

Zero-Carbon Hydrogen: An Essential Climate Mitigation Option

Nuclear Energy's Potential Role

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ENERGY OPTIONS
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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.

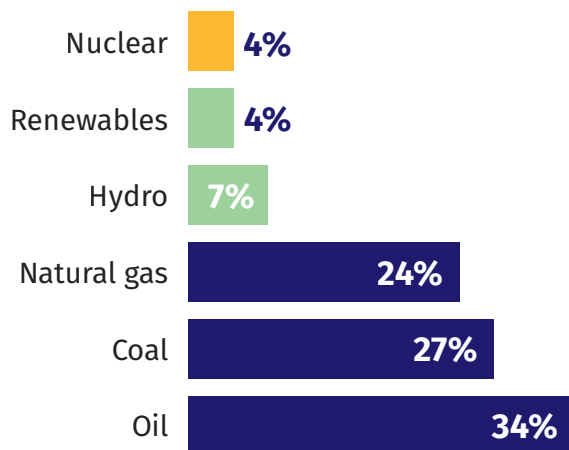
Establishing extensive production and application of zero-carbon hydrogen will require significant transformation of public policy, energy business structures, energy systems infrastructure, end-use energy application technologies and expansion of global hydrogen markets, together with the clearing of 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

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.

amounts of zero-carbon hydrogen will be 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:

- **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.

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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.

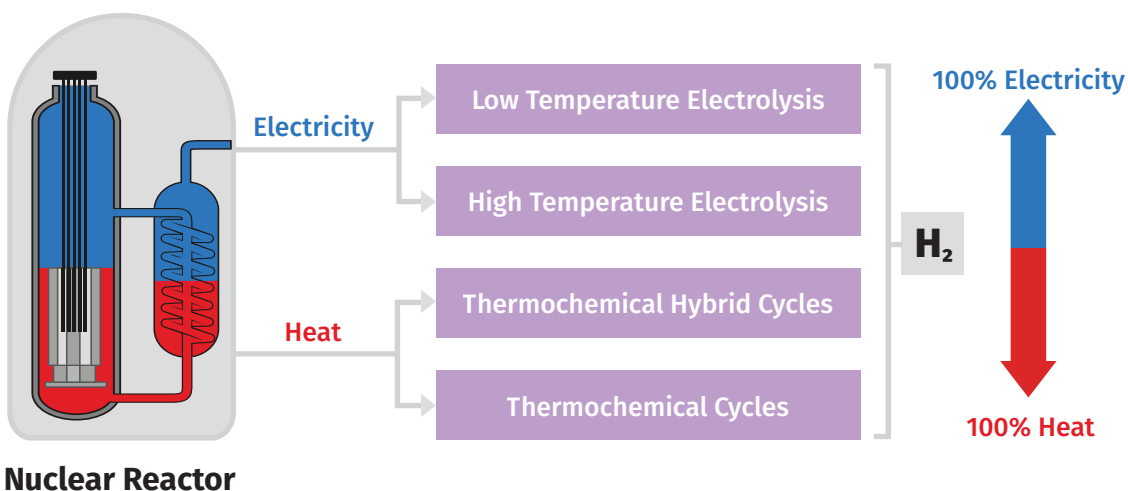
Nuclear fission is thus potentially well positioned for transformation and significant future deployment as zero-carbon hydrogen markets expand.

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.

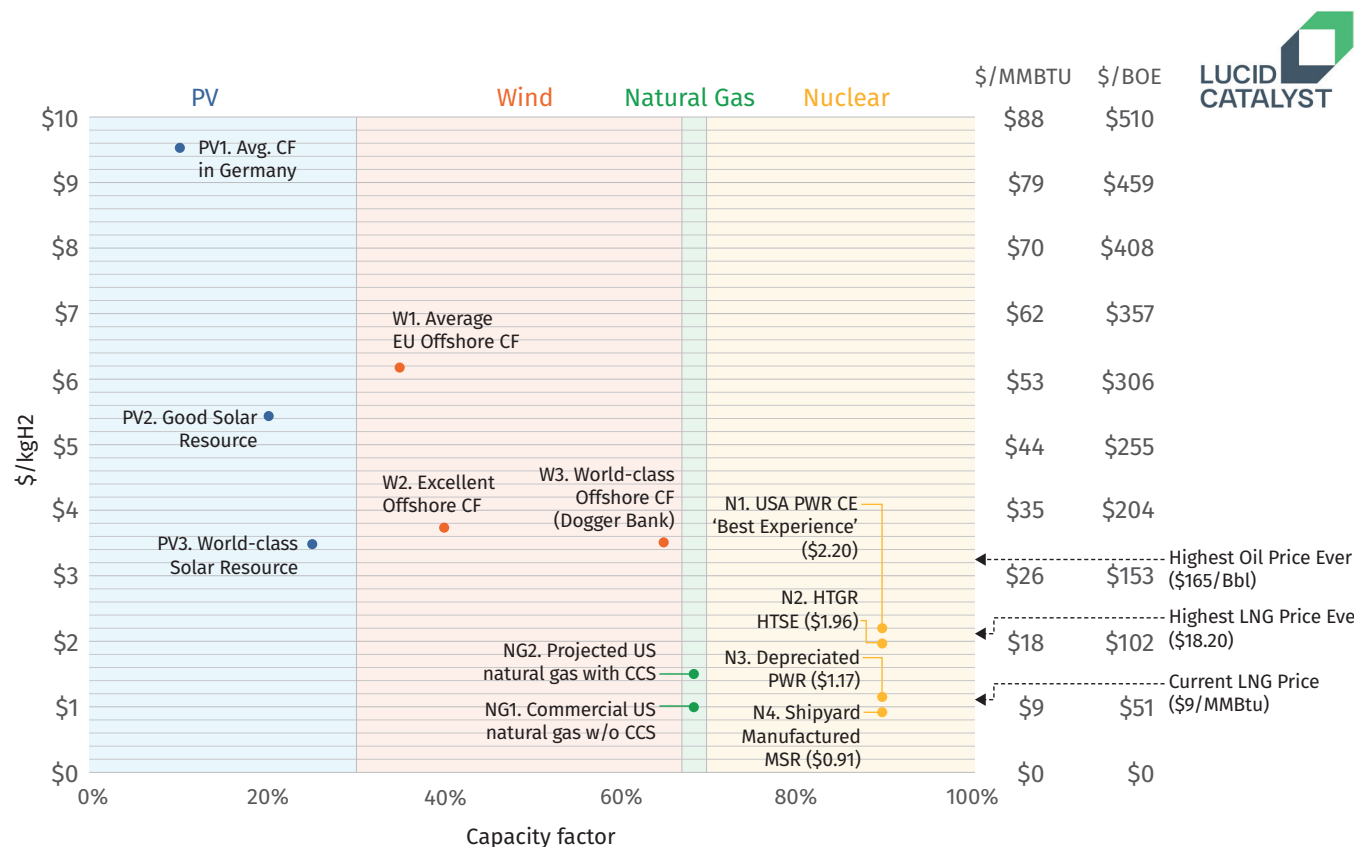
ESTIMATED NUCLEAR HYDROGEN PRODUCTION COSTS

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?

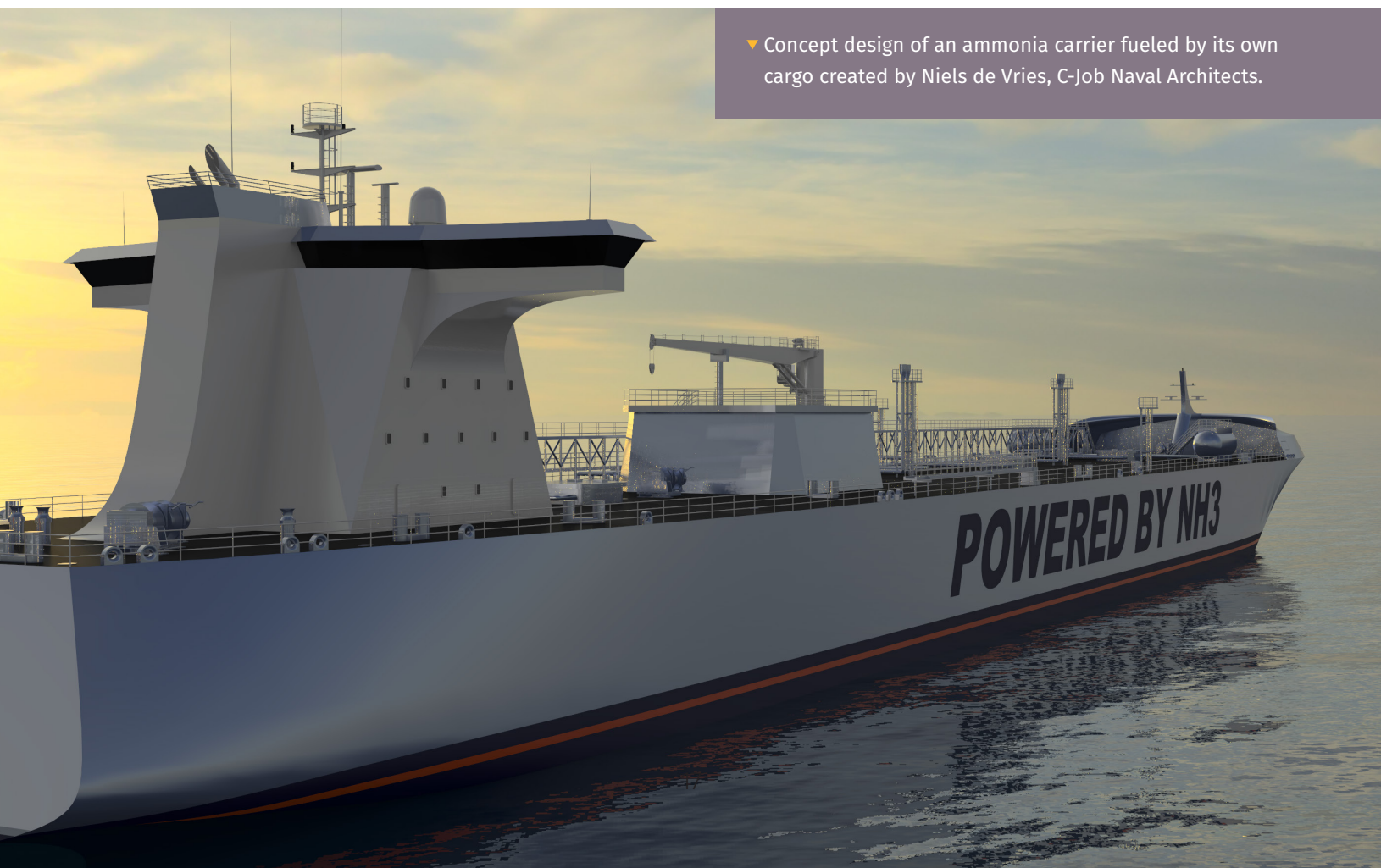
Recent Western experience deploying nuclear power has been challenging, raising questions about whether nuclear energy can meaningfully contribute to addressing climate change.

