Energy for Humanity: Economic Requirements for the Expanded Role of Nuclear Energy in De-Risking the Energy Transition in the Electricity and Fuels Sectors

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In 2019, several clean-energy nongovernmental organizations helped conceive and co-founded the Flexible Nuclear Campaign, because it was time to explore the expanded role that nuclear energy can play in de-risking countries' energy transitions by exploring additional paths to significantly reduced emissions. This chapter describes three ways to broaden the role that nuclear energy can play in clean energy transitions.

The first is an expanded role in electricity production through the design of nuclear configurations—using a combination of flexible operations and thermal energy storage— intended to complement renewables in future grids. The key here is providing guidance to designers of advanced nuclear systems about features and capital costs that will make their designs more valuable and competitive in future electricity markets.

The second is enabling nuclear energy to contribute to energy transitions beyond electricity production—in the primary energy sectors making up three-quarters of energy consumption currently served by oil and gas—by providing hydrogen that can be used directly or as a feedstock for synthetic fuels.

The third is redefining the deployment paradigm for nuclear energy based on a high-volume, low-cost, rapidly-deployable, commercially-attractive manufacturing model—in order to expand nuclear's role in all energy sectors with the goal of significantly reducing emissions and ensuring clean affordable energy for all.

These concepts show how the nuclear industry can apply commitment and creativity, combined with technical and business innovation, to deliver the scale and rates of deployment needed to provide large-scale and timely contributions toward clean energy transitions, just as the renewables industry learned to do. This chapter is an effort to open a broad and rigorous discussion of what it would take for this to occur.

1.1 Enhancing the Value of Nuclear Energy to the Electric Grid: Design and Capital Cost Targets for Flexible Advanced Nuclear Plants

In the United States, competitive power markets are experiencing extended periods of very low power prices, driven primarily by large supplies of low-cost natural gas. At the same, growth in demand for electricity has stagnated in many areas of the United States, driven by deindustrialization and efficiency improvements. These power market conditions would normally discourage new entrants; however, federal government incentives, state policies, and corporate purchases of renewable energy are driving significant deployment of wind and solar, further

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depressing wholesale power prices. Remarkably, in spite of these conditions, there are now more companies developing advanced reactors than at any other time before. However, reactor developers today must design for very different future market conditions than nuclear plants have seen in the past.

In this new environment, it is critical for advanced reactor designers to have clear signals from the market about what plants need to cost to be attractive investments, and what performance characteristics will create the most value for plant owners. Many advanced reactor designs, especially their balance-of-plant, are still in the conceptual design stage and therefore have large scope for reducing CapEx by making intelligent design choices and applying target cost design methods. Designers face critical questions such as: What is the maximum allowable CapEx for which plants can be built once they are commercially available? Further, how flexible should the reactor be? How much is that flexibility worth? How much effort and/or cost should be expended to deliver flexible performance and how much value can that create for the plant owner?

LucidCatalyst used the PLEXOS® electricity production cost modeling software to estimate the revenues earned by a generic high-temperature advanced nuclear plant in deregulated power markets in 2034 (LucidCatalyst 2020). These revenues (which included the opportunity to receive capacity payments that are seen in today's markets) were then analyzed in a power plant financial model to determine the maximum allowable CapEx for which a plant must be delivered to meet a market rate of return. The goal was to provide advanced reactor developers information about the CapEx targets they need to achieve by the time their reactors are to be commercially available. The team also analyzed the value of flexible operation, as several advanced nuclear plants are being designed with similar ramping and load-following capabilities as combined-cycle natural gas plants (LucidCatalyst 2020).

LucidCatalyst modeled two different future scenarios—each containing different resource mixes. The first is a baseline low renewables scenario, which presumes a continuation (and eventual expiration) of existing renewables policy. The second is a high renewables scenario that has the same resource mix as an NREL ReEDS scenario, which assumes low renewables and natural gas costs (thus high penetration of both resource types). These scenarios were modeled across four deregulated U.S. power markets: ISO-NE, PJM, MISO, and CAISO.

The PLEXOS modeling revealed that the average allowable CapEx across all scenarios and independent system operators is $3,234/kW (reflecting a range from $1,965/kW to $4,503/kW, depending on the power market, resource mix, and capacity payment amount). Each modeled scenario also included a run with a 12-hour, co-located thermal energy storage system. The additional energy revenues earned from higher prices and extra capacity payments earned from doubling the effective capacity of the plant, enabled an increase in the allowable CapEx for the nuclear + storage plant which ranged from $613/kW to $1,891/kW across the modeled scenarios and independent system operators. The table below provides the maximum allowable CapEx for each modeled scenario and power market.

