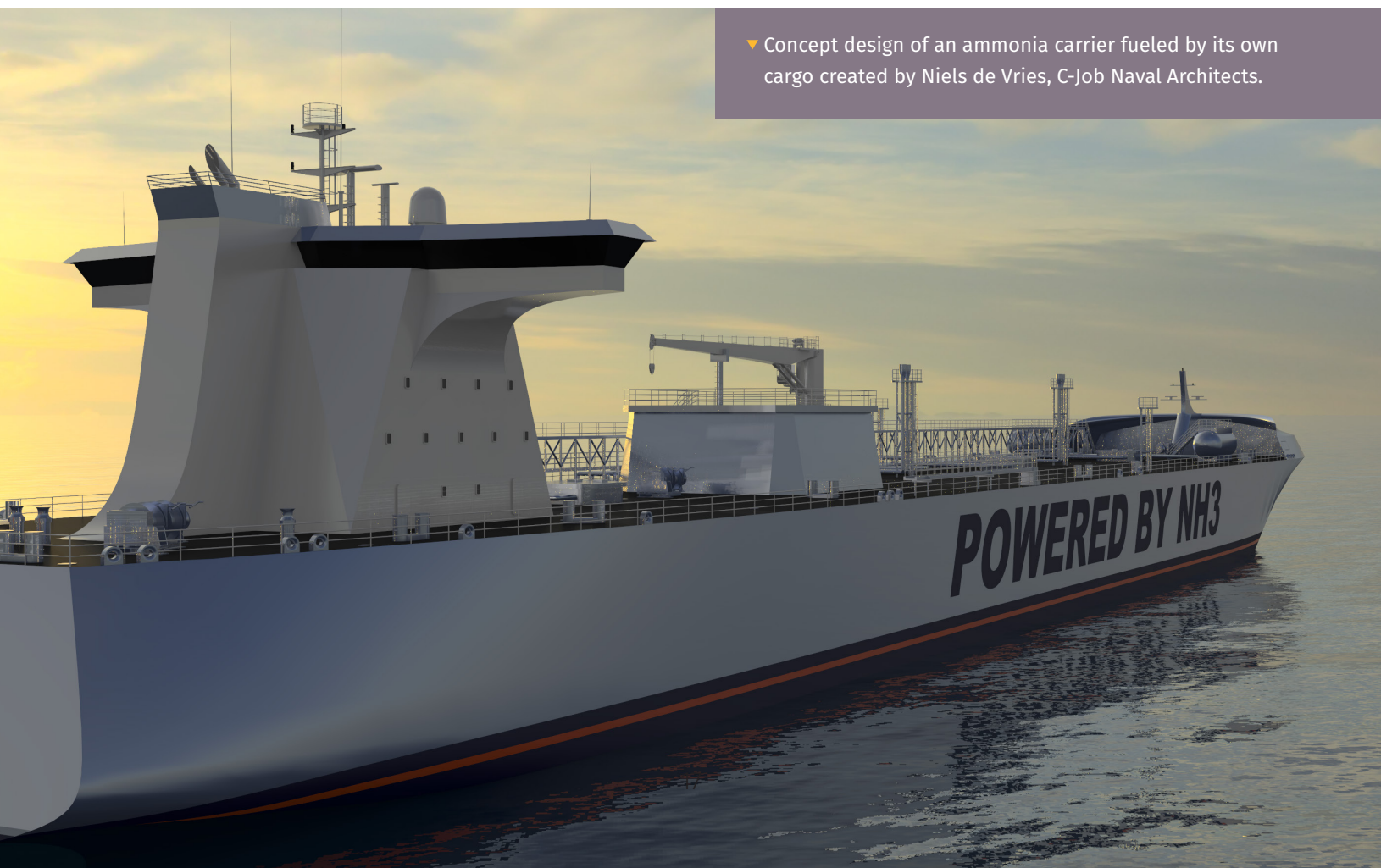
Recent Western experience deploying nuclear power has been challenging, raising questions about whether nuclear energy can meaningfully contribute to addressing climate change.