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/>

APPENDIX A:

EXPLORING THE POTENTIAL SIZE OF FUTURE ZERO-CARBON HYDROGEN MARKETS

Technological advances in energy applications using hydrogen gas and ammonia as fuels suggest they will likely dominate near-term zero-carbon hydrogen market applications.¹ There are no obvious fundamental constraints to scaling either fuel, in part as conventional ammonia already benefits from being a global commodity with a well-established logistical infrastructure, and a substantial industrial hydrogen market exists as well. As a viable liquid fuel, ammonia is ready to move into sectors, like mobility, that are heavily reliant of fossil fuels.

This Appendix applies EON's Global Energy Model (described in Appendix E) to explore how large future zero-carbon hydrogen market opportunities could *potentially* become and illustrate the amount of nuclear power capacity required to produce projected zero-carbon hydrogen demands.² This exploration assessed four case studies: 1) ammonia used as marine shipping fuel, 2) blending hydrogen gas into the US natural gas infrastructure, 3) ammonia supplying 10% of the global transportation fuels market by 2040 and 4) hydrogen displacing 25% of global oil and 10% of the global natural gas markets by 2050 and 2100. These explorations show that capturing even a small portion of potential future zero-carbon hydrogen market demand will dwarf today's ~400 GWe of global nuclear power capacity, the result of six decades³ of nuclear power deployment.

1.1 Using Ammonia Fuel to Decarbonize the Global Marine Shipping Industry

Marine shipping delivers over 90% of all global trade. The International Maritime Organization (IMO) is actively tightening marine fuel-related pollution standards and has agreed to cut marine shipping

greenhouse gas emissions by at least 50% by 2050. Using zero-carbon ammonia fuel appears to be the most likely path to eliminating marine shipping carbon emissions based on several recent studies.⁴ Some ships with diesel engines can potentially use ammonia with engine modifications, blending ammonia with a small amount of pilot fuel, like diesel. German-based MAN Energy Solutions, which provides engines for ~50% of all global marine shipping trade, recently claimed that 3,000 of its existing engines could potentially be converted to run on ammonia.⁵ MAN has also announced it is developing new shipping engines to operate on ammonia fuel, and they are ready to offer a LNG plus ammonia engine for LNG carriers, as customers are ready to order this option. Fundamentally new standards and procedures are not necessary to manage ammonia fuel's risk profile because standards established for the global fertilizer industry and for use of ammonia in commercial building HVAC systems provide useful experience and analogs upon which future regimes can be based.

The Environmental Defense Fund study, *Sailing on Solar*, makes a case that ammonia is the most effective means for enabling the IMO's goal of 50% GHG emissions reduction by 2050 and eventually eliminating marine shipping carbon emissions. This study used IMO 2050 marine shipping projections to estimate energy production needed to produce the zero-carbon ammonia needed for the IMO "low case" and "high case" scenarios. For nuclear-produced hydrogen, Table A1 derived from *Sailing on Solar* shows the new nuclear power capacity needed to supply IMO's estimated 2050 marine shipping zero-carbon fuel demand:⁶

Table A1. Estimated Nuclear Capacity (GWe) Needed to Produce Ammonia for a Range of Marine Shipping Fuel Use by 2050

% of Marine Shipping Fleet fueled by Ammonia in 2050	Low Case (GWe)	High Case (GWe)
10%	30	70
25%	90	170
50%	180	330
100%	360	650

If nuclear energy served only 25% of projected High Case 2050 demand, it could require nearly half of today’s global installed nuclear power capacity.⁷

1.2 Blending Hydrogen into the US Natural Gas Power Generation Infrastructure

The US consumed 8.51 trillion cubic feet (Tcf) of natural gas for residential and commercial

applications in 2018 (~30% of total natural gas consumption).⁸ Table A2 shows the production of this amount of energy in gigajoules (GJ) and that a high temperature gas nuclear reactor (HTGR), operating at a 90% capacity factor would require approximately **447 GWe** of new nuclear capacity. Studies find that existing natural gas supply networks could safely handle somewhere between a 5-15% blend of hydrogen by volume, assuming the gas infrastructure is in good condition.⁹ As hydrogen gas has less energy content than natural gas, by volume, a 15% energy blend would require about a 35% volume blend. However, considerable work is underway exploring how hydrogen blending, by energy, can be increased within current and future upgraded natural gas systems, and pilot projects are exploring a 100% hydrogen supply infrastructure. A 5% energy blend would require constructing ~22 GWe of nuclear projects, while a 15% energy blend would increase that capacity to ~67 GWe. On a global scale, this figure is much larger.

Table A2. Estimating the Nuclear Capacity Needed to Supply a 5% and 15% Blend of Hydrogen (by Energy) into US Natural Gas Power Generation Infrastructure

Parameter	Value	Notes
US Natural Gas Distribution System Use	8.51 Tcf	(Trillion cubic feet) — residential and commercial use; US EIA estimate (2018)
• in MMBtus	8.82 Billion	1.036 MMBtus in 1,000 cubic feet of natural gas ¹
• in Gigajoules (GJ)	9.3 Billion	1.055 GJ per MMBtu
• in tonnes of H ₂	0.08 Billion	0.120 H ₂ GJ per kg (LHV) ²
• in normal cubic meters of H ₂ (Nm ³)	0.870 Trillion	0.089 H ₂ kg per Nm ³ ⁽³⁾
Daily Nuclear H₂ production (Nm³)		
Conventional electrolysis	6.2 million	Daily H ₂ production estimates (by method) is sourced from a 2003 EPRI study, ⁴ which assumes a 4 x 288MWe HTGR operating at a 48% efficiency and 90% capacity factor.
Steam electrolysis	7.0 million	
Sulphur-iodine	8.4 million	
Annual Nuclear H₂ production (Nm³) per MWe-equivalent		
Conventional electrolysis	1.8 million	Annual H ₂ production per MWe is calculated by multiplying the daily production by 90% capacity factor (i.e., 90% * 365 days).
Steam electrolysis	2.0 million	
Sulphur-iodine	2.4 million	
Average	2.1 million	
Ammonia Cracking Efficiency (End Use)	95%	Reflects NH ₃ cracking efficiency (high end). ⁵
Estimated Nuclear Capacity Needed (GWe-equivalent)	447	Assumes the average of the annual H ₂ production methods above.
5% Energy Blend (GWe-equivalent)	22	
15% Blend (GWe-equivalent)	67	

¹ US EIA (2019). <https://www.eia.gov/tools/faqs/faq.php?id=45&t=8>

² EPRI (2003). Hydrogen Production Options with HTGRs. Table 2-3. <https://www.epri.com/#/pages/product/000000000001007802/?lang=en-US>

³ Ibid.

⁴ Ibid. Pg. 3-3

⁵ Giddey et al. (2017). Ammonia as a Renewable Energy Transportation Media. ACS Sustainable Chemistry & Engineering, 5(11), 10231–10239. Table 2.

1.3 Ammonia Captures 10% of the Global Transportation Fuels Market by 2040

According to the Reference Case in IEA's 2016 World Energy Outlook, Global transportation energy consumption will reach approximately 155 quadrillion

Btus (or "quads") by 2040. Assuming that nuclear-produced ammonia could capture 10% of this market, EON's analysis (shown in Table A3) arrives at **785 GWe**, double the current global installed nuclear capacity of 392 GWe.

Table A3. Estimating the Nuclear Capacity Needed to Supply 10% of the Global Transportation Fuels Market with Ammonia by 2040

Parameter	Value	Notes
10% of Total Energy Consumption in Global Transportation by 2040	15.5 quads	(10% of 155 quads)
• in Gigajoules (GJ)	16.35 Billion	1.055 GJ per MMBtu
• in tonnes of H ₂	0.14 Billion	0.120 H ₂ GJ per kg (LHV) ¹
• in normal cubic meters of H ₂ (Nm ³)	1.53 Trillion	0.089 H ₂ kg per Nm ³ ⁽²⁾
Daily Nuclear H₂ production (Nm³)		
Conventional electrolysis	6.2 million	Daily H ₂ production estimates (by method) is sourced from a 2003 EPRI study, ³ which assumes a 4 x 288MWe HTGR operating at a 48% efficiency and 90% capacity factor.
Steam electrolysis	7.0 million	
Sulphur-iodine	8.4 million	
Annual Nuclear H₂ production (Nm³) per MWe-equivalent		
Conventional electrolysis	1.8 million	Annual H ₂ production per MWe is calculated by multiplying the daily production by 90% capacity factor (i.e., 90% *365 days).
Steam electrolysis	2.0 million	
Sulphur-iodine	2.4 million	
Average	2.1 million	
Ammonia Cracking Efficiency (End Use)	95%	Reflects NH ₃ cracking efficiency (high end). ⁴
Estimated Nuclear Capacity Needed (GWe-equivalent)	785	Assumes the average of the annual H ₂ production methods above.