Table 1. Maximum Allowable CapEx by Independent System Operator and Scenario ($/kW)

	Low RE w/out ESS	with ESS	High RE w/out ESS	with ESS
ISO-NE				
Low Capacity Price Case ($50/kW-yr)	$2,289	$2,962	$1,965	$2,788
Mid Capacity Price Case ($75/kW-yr)	$2,566	$3,515	$2,242	$3,341
High Capacity Price Case ($100/kW-yr)	$2,843	$4,068	$2,519	$3,894
PJM				
Low Capacity Price Case ($50/kW-yr)	$2,358	$2,988	$2,186	$3,038
Mid Capacity Price Case ($75/kW-yr)	$2,634	$3,541	$2,462	$3,591
High Capacity Price Case ($100/kW-yr)	$2,911	$4,095	$2,739	$4,144
MISO				
Low Capacity Price Case ($50/kW-yr)	$2,244	$2,857	$2,000	$2,654
Mid Capacity Price Case ($75/kW-yr)	$2,521	$3,410	$2,276	$3,207
High Capacity Price Case ($100/kW-yr)	$2,797	$3,963	$2,553	$3,760
CAISO				
Low Capacity Price Case ($50/kW-yr)	$2,187	$3,397	$1,968	$3,306
Mid Capacity Price Case ($75/kW-yr)	$2,464	$3,950	$2,244	$3,859
High Capacity Price Case ($100/kW-yr)	$2,740	$4,503	$2,521	$4,412

LucidCatalyst performed additional sensitivity analyses to assess the impact of other factors on maximum allowable CapEx, including a scenario with a large fleet of advanced nuclear plants with energy storage systems. As expected, due to lower operating costs, advanced nuclear plants set lower energy clearing prices and thus decreased the allowable CapEx thresholds.

Table 2. Annual Average Market Prices for ISO-NE, PJM, MISO, and CAISO

		Average Annual Energy Price
ISO-NE	High RE Future (Without Flexible Adv. Nuclear)	$26.32/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$22.64/MWh
PJM	High RE Future (Without Flexible Adv. Nuclear)	$27.03/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$22.67/MWh
MISO	High RE Future (Without Flexible Adv. Nuclear)	$26.13/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$24.70/MWh
CAISO	High RE Future (Without Flexible Adv. Nuclear)	$38.06/MWh
	Fleet Deployment of Flexible Adv. Nuclear	$29.61/MWh

Because advanced nuclear plants can operate as base load resources as well as load following, they can supply a large fraction of firm power without raising the overall cost of electricity. These findings motivate independent system operators, public utility commissioners, policymakers, utilities, and other stakeholders to investigate the potential roles that these products could play in future grids and to continue supporting advanced nuclear commercialization efforts. This should also encourage organizations responsible for national and international energy modeling to include flexible, advanced nuclear with thermal energy storage in their projections for future energy systems. Figure 1 shows installed capacity for PJM across the range of scenarios, and Figure 2 shows generation. This illustrates the potential effectiveness of advanced reactor plants with energy storage to operate flexibly and cost-effectively while reducing emissions.

The CapEx thresholds highlighted in this report are relatively low compared to conventional nuclear new build plants in North America and the European Union. That said, they are well within the range of those reported by third-party cost studies (Energy Innovations Reform Project 2017) and advanced nuclear developers themselves. This range is also well within the costs being achieved in countries with continuous new build nuclear programs (Energy Technologies Institute 2018). Designers should integrate these cost requirements into their plant designs and consider whether adding thermal storage makes sense in their target markets.