Today, nuclear energy is used almost exclusively to produce electricity, and nuclear power projects can only be developed in national markets with adequate nuclear infrastructure to manage nuclear safety, technology export, weapons proliferation and waste management challenges.⁴³ Each country has its own nuclear regulatory system, and entering new national markets incurs large upfront cost and time commitments. Many countries with growing energy demand lack the nuclear institutional infrastructure

needed to deploy nuclear energy. So no practical global market exists for nuclear power projects. Extensive site-specific engineering and design keep market entry costs relatively high, and today effectively restart the nuclear project learning curve with each new project, further constraining market access for nuclear power projects.

Most national power markets open to nuclear deployment are relatively small or growing slowly and have not generated sufficient recent demand to facilitate a transition to optimal nuclear power deployment. Further, where power markets have deployed significant amounts of intermittent renewables generation, markets have been degraded

▼ Concept design of an ammonia carrier fueled by its own cargo created by Niels de Vries, C-Job Naval Architects.



If zero-carbon ammonia produced from nuclear energy served only 25% of projected 2050 marine shipping demand, it could still require developing additional nuclear capacity of nearly half today's total global nuclear power capacity.

for nuclear fission, which is most economic if operated at high annual capacity factors.⁴⁴ Current nuclear fission business models, regulatory frameworks and the limited “siloed” national markets they create today, have thus constrained nuclear energy technology from becoming a global commodity product like combustion turbines, coal boilers or PV.

In contrast, the global zero-carbon hydrogen markets must be *very large* to decarbonize the global energy system. For example, projections of marine shipping fuel demand in 2050 exceed current demand, even with substantial improvements in propulsion efficiency. To meet this projected demand with zero-carbon ammonia produced from nuclear energy would require as much as **650 GW** of advanced nuclear reactors dedicated to ammonia production. And if nuclear energy served only 25% of projected 2050 marine shipping demand, it could still require developing additional nuclear capacity of nearly half today's total global nuclear power capacity.⁴⁵

The large future hydrogen fuels markets needed to help decarbonize global energy systems can potentially transform the future of nuclear fission technologies by establishing much larger and more accessible markets that can support larger and lower cost nuclear energy systems. Nuclear energy technology's ability to produce electricity and heat

at very high capacity factors makes it potentially well suited to production of zero-carbon hydrogen production. Recent analyses have documented plausible pathways for transitioning nuclear energy to the low-cost, product-based commodity needed to significantly contribute to the zero-carbon hydrogen production needed to address climate change.⁴⁶

Key factors that could drive nuclear industry, technology and deployment innovation include:

- Large zero-carbon hydrogen markets could enable much larger investment in and scaling up of nuclear technologies than is possible with today's limited national electricity markets.
- Zero-carbon hydrogen could be produced within countries with existing national nuclear infrastructure (safety regulation, etc.) and then exported into global fuels markets — like marine shipping fuel.
- The high annual production capability of nuclear systems is well matched to zero-carbon hydrogen production. This contrasts with many power markets today where substantial and growing penetration of intermittent renewables generation is reducing the opportunity for conventional nuclear power to operate at high, economically optimal capacity factors.

The very large scale of future zero-carbon, hydrogen fuels markets could eventually support creation of truly global nuclear energy (or hydrogen fuels) companies and attract the significant capital investment needed to design, license and deploy low-cost, large-scale nuclear hydrogen production systems.

- Zero-carbon hydrogen production projects would require and enable optimization of nuclear energy system designs that would be product based and use a manufacturing-based delivery model. This would enable development of large, low-cost nuclear complexes to produce large volumes of low-cost hydrogen.
- Zero-carbon hydrogen markets should allow flexible nuclear hydrogen production siting so specific site barriers like power grid congestion and variations in local support for nuclear development can be avoided.
- The potential for large scale export of hydrogen fuels will provide global market access for large nuclear hydrogen production complexes — a radical shift from the limitations of today's nuclear power markets.