¹ ERPI (2003). Hydrogen Production Options with HTGRs. Table 2-3. <https://www.epri.com/#/pages/product/000000000001007802/?lang=en-US>

² Ibid.

³ Ibid. Pg. 3-3

⁴ Giddey et al. (2017). Ammonia as a Renewable Energy Transportation Media. ACS Sustainable Chemistry & Engineering, 5(11), 10231–10239. Table 2.

1.4 Hydrogen Displaces 25% of the Global Oil Market and 10% of the Global Natural Gas by 2050

The size of future hydrogen markets will be influenced by projected energy demand. To illustrate how large zero-carbon hydrogen markets could be, global energy demand through 2100 was projected using EON's Global Energy Model. A review of several recent global decarbonization studies shows that the average or "consensus" energy demand is typically used for projections, excluding plausibly higher energy use scenarios. EON believes compelling evidence points to ~1.7 billion people joining the global middle class by 2030.¹⁰ This means higher global energy demand projections would reflect the energy required to manufacture the products and energy services these people will demand.

As described in Appendix E, EON estimated the total global energy demand for 2050 and 2100 as supplied by oil, natural gas, coal, nuclear and renewables. EON then assessed the amount of hydrogen needed to meet 10% of global natural gas demand and 25% of global oil demand by 2050 and 2100. Finally, the nuclear capacity needed to produce these needed amounts of hydrogen was calculated. Table B4 shows the nuclear capacity needed to supply hydrogen needed in the 2050 and 2100 "Base Case" and "Higher Growth" energy demand scenarios. Displacing only 25% of EON's projected 2050 base case **global** oil and 10% of **global** natural gas demand with hydrogen would require development of *4000 to 6000 GW* of nuclear capacity, **ten times** today's total global installed nuclear capacity. EON's higher growth case would require about **25 to 35 times** today's total global installed nuclear capacity.

Table A4. 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

ENDNOTES

1. Current hydrogen use is primarily for oil refining and conventional ammonia production, primarily for fertilizer.
2. 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.
3. The first commercial nuclear power plant began operating in Shippingport Pennsylvania in May 1958.
4. www.maersk.com/news/articles/2019/10/24/alcohol-biomethane-and-ammonia-are-the-best-positioned-fuels-to-reach-zero-net-emissions
5. R. Laursen, 2018. Ship operation using LPG and ammonia as fuel on MAN B&W dual fuel ME-LGIP engines. NH₃ Fuel Conference, Pittsburgh, 2018. https://nh3fuelassociation.org/wp-content/uploads/2018/12/0900-Ammonia_vision-Rene-Sejer-Laursen-MAN.pdf
6. The economic model used in Sailing on Solar that included electricity required to produce the various levels of marine fuel displacement by electricity produced ammonia is described in Sailing on Solar's Appendix E. This analysis included all costs and energy required to produce the needed volume of ammonia, including nitrogen production needed for ammonia synthesis
7. 2020 global installed nuclear capacity is 390 GWe.
8. <https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php>
9. <https://www.cfr.org/blog/natural-gas-transition-fuel-hydrogen>
10. <https://www.brookings.edu/blog/future-development/2018/09/27/a-global-tipping-point-half-the-world-is-now-middle-class-or-wealthier/>

APPENDIX B:

OPTIMAL NUCLEAR HYDROGEN PRODUCTION

HOW DOES NUCLEAR ENERGY PRODUCE HYDROGEN?

1.1 Historical Perspective

The use of nuclear energy to produce hydrogen is not a new concept. As early as the 1960's, many countries anticipated that the future of nuclear energy would include using heat from reactors to meet a significant portion of the chemical process industry's energy demand, including hydrogen production. Heat production, particularly at the high temperatures anticipated from advanced reactors, added value to nuclear energy beyond electricity supply. Of the chemical processes envisioned as being linked to nuclear, hydrogen production has always been seen as particularly promising given its potentially broad role: a commodity, an energy carrier like electricity, a potential transportation fuel, and a feedstock in the manufacture of other high-value chemical and petrochemical products.

Some notable historical initiatives that link nuclear and hydrogen production include:

- In the 1960's, the Japanese nuclear and steel industries worked together on major R&D efforts to provide hydrogen for steel production. These efforts continue today as the steelmaking industry's dependence on coke derived from coal for iron ore processing is still responsible for about 15% of Japan's GHG emissions. Today's programs to develop technologies for nuclear hydrogen production for the steelmaking industry have been bolstered by ever-increasing interest by Japan in transitioning to a hydrogen economy.
- From the mid-1960's through the early 1980's, the European Joint Research Centre (ISPRA) completed

a major effort to identify and screen innovative candidate processes for nuclear hydrogen that included promising laboratory testing, corrosion studies and designs for the full-scale equipment required for hydrogen production. Similar projects were completed in the US at the Gas Technology Institute (GTI). Westinghouse also performed its own development of a process in the 1970's known as hybrid sulfur process — discussed briefly below.

- In the 1970's and 1980's, a broad-based German industrial consortium supported an extensive, several decades long national initiative to design and deploy high temperature gas nuclear reactors to provide process heat for hydrogen production.¹ Hydrogen synthesis processes were down selected, the leading candidates were taken through more detailed engineering, and two prototype reactors were built and operated. Major facilities were built to test and qualify the equipment required to extract and transport heat from nuclear reactors for these applications. This was a significant effort, which greatly advanced this field. Total investment in the German process heat technology program including specific funding in support of hydrogen production was about \$6 billion USD (2019).
- By 1979, General Atomics, which was developing a low-cost, high-temperature, gas-cooled reactor had already constructed a laboratory scale prototype of a thermochemical process for producing hydrogen using nuclear energy, known as the sulfur iodine process (S-I). This was soon followed by a similar system at the high temperature gas-cooled test reactor (HTTR) site in Japan. This reactor was conceived of in 1969 and became

fully operational in 1999, with the goal of demonstrating nuclear hydrogen production at prototype scale. A subsequent system capable of 100 times the production rate of the HTTR prototype was built in the US under the international I-NERI program and commissioned at General Atomics in 2007. Recent developments at the HTTR have demonstrated the next step in scaling up this system, including that it can be built cost effectively with components sourced from industrial suppliers.

- In the US, the term “Hydrogen Economy” had been coined by 1972, and by late 1970’s, the hydrogen economy had become a formal part of the US energy policy. Nuclear power was highlighted as one pathway to meet the energy demands of large-scale hydrogen production. Significant US policy drivers over this time included the oil crisis, petroleum shortages and concerns over acid rain.

By 2002, international cooperation on nuclear-produced hydrogen and advanced reactors was growing, in part a result of increasing concerns over climate change. More than \$600M was spent on projects under the international Generation IV International Forum (GIF) program, much of which was focused on integrating advanced reactors with efficient hydrogen production processes using either high temperature heat or electricity. The benefits and value of nuclear energy as a pathway to cost-effective and environmentally-friendly hydrogen production was by then being enthusiastically embraced by an international community of nuclear suppliers, end users and governments. By the mid-2000’s, almost every nuclear-enabled country had nuclear hydrogen programs. The US DOE alone was spending over \$10M per year on basic R&D, materials qualification and infrastructure modelling. The DOE National Hydrogen Initiative was formally established in 2002 with a goal of demonstrated nuclear-based hydrogen from laboratory to commercial scale in about 15 years. Its aim was to replace existing large-scale hydrogen

production methods with a method that did not produce greenhouse gases, in an efficient, stable and economical manner and at the same time without depending on foreign sources of energy (oil and gas). Finally, the Energy Policy Act of 2005 mandated that the US initiative build an evolutionary high temperature gas reactor by 2021 called the Next Generation Nuclear Plant (NGNP) at which about 10% of the energy would be used to demonstrate carbon-free hydrogen production at a large scale.

1.2 The Ebb and Flow (and Resurgence) of Support for Nuclear Hydrogen

Despite the momentum that use of nuclear energy for hydrogen production had achieved by about the mid-2000’s, progress toward realization slowed. This was, due in part to the rising cost of constructing new light water reactors (LWRs) in the US and Western countries and the lack of R&D or innovation focus on addressing factors that were driving up the cost of nuclear plants. So, the slowing of progress on hydrogen was primarily driven by broad nuclear industry problems, which in turn constrained investment in the development of advanced high temperature reactors — the technology necessary for nuclear hydrogen production. China was an exception; they continued development of an advanced, gas-cooled HTGR — a reactor well suited for hydrogen production.²

The difficulty restarting the nuclear construction industry in the West for large LWRs — and expectations of similar cost increases for advanced nuclear — was compounded by the dramatic reduction in the cost of natural gas in the US. This not only tempered the enthusiasm for nuclear hydrogen investments but lowered the cost of hydrogen production from fossil fuels, further increasing the perceived cost gap between nuclear hydrogen and hydrogen from natural gas.³ Other adverse factors included shifts in US government priorities.⁴

However, this trend has changed over the past five years as the resurgence of interest in advanced nuclear technology has rekindled interest in nuclear

hydrogen production. Increasing urgency about the timing and pace of energy system transformation required to address climate change is reviving awareness of the need for zero-carbon hydrogen production processes. Climate change concerns have thus replaced the US energy security issues that drove the first wave of nuclear hydrogen support from the 1990's and 2000's. Today, nuclear hydrogen programs are underway in the US, South Korea, Japan, Canada, China and the EU, although at reduced levels of funding support compared to the 2000's.