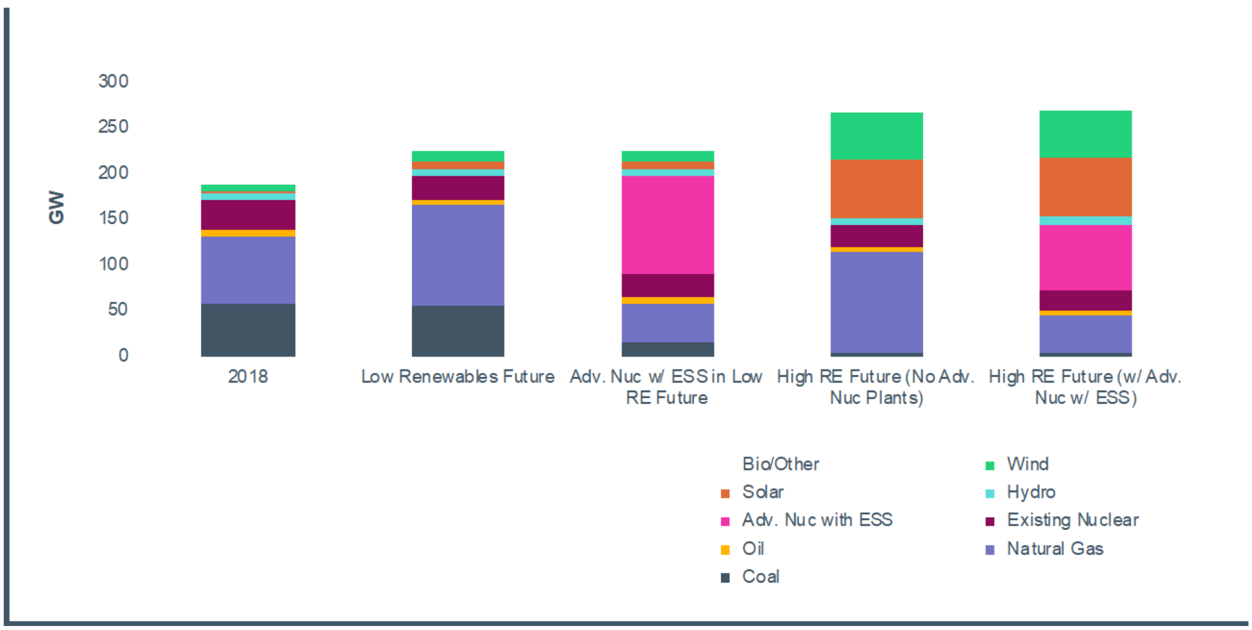

Figure 1. PJM installed capacity

Source: LucidCatalyst.

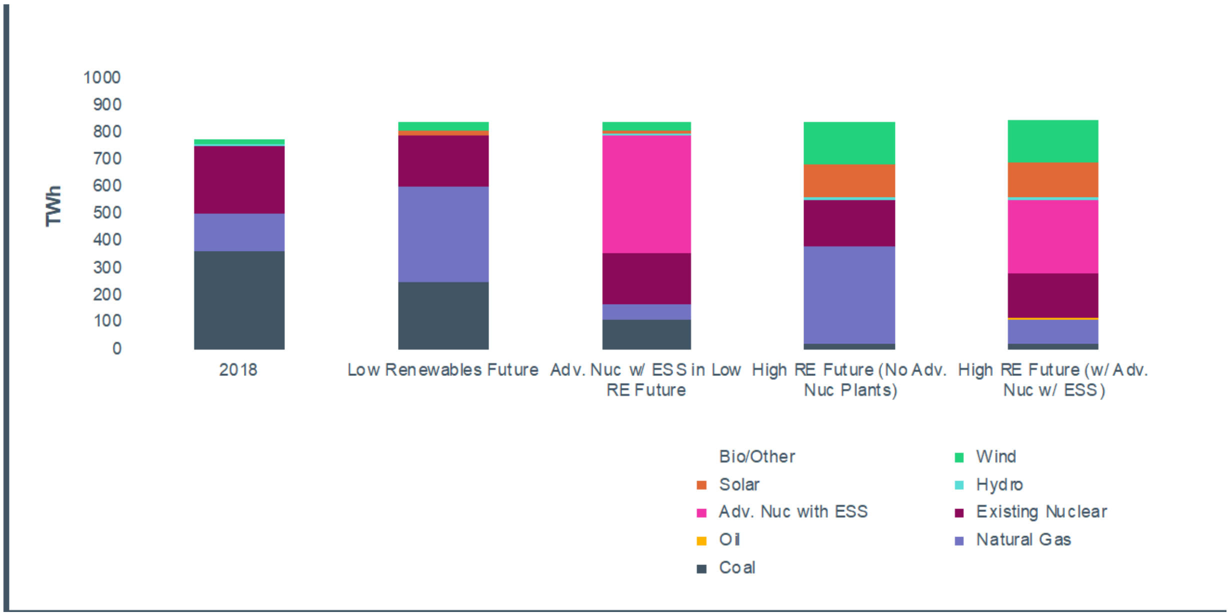

Figure 2. PJM generation

Source: LucidCatalyst.

1.2 Nuclear Energy is Well-Suited to Emissions-Free Hydrogen Production

Despite progress on driving down emissions in the power sector, credible projections indicate that fossil fuels will continue to supply the bulk of global energy by mid-century. This assumes extensive deployment of electrification, efficiency, renewables, and other clean technologies (BP 2019; DNV GL 2019; EIA 2019; IEA 2019b). The *IEA World Energy Outlook 2019's Stated Policies Scenario* assumes substantial electrification of transport sectors and significant long-term growth of renewable energy (IEA 2019b). Nevertheless, IEA projects that fossil fuels (coal, oil, and gas) will supply approximately 75% of primary energy by 2050[1] (IEA 2019b).

At the same time, three billion people will lack access to electricity in 2050, up from the 840 million people today who lack access to sufficient electricity (Sustainable Energy for All 2019). To avoid this outcome, growth in energy access will need to be better represented in global climate mitigation strategies (IEA World Energy Outlook 2019).