The very large-scale of future zero-carbon hydrogen fuels markets could eventually support creation of truly global nuclear energy (or hydrogen fuels) companies (or lines of business) and attract the significant capital investment needed to design, license and deploy low-cost, large-scale nuclear hydrogen production systems. This could lead to commodity-like nuclear energy systems that are manufactured for a highly competitive world market, where economics and cost-reduction curves are more like energy technologies: natural

gas combustion turbines, PV, wind turbines and internal combustion engines. The size of the hydrogen fuels markets and the cost levels required to penetrate this market would enable large-scale manufacturing of low-cost electricity generation products for the electricity market as well. Manufactured plants, optimally designed for large-scale hydrogen production, would have much lower costs than even today's lowest cost light water reactors.

In the near-term, some potential export and domestic markets for zero-carbon hydrogen can also drive demand and bolster policy efforts. For example, limited amounts of low-cost, zero-carbon hydrogen produced with electricity from existing nuclear plants that have paid off their capital costs could be blended into natural gas distribution systems or used as feedstock for “green ammonia” fertilizer production. These early demonstrations could diversify use of some existing nuclear plants⁴⁷ and expand awareness of emerging zero-carbon hydrogen markets and nuclear's potential as a hydrogen supplier. As zero-carbon nuclear hydrogen production costs drop and demand increases, a positive feedback cycle will drive further transformation of nuclear energy hydrogen production systems, and market size will expand, providing opportunities to further evolve the nuclear industry.

CREATING LARGE ZERO-CARBON HYDROGEN MARKETS

Moving from today's limited hydrogen markets that primarily rely on fossil fuels, to the **much larger**, zero-carbon markets needed to displace significant fractions of future fossil fuel consumption will require rapid expansion of an extensive global public hydrogen fuels policy portfolio. Important hydrogen-focused public policy, research, development and commercialization activity is emerging globally and driving early zero-carbon hydrogen fuels production and applications. These activities must be broadly

scaled up and deployed to create sufficient zero-carbon hydrogen demand to address climate change. As zero-carbon hydrogen production technologies evolve to compete economically and practically with fossil fuels, markets will begin to take over, and the need for direct policy initiatives will diminish and ultimately disappear — a process that will likely take at least several decades. Much expanded near-term global hydrogen policy expansion is needed to accelerate this transition.



CONCLUSIONS

The world needs more affordable and broadly deployable zero-carbon energy technology solutions to reduce the many risks challenging complete and rapid decarbonization of the global energy system.

To address this challenge, vast amounts of zero-carbon hydrogen will be needed as direct hydrogen fuel or fuel feedstock. Fortunately, a wide range of energy technologies can potentially produce large amounts of economically-competitive, zero-carbon hydrogen.

Using nuclear fission heat and/or power to produce zero-carbon hydrogen is one possible option to provide a practical and scalable approach to decarbonizing significant portions of the future energy system that is currently fueled by oil, natural gas and coal. This means demand from markets switching to low-cost, zero-carbon hydrogen could potentially enable a new nuclear energy commercialization model, with radical improvements to nuclear plant design and deployment. These changes could transform the nuclear investment and applications landscape and enable nuclear fission to make a significant contribution to addressing climate change.

This large future market opportunity could help address the “chicken or the egg” investment problem for advanced reactors. If nuclear plants cannot be made cheaply (today’s reality), a large market — or any market — will not exist, and without a large market, investment in production processes that drastically lower cost cannot be justified. Once large zero-carbon hydrogen markets exist, development of low-cost nuclear plants to make cost-effective, zero-carbon hydrogen should attract well-capitalized investors.