1.3 Why Use Nuclear for Hydrogen?

Every kilogram of hydrogen produced by a natural gas-fuelled SMR hydrogen production facility results in about nine kg of CO₂ emissions. Hydrogen produced using heat or electricity from a nuclear reactor produces no CO₂.

To better understand nuclear hydrogen production's advantages, a summary of an "ideal" hydrogen production pathway and how nuclear fits follows:

- **Heat and Power** - All methods of hydrogen production, except those that rely on photochemical routes, require heat, electrical power or both. A nuclear reactor can provide large quantities of both heat and electricity from one common source: the reactor.
- **Efficiency** - Production of hydrogen, especially carbon-free hydrogen, is an energy intensive process. To improve process efficiency and economics, it is advantageous to provide low-cost electricity and/or higher temperature heat, which increases process thermodynamic efficiency. Advanced high-temperature nuclear reactors can provide both: high temperature heat (500-900°C) and electricity.⁵ Nuclear pathways to hydrogen production include 1) using highly efficient versions of electrolysis, i.e. high temperature electrolysis (HTE) with efficiencies that can exceed 50% thermal-to-hydrogen⁶ and reach 100% electricity-to-hydrogen or 2) high temperature chemical

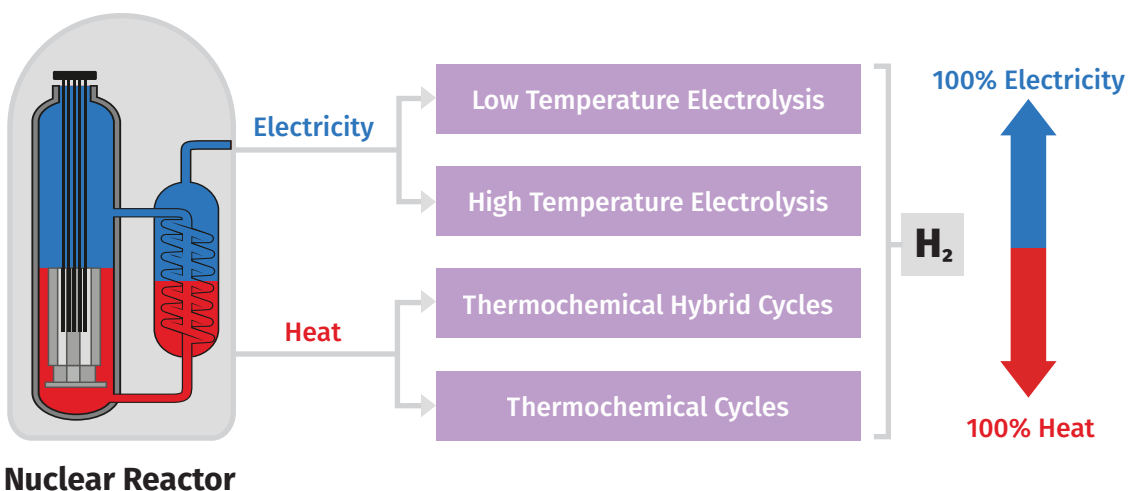
processes driven by heat that internally recycle 100% of the compounds used for hydrogen generation with thermal-to-hydrogen efficiencies that approach 60%, with no byproduct like CO or CO₂.⁷

- **Feedstocks and Byproducts** - The most efficient hydrogen production processes consume only water and yield hydrogen and oxygen.⁸ Feedstocks, like natural gas, that have price volatility are not required, and no byproducts that require capture or treatment are created, other than spent fuel waste. While hydrogen can be produced through Low Temperature Electrolysis (LTE), the net electrical efficiency of LTE is about 60%⁹ or about 28-30% on a thermal-to-hydrogen basis, much lower than high temperature efficiencies that approach 60%.¹⁰
- **Safety** - Advanced, high-temperature gas reactors are sufficiently safe so that they can be located near the hydrogen production systems and facilities that subsequently convert the hydrogen into energy carriers like ammonia.
- **Hydrogen Quality** - Hydrogen produced with nuclear energy can be extremely pure and thus meet the requirements of a wide range of end uses, including fuel cell vehicles, which require low carbon monoxide, sulfur and oxygen content.
- **Scalability** - Nuclear energy systems can produce large amounts of heat and electricity in a small footprint and can be deployed at large scale, along with associated hydrogen production facilities.
- **Siting Flexibility** - Moving hydrogen is expensive. Nuclear-produced hydrogen offers the cheaper option of producing hydrogen close to end users, siting constraints permitting.

1.4 Brief Overview of Process Options

Options for generating hydrogen with nuclear power range from those using only electricity to those that use only heat.

Figure B1. Options for Nuclear Reactor Coupling to Hydrogen Production (Sink, DOE 2004)



Starting with LTE (Figure B1), advanced reactors that operate at higher temperatures than LWRs could be used to improve the thermal energy to hydrogen efficiency¹¹ of the current commercially-available electrolysis process from about 28-30%¹² to as high as 35-38% as advanced reactors can generate electricity at higher efficiency.¹³ This path has been considered a near-term solution to improving the efficiency of carbon-free hydrogen generation.¹⁴

Figure B1 illustrates the hybrid and conventional **thermochemical** processes. Thermochemical production of hydrogen R&D has been active for 50 years. In the 1990's, US DOE and its international partners (through what were known as the NERI and I-NERI programs) evaluated over 115 candidate thermochemical cycles for producing hydrogen with nuclear energy and conducted detailed reviews of

about 25. Several had predicted hydrogen generation efficiencies of up to 60%, almost twice that of conventional electrolysis. One hybrid cycle, the hybrid sulphur (HyS) process, which uses both chemical pathways and electrolysis, was extensively pursued by Westinghouse in the 1970s and remains a leading candidate for coupling with some advanced reactor designs. The HyS process efficiency exceeds 40%.

HTE still primarily uses electricity (about 90% electricity, 10% process heat). However, the advanced solid oxide electrolysis cells (SOECs) used in HTE are much more efficient at 850°C compared to LTE cells at 65°C. The net thermal energy-to-hydrogen efficiency of hydrogen production through this path can approach 50%. Figure B2 shows a simplified representation of an electrolysis cell and a prototype design for a hydrogen production module.

Figure B2. HTE Cell Representation and Engineering Scale Prototype Design (INL 14622)

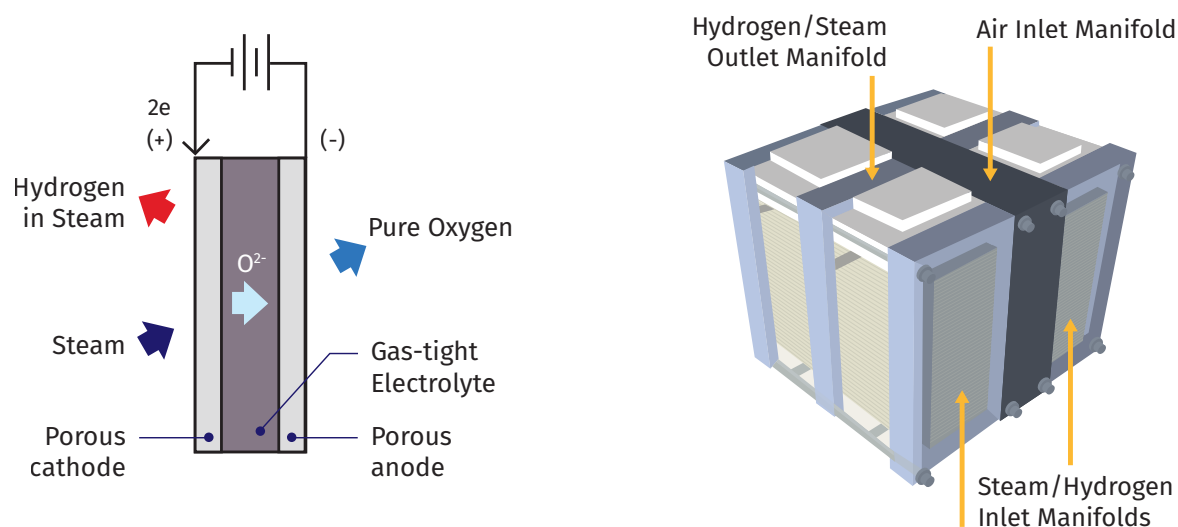


Figure B3. Sulphur Iodine (S-I) Process with 100% Recycle of Intermediates (Nuclear Engineering International)

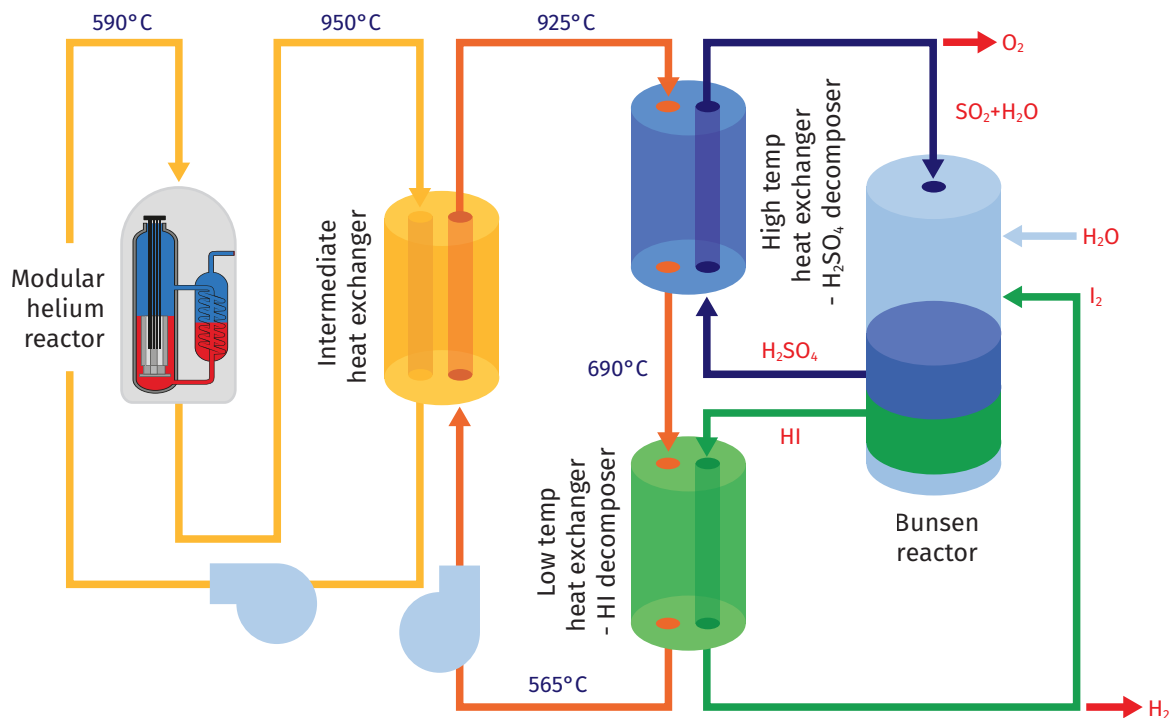


Figure B3 shows a simplified flow sheet for another example of thermochemical process — the sulphur-iodine process.¹⁵ It is fed by water, produces only pure hydrogen and oxygen and it recycles all reaction