[1] In the IEA Stated Policies Scenario, energy demand rises by 1% per year to 2040. Low-carbon sources, led by solar PV, supply more than half of this growth, while natural gas, boosted by rising trade in liquefied natural gas, accounts for another third. Oil demand flattens out in the 2030s, and coal use edges lower. Some parts of the energy sector, led by electricity, undergo rapid transformations. Some countries, notably those with net zero aspirations, go far in reshaping all aspects of their supply and consumption. However, the momentum behind clean energy technologies is not enough to offset the effects of an expanding global economy and growing population. The rise in emissions slows but, with no peak before 2040, the world falls far short of shared sustainability goals.

Failing to achieve net zero emissions and providing basic access to electricity for large numbers of people will have severe global consequences. New solutions are required, especially for fuels use, both liquid and gas.

In light of this, numerous recent studies have examined emissions-free hydrogen production as a decarbonization tool, with estimated production costs from various clean electricity sources indicating this to be a potentially promising opportunity (Glenk and Reichelstein 2019; IEA 2019a; IRENA 2018).

By 2050, clean hydrogen produced using nuclear and/or renewable energy could help avoid half of cumulative future carbon emissions from a large fraction of otherwise locked-in fossil fuels. However, this depends upon very low-cost clean hydrogen being available in the near term.

Drawing on the IEA World Energy Outlook 2019's Stated Policies Scenario, it is possible to identify the most relevant sectors for hydrogen substitution. These are: natural gas for nonelectricity uses, oil for transportation, and oil for other uses (IEA 2019b).

The vehicles, machinery, heating systems, and other applications in these sectors could consume drop-in synthetic fuels from hydrogen rather than conventional fossil fuels. All coal consumption and natural gas for electricity generation are excluded from this analysis because these sectors could be decarbonized in a relatively straightforward manner with other clean electricity sources rather than synthetic fuels.

Fossil fuel consumption for IEA World Energy Outlook 2019's Stated Policies Scenario sectors considered (natural gas for nonelectricity uses, oil for transportation, and oil for other uses) (IEA 2019b) are expected to be responsible for nearly 20 GT of CO_2 emissions in 2050 (55% of total CO_2 emissions from fossil fuel consumption). Emissions from the included sectors rise faster in the IEA Stated Policies scenario than those from the excluded sectors (coal for all uses and natural gas for electricity). Cumulatively, over the period from 2020 to 2050, the included sectors are predicted to emit 525 GT of CO_2 (IEA 2019b).

The sectors addressed are, by definition, difficult to abate, because emissions are not being eliminated by the stated policies assumed in the IEA analysis. The strategies outlined therefore are intended to drive emissions reduction in parts of the economy for which viable solutions are currently not foreseen to be available by mid-century. These strategies should therefore be seen as complementary and needed for net zero emissions by mid-century.

1.2.1 Target Costs for Hydrogen as a Feedstock for Synthetic Fuels

To achieve the scale and pace of emissions reduction required, we assume that zero- and carbon-neutral fuels substitutes need to achieve price and performance parity with fossil fuels. This is also necessary to enable energy access and continued economic growth, and to reduce the risks associated with the need for political support, government subsidies, and behavior change if prices are not competitive.

The rapid decrease in hydrogen costs from nuclear plants would allow for faster substitution of large amounts of fossil fuel consumption in the IEA World Energy Outlook 2019's Stated Policies Scenario sectors addressed in this report. Based on hydrogen cost and market size data analyzed, more than half of fossil fuel consumption in these sectors could be decarbonized by 2030, and all of it by 2050.

As shown in Figure 3, emissions-free hydrogen production using nuclear technology can be cost-competitive with other zero-CO_2 production methods and has the potential to be cost competitive with steam methane reforming of low-cost natural gas, which is the cheapest pathway to making hydrogen today (Allen et al. 1986; BloombergNEF 2020; Boardman et al. 2019; Gogan and Ingersoll 2018; Hydrogen Council 2020; IEA 2019a; NREL 2019; Ruth et al. 2017; Yan 2017). Even current first-of-a-kind U.S. and EU conventional LWR are not optimized for low-cost construction can produce clean hydrogen at costs comparable to wind and solar resources with good capacity factors.