Today’s global hydrogen market exceeds \$100 billion, and it must grow dramatically. As the zero-carbon hydrogen market expands through the cycle of carbon policy, government-funded demonstrations and private sector innovation, costs will continue to fall, and application opportunities will expand. There are no fundamental physical or technical barriers to this expansion — only costs — so the opportunity to produce low-cost, zero-carbon hydrogen fuel could be much higher than currently anticipated or illustrated in this report’s examples. Today’s global fuels market exceeds \$1 trillion annually, which sets an attractive baseline for future zero-carbon fuels markets.

ENDNOTES

1. The term “zero-carbon” in this report primarily means hydrogen produced with no carbon emissions but will also include “low to very low carbon” hydrogen that can be produced from some forms of natural gas conversion to hydrogen with carbon capture and sequestration, which could be available soon and at a relatively low cost to help contribute to near-term use of hydrogen to reduce carbon emissions.
2. SHGE involves very deep drilling into hot, dry crystalline rocks and then injecting water (or CO₂) into these formations where high temperatures and pressure creates “supercritical” fluid that is returned to the surface to support highly efficient, low-cost energy production, as extensively explored in: <https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf>
3. UK Energy Technologies Institute, Nuclear Cost Drivers Project, 2018. www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report
4. BP (2019). BP Statistical Review of World Energy 2019 | 68th edition. p. 9. <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf>
5. Zamfirescu, C. and I. Dincer, (2008) Using ammonia as a sustainable fuel, Journal of Power Sources 185(1):459-465, 10.1016/j.jpowsour.2008.02.097
6. For example, wind, PV, SuperHot geothermal energy, fusion energy and large-scale natural gas development with innovative CCS.
7. https://www.catf.us/wp-content/uploads/2018/12/Fuels_Without_Carbon.pdf
8. <https://www.iea.org/reports/the-future-of-hydrogen>
9. One example is hydrogen fuel for California’s fuel cell vehicle fueling system that currently is supplied primarily from industrial gas companies that produce hydrogen from natural gas, but there are plans to transition to 100% renewables-based hydrogen. See: <https://driveclean.ca.gov/hydrogen-fueling> Another example is South Korea, see https://www.ifri.org/sites/default/files/atoms/files/sichao_kan_hydrogen_korea_2020_1.pdf
10. METI (2019). Formulation of a New Strategic Roadmap for Hydrogen and Fuel Cells. Released March 12, 2019. https://www.meti.go.jp/english/press/2019/0312_002.html. English version and summary can be found: https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf and https://www.meti.go.jp/english/press/2019/pdf/0312_002a.pdf
11. Hydrogen fuel cell vehicles (FCVs) can be visualized as electric vehicles that carry their own mini power plant and fuel tank, obtaining much better mileage. There is considerable crossover between plug-in electric and FCVs contributing to FCV efficiency and market potential.
12. See <https://www.ammoniaenergy.org/ihl-corporation-pushes-its-ammonia-combustion-technologies-closer-to-commercialization/> for a recent update on IHI’s ammonia co-firing work.
13. J-ENG (2019). “J-ENG and National Marine Research Institute cooperate on the research of “combustion using carbon-free fuel.”. <https://www.j-eng.co.jp/en/news/press/109.html>
14. https://www8.cao.go.jp/cstp/panhu/sip_english/20-23.pdf
15. http://h2est.ee/wp-content/uploads/2018/09/ammonia_as_hydrogen_carrier_Bunro_Ahiozawa_2018-09-04.pdf; https://www8.cao.go.jp/cstp/panhu/sip_english/20-23.pdf
16. <https://ssl.toyota.com/mirai/fcv.html>
17. See “South Korea’s Hydrogen Strategy and Industrial Perspective for a detailed description of hydrogen fuels action and policy in South Korea — at https://www.ifri.org/sites/default/files/atoms/files/sichao_kan_hydrogen_korea_2020_1.pdf
18. MOTIE, available at <https://docs.wixstatic.com>
19. <https://www.ammoniaenergy.org/articles/the-maritime-sectors-ammonia-learning-curve-moving-from-scenario-analysis-to-product-development/>
20. <https://www.h21.green/>
21. <https://cleanenergypartnership.de/en/h2-infrastructure/network-of-filling-stations/>
22. <https://www.rechargenews.com/transition/german-pipeline-operators-present-plan-for-world-s-largest-hydrogen-grid/2-1-810731>