intermediates inside the process system boundary. Other leading thermochemical cycles are based on calcium/bromine and copper/chloride.

In summary, using nuclear reactors to produce hydrogen has a rich history. Significant progress developing hydrogen production pathway processes occurred from the 1960's to the mid 2000's. While the rate of hydrogen production processes declined as the nuclear industry lost momentum, interest in promoting the technology and deploying it even further has resumed, primarily based on ever-increasing climate change concerns. This renewed interest in hydrogen production processes coincides with recent interest and investment in advanced reactor development.

1.5 Estimates for Zero-CO₂ Hydrogen Production Costs

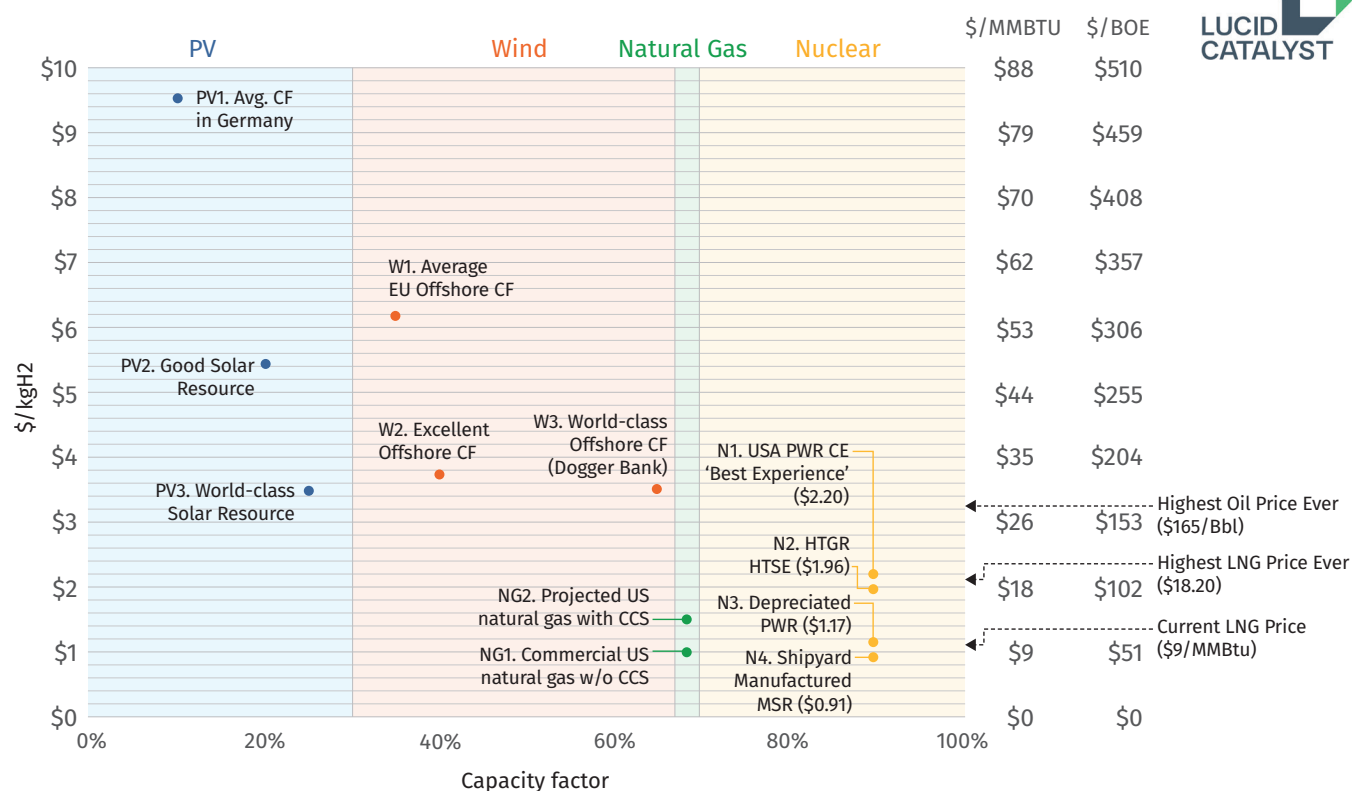
Several analyses have examined potential zero-CO₂ hydrogen production costs from nuclear, PV and wind energy.¹⁶ EON's consultants reviewed these studies and combined some key results with their modeling of different projected nuclear reactor and hydrogen production pathways. The IAEA's Hydrogen Economic Evaluation Program ("HEEP") model was used to compare nuclear's projected optimal costs, assuming very large scale zero-carbon hydrogen markets, against relatively aggressive assumptions for future PV and wind costs based on NREL's Annual Technology Baseline (ATB).

Projections of optimal nuclear hydrogen production¹⁷ could **potentially** be cost competitive with some other zero-CO₂ production methods today and may **potentially** be cost competitive with SMR of low-

cost natural gas, the cheapest path today to produce hydrogen — about \$1/kg at US natural gas prices. Adding deep carbon capture and sequestration (about a 90% reduction) to such projects is projected to cost about \$0.50/kg, for a total costs of about \$1.50/kg.¹⁸ These hydrogen costs vary significantly by region, with similar costs in the Middle East but much higher costs in Europe and China driven by higher natural gas costs in those regions. Projected hydrogen production costs **using grid electricity** are also shown below. However, the future zero-carbon fuels markets explored in this report are large enough to be primarily addressed by large, dedicated standalone hydrogen production projects. Figure C1 includes projected hydrogen costs from wind, PV and nuclear technologies deployed at this scale.

Commercially promising natural gas reforming technology being developed by GTI,¹⁹ Haldor Topsøe²⁰ A/S and others could further reduce near-term, natural gas-based hydrogen production costs. The potential for very large-scale hydrogen production, at very large gas reserves with innovative reforming technology and local CCS could potentially produce essentially zero-carbon, low-cost hydrogen. Considerable technology competition for low-cost zero/low-carbon hydrogen could exist in the early stages of zero-carbon hydrogen market evolution. Given how large the energy system decarbonization challenge is, having several competing zero-carbon hydrogen production technologies should reduce decarbonization risk.

Figure B4. Estimated Hydrogen Production Costs by Generation type (2018 USD)



Data Point	Description (Source)	Notes
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	Shipyards 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

1. Burger, Dr. Bruno (2019). Net Public Electricity Generation in Germany in 2018. Fraunhofer Institute for Solar Energy systems ISE. https://www.ise.fraunhofer.de/content/dam/ise/en/documents/News/Stromerzeugung_2018_2_en.pdf
2. NREL (2019). Annual Technology Baseline: Electricity. <https://atb.nrel.gov/electricity/2019/index.html?t=su>
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5. General Electric (2019). An Industry First: Halide-X 12 MW offshore wind turbine platform. <https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine>
6. Equinor (2019). Equinor wins opportunity to develop the world's largest offshore wind farm. September 20, 2019. <https://www.equinor.com/en/news/2019-09-19-doggerbank.html>
7. <https://www.osti.gov/servlets/purl/6927146/>
8. Krull, P., Roll, J., & Varrin, R. D. (March 2013). HTSE Plant Cost Model for the INL HTSE Optimization Study, Dominion Engineering Report R-6828-00-01.
9. The Future of Hydrogen, International Energy Agency, 2019.