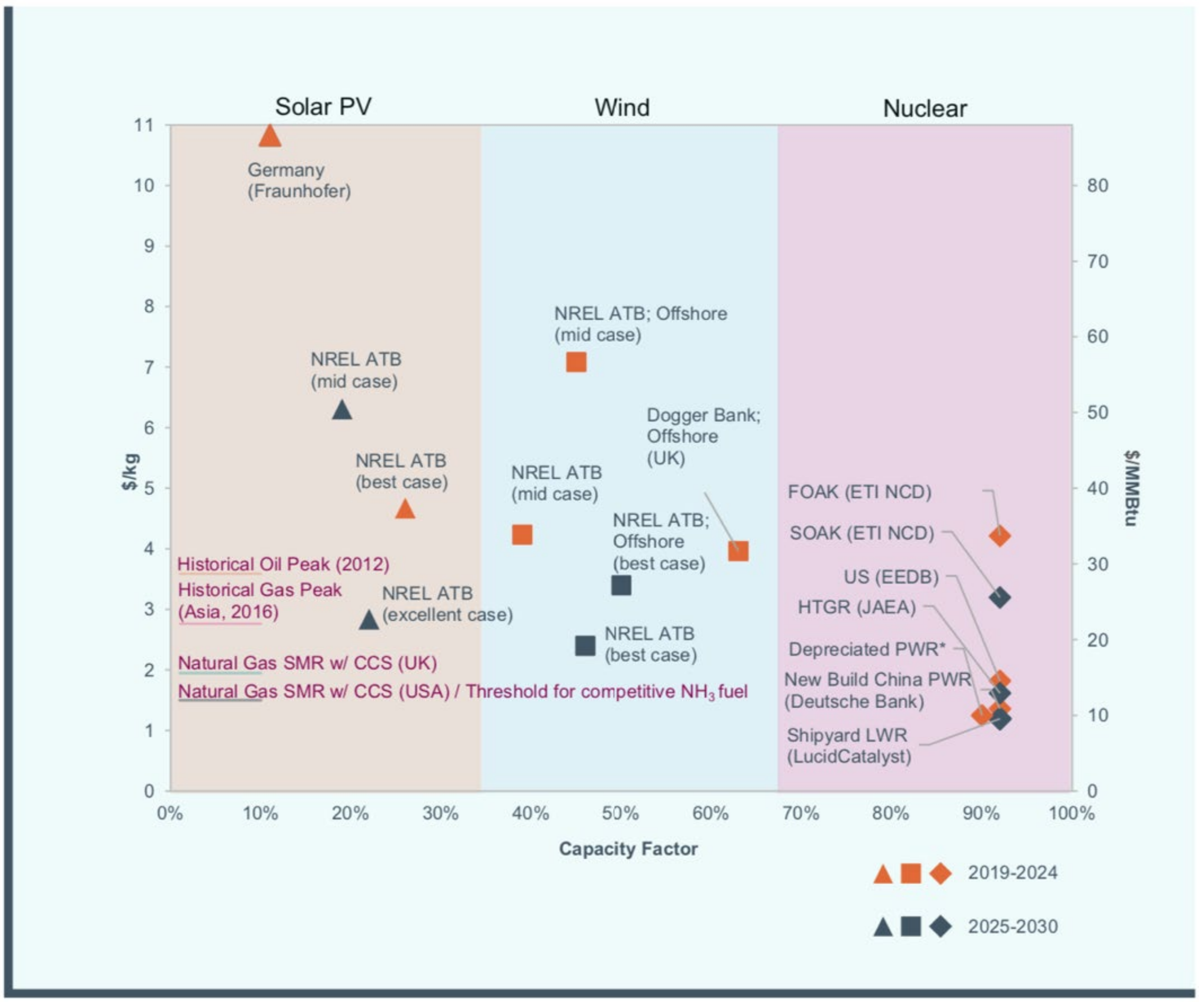

Figure 3. 2018–2030 hydrogen production costs

Source: (LucidCatalyst 2020)

Nuclear energy has particular attributes well-suited to the production of hydrogen. Electricity and heat production at very high capacity factors enables large-scale production of relatively low-cost, zero-CO_2 hydrogen (Boardman et al. 2019).[2] High power density also enables a relatively tiny environmental footprint. Nuclear production of hydrogen offers additional flexibility in how nuclear energy supports grid demand, assuming that the coupled hydrogen plant can be operated in a flexible manner as well.

Hydrogen can be produced with grid electricity or surplus energy from clean sources like renewables and nuclear. However, future zero-carbon fuels markets are so large that they will also need to be addressed by large, dedicated zero-carbon hydrogen production facilities. This is because the ultimate size of the zero-carbon hydrogen market—if expanded to produce synthetic substitutes for fossil fuels—could be far larger than the global electricity market. Therefore, the emphasis here is primarily on cost and scalability potential of hydrogen production from large, dedicated projects.

Low-cost hydrogen (below $1.50/kg) can enable large-scale production of carbon neutral fuels such as Jet A fuel for aviation, and ammonia to replace bunker fuel in marine shipping and peaker gas plants as well as other uses. Low-cost hydrogen requires low-cost, high capacity factor energy, as well as low-cost and highly efficient electrolyzers. Reaching aggressive cost targets is helped by using advanced high temperature electrolysis as well as thermochemical, heat driven processes.