23. https://www.certifhy.eu/images/media/files/CertifHy_folder_leaflets.pdf
24. <http://www.fchea.org/in-transition/2019/3/18/france-fuel-cell-industry-developments>
25. <https://www.truckinginfo.com/330270/toyota-and-kenworth-unveil-jointly-developed-hydrogen-fuel-cell-truck>
26. US Department of Energy (2019). H2@Scale. <https://www.energy.gov/sites/prod/files/2019/09/f67/fcto-h2-at-scale-handout-2019.pdf>
27. Patel, Sonal (2019). *Three More Nuclear Plant Owners Will Demonstrate Hydrogen Production*. Power Magazine. <https://www.powermag.com/three-more-nuclear-plant-owners-will-demonstrate-hydrogen-production/>
28. Appendix E, EON'S GLOBAL ENERGY MODEL describes this model and the analysis for this project.
29. For example, IEA and US EIA.
30. The primary economic competition for nuclear zero-carbon hydrogen production will likely be very large-scale natural gas hydrogen production combined with local sequestration of the carbon captured from methane reforming processes.
31. The first commercial nuclear power plant began operating in Shippingport Pennsylvania in May 1958.
32. For example, see the UK Energy Technologies Institute's nuclear cost drivers study - <https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report>
33. A deeper description of OPTIMAL NUCLEAR HYDROGEN PRODUCTION is provided in Appendix B.
34. Today's light water reactors (LWRs) can deliver electricity to power conventional production technologies such as low-temperature electrolysis (LTE) at these efficiencies.
35. Higher efficiencies are not achievable in any heat-to-work process since converting heat from the reactor to work (at the main generator) to produce electricity suffers thermodynamic losses.
36. See Appendix C: LARGE NUCLEAR FACTORIES FOR HYDROGEN PRODUCTION for discussion of optimal nuclear hydrogen production systems and Appendix D: FUTURE DEMAND FOR ZERO-CARBON HYDROGEN CAN CREATE LARGE FAVORABLE MARKETS FOR NUCLEAR FISSION for more details on this analysis.
37. With established nuclear safety regulation, nuclear waste management systems, etc.
38. IEA (2019). The Future of Hydrogen. Report prepared by the IEA for the G20, Japan. https://webstore.iea.org/download/direct/2803?fileName=The_Future_of_Hydrogen.pdf; IRENA (2018), Hydrogen from renewable power: Technology outlook for the energy transition, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf; Glenk, G., Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nat Energy* 4, 216–222. <https://www.nature.com/articles/s41560-019-0326-1>
39. More details can be found in Appendix B, Figure B4
40. IEA Future of Hydrogen report.
41. <https://www.osti.gov/servlets/purl/1>
42. www.topsoe.com/processes
43. Institutional nuclear “infrastructure” includes, at a minimum: a regulatory authority that oversees reactor licensing, site licensing, decommissioning, and operational oversight. It may also include research institutions (i.e., national laboratories), universities, and other organizations responsible for facilitating project development, nuclear technology export, proliferation controls, spent fuel management, and training for nuclear contractors and laborers.
44. Recent work is exploring combining base load nuclear power generation with thermal storage that could address some high-intermittent generation market constraints if the costs of such hybrid systems could be low.
45. Projected 2050 marine shipping fuel demand ranges and amount of electricity capacity required to produce ammonia to meet these fuel demand ranges is from Section 2.5, *Sailing on Solar*, Environmental Defense Fund, 2019. See description of analysis using this source information in Appendix B.
46. For example, see the UK Energy Technologies Institute's nuclear cost drivers study - <https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report>
47. US DOE is funding initial pilot projects: <https://www.powermag.com/three-more-nuclear-plant-owners-will-demonstrate-hydrogen-production/>



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