ENDNOTES

1. Hydrogen production pathways included thermochemical processes, which did not consume or emit GHGs as well as nuclear-assisted steam methane reforming (SMR) in which much of the energy used for the processes was supplied by nuclear energy as high temperature helium or steam, thereby reducing carbon emissions from conventional SMR (known as the Prototype Nuclear Process Heat or PNP Project in Germany). Japan also considered and completed significant R&D on a similar process.
2. China never wavered from its commitment to build advanced HTGRs, and the first large unit at Shidao Bay should come online by 2021. China also maintained its goal of commercializing hydrogen production with nuclear in the future.
3. Via natural gas fed SMR — a significant source of carbon emissions in the US and worldwide.
4. Additionally, in about 2007, the US DOE refocused funding efforts away from NGNP (and its hydrogen objective), to programs supporting spent fuel management, such as reprocessing including the GNEP program, which was subsequently cancelled.
5. Nuclear is uniquely positioned to provide high temperature heat with a number of reactor types including HTGRs, molten-fluoride-salt cooled high temperature reactors (FHRs), and high temperature lead-cooled fast reactors (LFRs).
6. On an LHV basis.
7. Thermal-to-hydrogen efficiency governs the amount of installed nuclear capacity needed per unit of hydrogen produced, which is linked to factors like volume of high-level nuclear waste produced per unit of hydrogen.
8. These large volumes of produced oxygen may have some potential applications like oxy-combustion of natural gas that would reduce the costs and technical challenges of capturing CO₂ from such systems.
9. O'Brien, JE, MG McKellar, EA Harvego, 2010. High-temperature electrolysis for large-scale hydrogen and syngas production from nuclear energy — summary of system simulation and economic analyses, International Journal of Hydrogen Energy, 35 (10) <https://inldigitallibrary.inl.gov/sites/sti/sti/4247218.pdf>
10. Hydrogen can also be produced by thermal decomposition or thermolysis of water at very high temperatures: 2500-4000°C. Some R&D is being conducted to develop thermolysis processes using concentrated solar power (CSP), albeit at a small scale.
11. Defined as the amount of nuclear thermal energy needed to produce a specified volume of hydrogen.
12. Today's LWRs can deliver electricity to power conventional production technologies such as LTEs at these efficiencies.
13. 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. As noted in footnote 7 above, thermal-to-hydrogen efficiency influences the amount of installed nuclear capacity needed to produce a specified volume of hydrogen, as well as volumes of nuclear waste produced per specified volume of hydrogen produced.
14. See, Evaluation of non-electric market options for a light-water reactor in the Midwest, <https://www.osti.gov/biblio/1559965>.
15. S-I Process or I-S process in some publications
16. 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>
17. Several recent analyses have explored pathways to significantly reduce the costs and expedite deployment rates of nuclear energy. Included in these is the UK Energy Technologies Institute, Nuclear Cost Drivers Project, 2018. www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report.
18. IEA Future of Hydrogen report, at page 39. Both costs are considerably higher due to gas prices in Europe and China. <https://www.iea.org/reports/the-future-of-hydrogen>
19. <https://www.osti.gov/servlets/purl/1>
20. www.topsoe.com/processes

APPENDIX C:

LARGE NUCLEAR FACTORIES FOR 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 and 3) significant scale-up of thermochemical or electricity-based hydrogen production processes. Accomplishing these will require transformative nuclear plant designs, advanced manufacturing approaches and centralized deployment models. **A simple statement of this challenge is to ask “Can we make high-temperature nuclear energy systems for less than \$1000/kWe?”** The answer is “**probably yes**” as explored below.

Broadly speaking, two methods 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 refinery model for nuclear fuel production, which realizes economies of scale and deployment scalability; nuclear capacity is deployed at 10’s of gigawatts at a refinery-scale site, with extensive integration of site infrastructure. The second concept is a proposed paradigm for design: fabrication and deployment of the plants

themselves based on experience in the shipbuilding and offshore oil and gas industries. These are radical departures from today’s industrial, business and technology model that defines 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.

1.1 The Gigafactory/refinery model: bringing a highly productive construction and production environment to the project

Construction of a conventional gigawatt-scale nuclear power plant is one of the largest capital-intensive projects that can be undertaken by a power company. In Western countries, the cost of a two-unit plant today may exceed \$20 billion USD, and the construction time can exceed 10 years.¹ Total installed global capacity growth today is less than about 10 gigawatts per year, given these economics, along with regulatory and political constraints.

In contrast, the potential market for clean fuels produced with nuclear energy is immense and may require many 1000’s of gigawatts-equivalent of energy, even if nuclear energy is only supplying a portion of total demand. Meeting this market demand will require designing and building advanced reactors **specifically optimized for fuel production** to enable the required high deployment rates and low costs. Given that fuels can be globally transported, nuclear deployment would no longer be constrained to development of a few gigawatts of energy at a single site, each site geographically separated and within “siloes” national power markets.

Freed from the geographical and distribution constraints inherent in electricity production, an effective deployment model would resemble that used by the oil and gas industries. There, a centralized site produces far greater equivalent energy products compared to a nuclear power station. Such centralized hydrogen production facilities could be deployed in a range of sizes, up to a very large (mega) oil refinery size.

Comparing the potential “refinery model” to a conventional nuclear power plant deployment (business as usual) facility and scale is illustrative. Table C1 below compares a large petrochemical facility (a mega refinery) compared to a current generation, two-unit LWR for plant size, material quantities, number of construction workers, relative output and cost.² Note that the refinery is 20 times larger in terms of raw materials but is constructed

in less than half the time; it uses up to 5000 pieces of large equipment — not just a few hundred; it produces dozens of end-products (as might be the case if nuclear were used for fuels and manufacture of other products); the permanent staff is only slightly higher yet the relative plant energy output is 5 to 10 times that of the nuclear plant. Finally, the “mega refinery” project’s relative nuclear capital construction cost is about 10% to 30% of the power plant. Refinery safety records rival the power industry’s record, and the quality focus is comparable.

These mega petrochemical sites also integrate site-wide support facilities, interconnections to pipelines, utilities, port infrastructure, site services, along with O&M and construction services on site with vertical integration of materials, fabrication and manpower.

Table C1. Comparison of Mega Scale Petrochemical Facility to Two Unit LWR

	Large Petrochemical Facility (~1 MM bbl/D)	Two Unit LWR (3 GWe Total)
Site Land Area	11 square miles	<0.1 square miles
Construction to Rigorous Codes and Standards	Yes	Yes
Peak Construction Workers	70,000	7,000
Permanent Staff	3,000	2,000
Tons Concrete	4,000,000	200,000
Tons Steel	1,000,000	40,000
Large Pieces of Major Equipment	5,000	200
Customization in "Unit Ops"	High	Low
Number of Products	Dozens to Hundreds	One
Construction Schedule	36 months	>72 months
Overnight Cost	\$6-45 Billion	\$20 Billion
Relative Size for Given Energy Throughput Equivalent	5 to 10	
Relative Cost	10 to 30%	

A first takeaway from this comparison above is that mega-scale energy producing refineries already exist throughout the world and can serve as a model for a large nuclear reactor-based hydrogen or hydrogen fuel production site or an “industrial park” that is large by comparison to today’s power plants. The goal would be to realize the benefits of economies of scale seen by the petrochemical industry in terms of reduced capital and O&M costs.

But perhaps an even greater opportunity may exist for nuclear above and beyond that suggested by the information on the table. A site using nuclear plants to produce hydrogen or hydrogen fuels is likely much less complex in terms of number of unique pieces of equipment required and may therefore benefit from repeat deployment of a common building block.

As a specific example, building a nuclear facility that produces hydrogen that has a comparable output of a medium-scale refinery — about 150,000 barrels per day equivalent — would require ~14GWe of reactors.³ If this project were assembled from high temperature reactor units, rated at 600MWt each (~220-288 MWe depending on steam cycle versus Brayton cycle), it would require 56 identical units — a simplicity that may suggest even greater economies of scale than those seen in the petrochemical industry at mega sites.

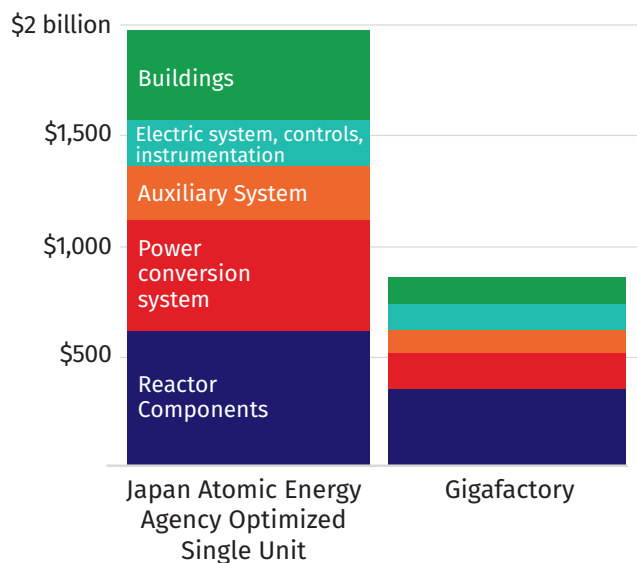
This scale and on-site construction duplication in the nuclear project are large enough to enable innovations that could result in radical cost reductions beyond just the common siting and sharing of infrastructure and services. This is enough units to justify designing and building a highly efficient manufacturing, assembly and installation system for the units. It would also justify redesign of all the components in the plant for low-cost

manufacture and assembly/installation. The scale of the project and the number of units make it possible to amortize a very significant investment in high-volume manufacturing.

For example, as seen in Figure C1, if the factory to build/assemble all the components cost \$2 billion, even if this cost were only amortized over the 56 units for the project, it would cost much less than the savings that could come from such an arrangement compared with optimal — probably shipyard — production of units off site. Furthermore, once the “gigafactory” finished supplying the first project, it could be disassembled and moved to a new location to build the next project. Additional areas of capital cost reduction would result from the optimization and/or sharing of auxiliary (non-safety) systems, optimization of the required structures for prefabrication in a high productivity process, and greatly reduced installation duration for each reactor. This approach was applied, at a conceptual level, to the already highly optimized Japanese HTGR⁴ cost model, which found substantial opportunities for further cost reduction, with overnight capital costs potentially less than \$1000/kWe.⁵ This suggests it should be possible to achieve capital and operating cost levels for producing hydrogen with nuclear energy at costs potentially competitive with producing hydrogen from innovative reforming of very low-cost natural gas with local CCS. This optimal approach to large-scale nuclear hydrogen production is very different from how nuclear plants are designed and delivered today, even in countries where nuclear plants are routinely delivered today at low cost.

The processes that can use nuclear electricity and/or heat to produce hydrogen from water **must be**

Figure C1. Cost reduction potential for Manufactured HTGR Plant



scaled up greatly as well. Environmental Defense Fund’s *Sailing on Solar* report⁶ notes that optimal sizing of current electrolyzers is about 2 MW, so a 600 MWe HTGR would require about 300 such units today. Housing 300 units today would require about 36 large warehouses.