Due to its ability to produce electricity and high-temperature steam reliably at capacity factors over 90%, nuclear technology is well suited to produce large volumes of low-cost hydrogen at a global market scale. Production from nuclear technology is highly advanced. Decades of research, including whole programs in national laboratories, both with conventional (light water) and advanced reactors, has shown the transformative and near-term potential for low-cost, high-volume clean hydrogen production. Recent analyses and planned LWR-generated hydrogen demonstrations in the United States are summarized in Chapter 5.

1.2.2 Transformative Nuclear Project Delivery Models for Low-Cost and Large-Scale Deployment for Power, Hydrogen, and Fuels

The nuclear industry as it is configured today is unlikely to be able to deliver the scale of plants necessary within the required timeframe to make a substantial contribution to synthetic fuels production. To drive a massive increase in clean hydrogen production, the nuclear industry will need to transform project delivery and deployment models in order to scale up and deliver the products needed for clean heat, fuels, and power. These would be achievable with the application of the same intensity of focus on cost reduction, performance improvements, and deployment rates that have enabled renewable technologies to begin transforming the global energy system.

Steep, near-term cost reduction is achievable by shifting from traditional construction projects to high productivity manufacturing environments, such as shipyard-manufactured plants or floating production storage and offloading vessel (in Figure 5) or a Hydrogen Gigafactory model (defined

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[2] "Affordable clean hydrogen can be produced using energy from the nuclear power plant. The DOE target for the levelized cost of hydrogen production (i.e., <$2.00/kg H_2) can be met and exceeded. The analysis indicates an LWR electricity/hybrid plant can also outperform conventional natural-gas steam reforming under specific operating conditions and clean energy allowances. The economic evaluation indicates H_2 can be produced for around $1.50/kg, based on the financial parameters invoked for a publicly bonded capital project" (Boardman et al. 2019).

below and pictured in Figure 6). Moving from traditional construction to high productivity manufacturing will dramatically lower the cost of clean hydrogen and synthetic fuels production using high temperature advanced reactors. Leading shipyards already have extensive manufacturing capacity, which can produce designed-for-purpose hydrogen production facilities. Existing global shipyard capacity combined with new and/or upgraded capacity could deliver sufficient synfuel floating production storage and offloading vessels to fully replace fossil fuels in the difficult-to-decarbonize sectors identified in this chapter.

These new delivery models achieve hydrogen costs that enable cost-competitive synfuels at large scale as early as 2030. Achievable hydrogen production costs for 2030–2050 are shown in Figure 4.