1.2 Shipyard model: Bringing the project to a highly productive manufacturing environment

Over the past 20 years, studies comparing shipyard construction of naval vessels and construction of commercial nuclear plants have focused on use of modular construction as a path to more economical builds. While this opportunity still exists, it is worth expanding the discussion of shipyard construction beyond the limits of just modules.

Since the 1970’s, shipyards have evolved into some of the most productive manufacturing environments in any industry — particularly when it comes to large-scale construction. Decades of competitive market forces and a generally robust demand for ships,

offshore platforms and offshore production facilities have fostered world-class design capabilities, manufacturing and quality assurance programs in many countries. The goals of the shipyards and their owners are not unlike of those of future manufactures of nuclear plants — produce a high-quality, low-cost product on schedule, in high volumes.

These high-tech shipyards are well suited for fabricating advanced reactor systems, large-scale hydrogen production systems and designing and then building ships to house them. Some studies have already concluded the scale of the manufacturing systems at shipyards means that it is possible, today, to build an entire nuclear plant in a shipyard and float the finished product to its final location.

Much recent interest in the “shipyard model” has focused on the considerable work being done by major shipyards and some nuclear developers to advance this idea and explore ways to manufacture as much of the nuclear plant as possible in shipyards, rather than on site.

The “shipyard model” offers many advantages:

- **Price** - The cost of building large ships in modern shipyards is comparatively low relative to construction of major equipment and facilities in other industrial sectors. Material costs represent 72% of the overall costs with labor and overhead corresponding to only about 16% and 10% of the delivery cost — far lower than the comparable costs in nuclear construction, where labor and overhead/engineering typically constitute about 75% of the plant cost.⁷ Deliveries are on a fixed price basis, and the yard takes on the schedule risk and usually provides performance guarantees. Multi-unit orders often have a cost reduction curve reflected in the pricing, based on the experience of the shipyard in reducing costs when manufacturing multiple units of the same design.
- **Scale** - The largest shipyards in the world are in Korea, China, and Japan. The gross tonnage

produced by these three countries in their recent peak year was 25 million, 25 million, and 14 million, for a total gross tonnage of 64 million. Currently none of these shipyards produce at their maximum rate, and there is considerable excess capacity. A recent study by a company that is planning to have its nuclear plants made in a shipyard in Korea suggested that a single large shipyard, without any investments to expand production would be able to make as many as 40 power plant sized ships (at 500 MW each) per year — 20 GW per year.⁸ This shipyard represents less than 5% of global capacity. Furthermore, even in peacetime, shipyards have been able to rapidly scale up production when there is sustained demand. Between 2000 and 2013, Korean and Chinese shipyards increased their annual output by three times and Japan by two times.

- **Schedule** - Shipyards routinely operate under tight schedules. An entire \$350 million large container ship, offshore rig or floating platform can be built in as little 18-36 months. Shipyards are under constant pressure to innovate and improve productivity, quality, and schedules and are challenged by the market more rigorously than nuclear construction projects under an engineering procurement contractor approach.
- **Innovation** - Shipyards are leading innovators in design and build processes, having adopted the most advanced 3D design and simulation tools, as well as implementation of such advanced cost-reduction technologies as robotics/automation in fabrication and inspection. Shipyards are also at the forefront of large component handling, routinely moving 1,000 ton modules from assembly to the dry docks to be welded to the hull being assembled. In addition, steel and other major material supply is highly integrated with the shipyard and as the cost of steel is a major cost component, there is considerable investment in continuously improving productivity and reducing cost for materials and other supply chain

areas. State-of-the art modular construction techniques are ingrained in the production model and transferrable to nuclear builds.

- **Infrastructure** - Shipyards invest extensively in training, supplies, tools, support systems and transportation systems. Together these investments provide for an extremely efficient and productive work environment, which is very different from even the most efficiently organized construction site.
- **Business model** - Shipyards routinely rely upon long-term, collaborative relationships with the buyers, which encourages investment in the shipyards by the owner and commitments from buyers for future orders.
- **Quality** - Shipyards have developed, maintained and followed strict quality control and quality assurance programs not unlike the nuclear and aerospace industry. These programs must satisfy national and international standards to ensure safe transport of volatile commodities such as LNG and other chemicals.
- **Productivity** - Shipyard productivity is among the highest in the world. Labor costs constitute only 10 to 15% of the final assembly and delivery cost as opposed to up to 35% of the costs in best-in-class conventional nuclear construction.⁹ The most productive shipyards in Korea and Japan have been able to sustain 10-15% per year improvements in productivity over multiple years.
- **Training and Skilled Labor** - The largest shipyards employ staffs of 25,000 or more personnel, with extensive cross training and skill sets. Unlike construction workers, who are temporarily onsite for a project, who frequently do not live near the projects on which they work, and who are usually hired just for a single project, the workers at a shipyard are all local residents, and view the shipyard as their long-term career. This provides very strong alignment for deep development of skills and a

culture of quality that is built around the production processes that are executed every day.

- **Flexibility in Resource Allocation** - Shipyards embrace techniques and methods for optimal resource allocation including
 - Experience with earlier detection of defects and faults compared with on-site construction;
 - Ability to divert labor and parts to the fabrication areas with the greatest need;
 - Tight tracking of parts and status, with barcodes, and/or RFID tags, throughout the facility (and possibly the broader supply chain);
 - Ongoing productivity and specialization improvements by dedicated teams, which are located in the same place, perform the same task, and work on multiple orders;
 - Substantially greater opportunity to reduce

sequential delay linkages — since the delay will be the longest individual delay instead of the sum of all individual delays — and reduce risk of schedule overruns, which consequently reduces the risk of budget overruns and interest payments; and

- Manufacturing and assembly do not begin until design is complete, and the design is inherently focused on manufacturing an assembly in the construction facility. This dramatically reduces concurrent engineering and construction and associated possibility for expensive design changes.

Advanced reactor suppliers, who envision building plants using the shipyard model, will need to design plants, or redesign existing reactor systems, so that components, systems, modules or entire plants can be fabricated in shipyards. Such plant design should be informed by and reflect state-of-the-art shipyard practices as presented above.

ENDNOTES

1. While construction costs in Asia and now the Middle East are lower, all nuclear plants built to generate electricity are constrained by local demand and will require transmission to move the electricity to more distant markets. In some areas of the world, such transmission is not practicable or economically viable.
2. Petrochemical plant facts based on information published by Bechtel for the Jamnagar site in India, with project cost based on a similar planned Saudi Aramco facility in India south of Mumbai.
3. Assuming 30% thermal-to-hydrogen conversion efficiency
4. <https://jopss.jaea.go.jp/search/servlet/search?5065262&language=1>
5. In 1973, General Atomics was contracted by Philadelphia Electric to build twin 1200 MWe high temperature gas-cooled plants near the Peach Bottom site on a turnkey basis for less than \$600/kWe. Adjusting for inflation and subtracting out financing costs at 1970's interest rates (9%), this is equivalent to about \$1000/kWe in 2019 dollars (see <https://www.nytimes.com/1975/09/17/archives/plans-for-a-nuclear-plant-put-off-in-pennsylvania.html>). Similar contracts were awarded to General Atomics in the 1970's for the Summit Plant in Delaware and the Vidal Plant in California.
6. Ash, N. and Scarbrough, T., 2019 *Sailing on solar: Could green ammonia decarbonise international shipping?*, Environmental Defense Fund, London,.
7. <https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report>
8. <https://www.statista.com/statistics/911598/south-korea-leading-shipbuilding-companies-based-on-global-market-share/>
9. ETI Summary Report, Op. Cit.

APPENDIX D:

FUTURE DEMAND FOR ZERO-CARBON HYDROGEN CAN CREATE LARGE FAVORABLE MARKETS FOR NUCLEAR FISSION

Recent Western experience deploying nuclear power has been challenging, raising questions about whether nuclear energy can usefully contribute to addressing climate change. This Appendix explores potential levels of future zero-carbon hydrogen production needed for a transition to a zero-carbon global energy system and further explores why these future market-demand levels could potentially enable nuclear fission to play an important role in zero-carbon hydrogen production, along with other competing technologies.

Today, nuclear energy is used almost exclusively to produce electricity. Nuclear power projects can only be developed in markets where adequate national nuclear infrastructure exists to manage nuclear safety, nuclear technology export, non-proliferation and nuclear waste management.¹ Each country's market has its own nuclear regulatory system, which means there is no global market for nuclear power and entering new markets requires incurring large upfront cost and time commitments. Furthermore, the current delivery model for nuclear power plants — large, one-off construction projects, with very extensive site-specific engineering and design — keeps market entry costs relatively high and effectively restarts the nuclear project learning curve with each new project.

This combination of factors constrains 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 entertain a transition from power plants to building markets for nuclear

products. And many of these markets have deployed significant amounts of intermittent wind and solar generation further degrading these markets for nuclear fission, which is most economic if operated at high annual capacity factors. Current nuclear fission business models, regulatory frameworks and the limited, geographically-constrained markets they create, have kept nuclear energy technology from becoming a global commodity product like combustion turbines, coal boilers or PV.

Hydrogen fuels markets can **potentially** transform the future of nuclear energy technologies for several reasons: The global zero-carbon hydrogen market will need to 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. If nuclear energy served only 25% of projected 2050 demand, it could still require nearly half still of the current global nuclear fleet.

Large zero-carbon hydrogen fuels markets could provide significant opportunities for greatly expanded development of nuclear energy for several reasons:

- Zero-carbon hydrogen markets could enable much larger investment in and scaled-up deployment of nuclear technologies than is possible with today's limited national electricity markets.