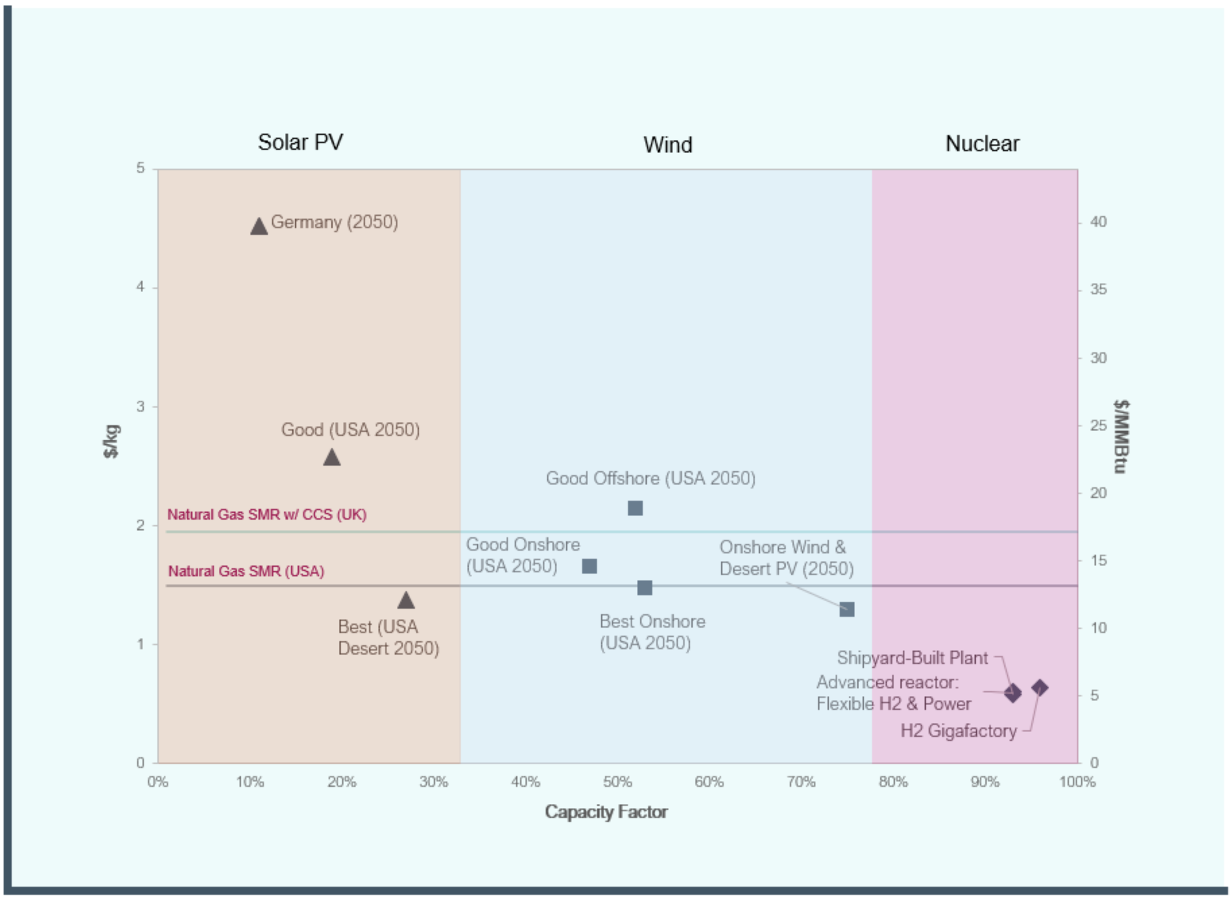

Figure 4. Hydrogen production costs 2030–2050

Source: LucidCatalyst.

Figure 5 and Figure 6 show a conceptual shipyard manufactured floating production storage and offloading vessel with the potential to produce hydrogen, power, ammonia, and desalination moored close to shore. Not shown are the pipelines and underwater transmission cables sending products to shore.

Figure 5. Shipyard-manufactured hydrogen, ammonia, and desalination facility

Source: LucidCatalyst.

The production of fuels which are transportable commodity with a global market enables a new business model for nuclear energy. As the product changes from local electricity to global fuels deliveries, the siting and scale of operations are transformed. Offshore deployment increases siting opportunities and reduces costs, further enabling global-scale production of low-cost hydrogen and synthetic fuels in the 2030s and beyond.

The Hydrogen Gigafactory concept (illustrated in Figure 6) is a next generation refinery to be located on brownfield sites, such as large coastal oil and gas refineries. This refinery-scale hydrogen production facility is sized to produce one-tenth of U.K. hydrogen demand in 2050. The Hydrogen Gigafactory delivery model, with its highly integrated, high productivity onsite manufacture, assembly, and installation of key components and compact layout, can deliver large quantities of very low-cost hydrogen. For countries developing such refinery-scale facilities, this represents huge potential to establish world-leading domestic supply chain capability, potential competitive export of synthetic fuels, and affordable decarbonization.

By rethinking nuclear deployment from this cost-reduction perspective and scaling up operations, this chapter defines a path to ultra-low-cost hydrogen at under $1/kg. The rapid achievement of low hydrogen costs via these innovative delivery modes could accelerate deep decarbonization across the difficult-to-decarbonize sectors. By 2050, low-cost clean hydrogen could help avoid substantial global cumulative future carbon emissions from a large fraction of otherwise locked-in fossil fuels.

Figure 6. 2018–2030 Hydrogen Gigafactory

Source: LucidCatalyst.

Achieving the extent of decarbonization required within 30 years will be a herculean effort. Major constraints, including the extent of capital available for investment in new infrastructure need to be taken into account. The investment required to maintain the anticipated flow of oil (approximately 100 million barrels of oil per day) is $16.8 trillion over the period 2020–2040 (Hureau and Serbutoviez 2020).

By contrast, the innovations described here would require a lower investment than would otherwise be required to replace the oil and gas flows in hard-to-decarbonize sectors from the IEA stated policies scenarios. Figure 7 shows the total investment required for 350 EJ full fuel substitution by 2050, either by floating production storage and offloading vessels,[3] or by renewables (a combination of excellent capacity factor wind and solar) (NREL 2019) compared to the projected exploration-production investment required to maintain and grow this flow of conventional oil and gas to 2050. In other words, meeting the same energy need for liquid fuels and gas (the 350 EJ identified earlier) through floating production storage and offloading vessels and Gigafactories requires substantially less investment between now and 2050 than continuing to invest in oil and gas production to meet this future requirement. The nuclear case supplies 350 EJ and includes the full cost of hydrogen plus conversion to synthetic fuels, resulting in an investment requirement considerably less than current investment projections to maintain the equivalent flow of oil and gas supply. The implication is that these fossil fuel supplies could be replaced with clean

[3] The floating production storage and offloading vessels investment case assumed a weighted average installed cost over 2030–2050 timescale of 1.3 billion per GW-class floating production storage and offloading vessel, including electrolysers, fuel production equipment, and onboard storage.

substitutes within three decades for less investment than would be required to continue supplying them through conventional oil exploration and production methods.

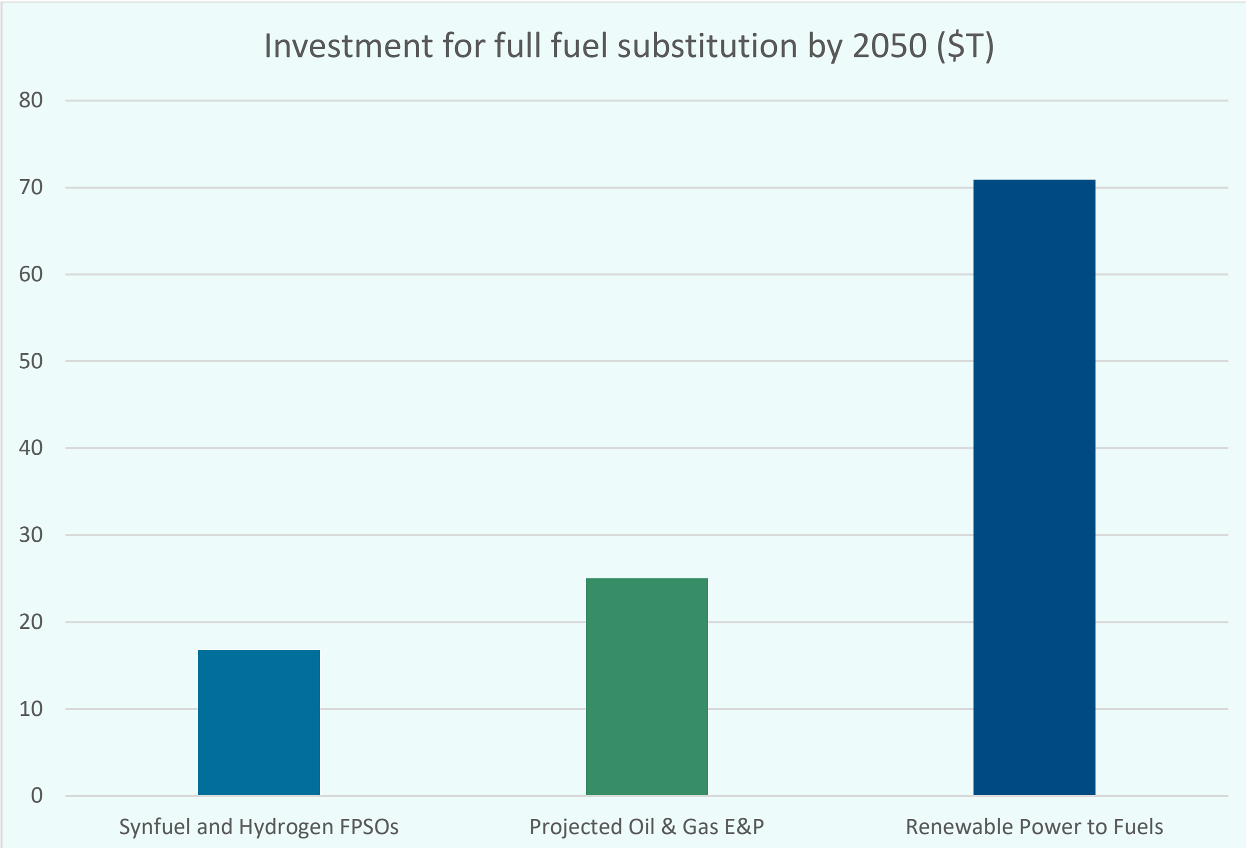

Figure 7. 2018–2030 hydrogen production costs

Source: LucidCatalyst.

Synthetic fuel production cost is a function of the cost of the hydrogen feedstock required. For synthetic fuels to achieve a price range that corresponds to typical cost ranges for standard fuels requires extremely low-cost hydrogen feedstock. Specifically, to achieve ammonia costs that are comparable to fuel oil for ships, requires hydrogen at $1.50/kg or below, and $1.10/kg or below for synthetic hydrocarbons, such as Jet A for aviation fuel. This can be achieved by combining advanced nuclear technologies with innovative delivery and deployment models in designed-for-purpose facilities intended to quickly achieve very low costs and large-scale deployment for rapid, near-term emissions reduction.

Our forthcoming study, *Decarbonizing Prosperity,* shows how scalable, cost-effective hydrogen can be produced in the near term (LucidCatalyst 2020). The study combines key results from techno-economic modeling of clean hydrogen production pathways. Given the high stakes, every effort should be made to realize this potential. For too long, risks associated with nuclear energy have been considered outside of the context of risks with other technologies, and without due consideration to the risks of failing to decarbonize. This chapter is a call to action for leaders to become educated about nuclear power, put risks into context and make informed, evidence-based and outcomes-focused decisions having properly evaluated the alternatives. To facilitate such informed decision-making, governments may wish to investigate the cost reduction and scale-up potential of factory-based and shipyard-manufacturing models for clean fuels production.

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