Hydrogen fuels could be produced within countries that have existing national nuclear infrastructure and then exported into global fuels markets — like marine shipping fuel. This would essentially provide “local” nuclear hydrogen projects access to fully global hydrogen markets — in stark contrast to today’s situation where nuclear power production is limited to relatively local and often sub-optimal for nuclear power.

- Nuclear energy technology’s capability to produce electricity and heat at very high capacity factors makes it well suited to the production of zero-carbon hydrogen. This is in contrast to many power markets today where large and growing penetration of intermittent renewables generation is reducing the opportunity for conventional nuclear power to operate at high, economically-optimal capacity factors.
- Recent analyses have documented plausible technology pathways for transitioning nuclear energy to the low-cost, product-based commodity needed to make a significant contribution to zero-carbon hydrogen production.²
- The very large scale of potential zero-carbon hydrogen markets will require and enable a new optimization of nuclear energy system designs that would be product based while using a manufacturing-based delivery model. This would enable large, low-cost nuclear complexes capable of high-volume production of low-cost hydrogen.
- Zero-carbon hydrogen could provide greater latitude in siting nuclear plants by removing constraints like power grid congestion and localized market constraints and better accommodate seismic risks and variations in local support for nuclear development.

The 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 the rest of today’s energy technologies: natural gas combustion turbines, PV, wind turbines and internal combustion engines. The size of the hydrogen fuels market and the cost levels required to penetrate this market would enable large-scale manufacturing of low-cost electricity generation products for the traditional 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.

Near-term zero-carbon hydrogen markets will require **policy support**, as seen today in Japan, South Korea, California, the UK and elsewhere in Europe, which means that the full contribution that nuclear energy systems could make to meeting the global demand for hydrogen fuels may take several decades to develop.

However, some potential near-term export and domestic markets for nuclear hydrogen can also drive demand and bolster policy efforts. For example, low-cost, zero-carbon hydrogen produced with electricity from existing nuclear plants that have paid off their capital costs can be blended into natural gas distributions systems or used as feedstock for “green ammonia” fertilizer production. These opportunities could diversify use of some existing nuclear plants as well as eventually support new nuclear projects dedicated to low-cost hydrogen production. For example, US DOE recently established a H2@Scale initiative, which funds projects and National Laboratory activities to “accelerate the early-stage research, development and demonstrations to apply hydrogen technologies.”³ In August, 2019, the DOE announced funding for a project with Exelon — which has the largest US nuclear power plant fleet

— to produce, store and use hydrogen produced from an existing nuclear plant. And ARPA-e subsequently provided funding to FirstEnergy Solutions, Xcel Energy and Arizona Public Service to demonstrate hydrogen production from existing nuclear facilities as well.⁴

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 transform the future nuclear industry.

ENDNOTES

1. 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.
2. Energy Technologies Institute, Nuclear Cost Drivers Project, 2018. www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report
3. US Department of Energy (2019). H2@Scale Handout. <https://www.energy.gov/sites/prod/files/2019/09/f67/fcto-h2-at-scale-handout-2019.pdf>
4. 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/>

APPENDIX E:

EON'S GLOBAL ENERGY MODEL

EON developed a global energy model to forecast future energy demand and used this model to characterize future zero-carbon hydrogen market potential. This Appendix addresses EON's motivation for the model, how it estimates energy demand by fuel type and, by extension, potential hydrogen market demand through 2100.

EON's global energy model provides a practical tool for energy decarbonization analysis reaching out to 2100 and allows easy modification of key parameters (including population growth, economic activity and energy demand).¹ This provides capability to look beyond and outside of "mainstream" climate energy scenarios that typically use "middle-of-the-road" assumptions for such important drivers as population growth, economic growth and energy intensity. While "mainstream" scenarios may be useful for developing "consensus estimates", they narrow the range of "visible" scenarios of future energy use and resulting carbon emissions and thus tend to exclude plausible scenarios with much larger energy use and carbon emissions. In addition, much of the climate/energy literature and energy/carbon projections focuses on the 2040 to 2060 time frame. This underestimates the scale of future energy needs and carbon emissions displacement. Many underlying trends that will drive increases in energy use, like urbanization, economic growth and industrialization are projected, by many, to continue to grow rapidly throughout the second half of the century. A nearer-term perspective also hides potential benefits of investment in technologies that would impact energy supply and carbon emissions in the 2040's and well beyond. EON's model enables exploring a broad range of population projections, economic growth and developing world energy intensity.

EON's model shows that if less-limiting assumptions are made about economic growth in the developing world, particularly in Africa, then economic growth, energy consumption and carbon emissions will be significantly higher than most existing projections, highlighting the critical need to supply affordable zero-carbon energy. While EON expects renewables (solar, wind, and hydro) to contribute to this growing energy need, developing countries will need significant increases in electricity supply, transportation fuels and energy support for chemicals, iron, steel and cement production, which could potentially account for 75% of developing country energy consumption.

Forecasting Energy Demand

Projections through 2050 used in EON's energy modeling are from the U.S. Energy Information Administration's (EIA's) International Energy Outlook 2019.² It provides detailed data through 2050, and supplemental sources are used for extrapolations from 2050 to 2100.³ In addition to presenting baseline projections, the following sub-sections describe the wide uncertainty bands around these metrics, including plausible scenarios of sharp acceleration beyond baseline growth rates.

- **Population** - Baseline population projections are from the EIA's International Energy Outlook (to 2050) and UN Population Division (to 2100).
- **Gross domestic product** - A supplemental source⁴ provide information on GDP trajectories. The average resident of a non-OECD country is currently nearly ten times poorer than their OECD counterpart. The gap will gradually narrow because of faster economic growth (normalized by population) in non-OECD countries.

- **Total energy consumption** - EIA's International Energy Outlook provides baseline projections of coal, natural gas and oil consumption for power production or other uses through 2050. Extrapolations to 2100 are based on mid-century trends in GDP energy intensity.
- **CO₂ emissions** - In the baseline scenario, CO₂ emissions reflect baseline changes in the energy mix from EIA's International Energy Outlook.

Energy Demand in the “higher growth” scenario

The Higher Growth case assumes higher economic growth and energy intensity improvement rates, at 1-2 % per year depending on period.⁵

Table E1. Global energy demand and emissions in “Base Case” and “Higher Growth” case for years 2050 and 2100

	2015	2050		2100	
		Base Case	Higher Growth	Base Case	Higher Growth
Global total energy demand					
Oil	194 quads*	243 quads	359 quads	599 quads	837 quads
Natural gas	129 quads	218 quads	322 quads	539 quads	753 quads
Coal	158 quads	165 quads	244 quads	407 quads	568 quads
Nuclear	26 quads	40 quads	59 quads	98 quads	137 quads
Renewables	72 quads	146 quads	216 quads	362 quads	506 quads
Total	579 quads	812 quads	1,200 quads	2,005 quads	2,800 quads
Global CO ₂ emissions					
Oil	12.2 Gt*	15.7 Gt	23.2 Gt	38.8 Gt	54.2 Gt
Natural gas	6.8 Gt	11.5 Gt	17.0 Gt	18.0 Gt	25.2 Gt
Coal	14.9 Gt	15.5 Gt	23.0 Gt	15.0 Gt	21.0 Gt
Total	33.9 Gt	42.8 Gt	63.2 Gt	71.9 Gt	100.4 Gt

* The unit “quads” refers to quadrillion BTUs.

* The unit “Gt” is gigatonnes of CO₂.

Potential Market Size for Dedicated Nuclear Hydrogen Production Plants

EON estimates potential nuclear hydrogen market size in 2050 as between 3,972 - 5,871 GW-equivalent (“GWe”) amount of nuclear capacity. This number jumps to 9,800-13,686 GWe by 2100.

EON estimates nuclear hydrogen market size by first taking the estimated energy demand (listed above) for oil and natural gas, which is listed as heat units (“quads”) and converting that to energy units (gigajoules or “GJ”). With energy converted to GJ, it is possible to estimate the equivalent energy in a volume of hydrogen gas. Using a 2003 EPRI study,⁶ which estimates the amount of hydrogen gas that can be produced by a given nuclear plant, it is possible to estimate the total installed capacity GW-equivalent (“GW-eq”) of nuclear reactors needed.⁷

Table E2 presents how EON estimated the GW-eq of reactors needed by 2050 and 2100.

Note that this analysis arbitrarily assumes nuclear hydrogen would only displace a relatively modest percentage of oil and natural gas energy (25% and 10%, respectively). Actual future nuclear hydrogen production could potentially be larger. These market percentages remain uniform from 2050 to 2100. Multiple reactor types can produce hydrogen and depending on the reactor outlet temperature, different processes can produce hydrogen (see detailed discussion in Appendix B). EON used an average hydrogen production rate for three hydrogen production methods (conventional electrolysis, steam electrolysis, and sulphur-iodine), which was 2.1 million cubic normalized meters (“Nm³”) of hydrogen per MWe.

Table E2. Estimated New Nuclear Capacity for Displacing Portions of the Oil and Natural Gas Markets (GW-equivalent)

Global Oil & Natural Gas Demand <i>(total demand taken from previous table)</i>	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

ENDNOTES

1. The Clean Air Task Force funded development of this model.
2. <https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf>
3. Burke, Paul J. and Csereklyei, Zsuzsanna, 2016. Understanding the Energy-GDP Elasticity: A Sectoral Approach, CAMA Working Paper No. 45/2016, <http://dx.doi.org/10.2139/ssrn.2813024>
4. Ibid.
5. <https://webstore.iea.org/market-report-series-energy-efficiency-2018>)
6. EPRI (2003). High Temperature Gas-Cooled Reactors for the Production of Hydrogen: An Assessment in Support of the Hydrogen Economy. Final Report, March 2003. <https://www.epri.com/#/pages/product/000000000001007802/?lang=en-US>
7. About 48 GWe of nuclear capacity can produce sufficient hydrogen to displace 1 Quad of fossil energy.



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