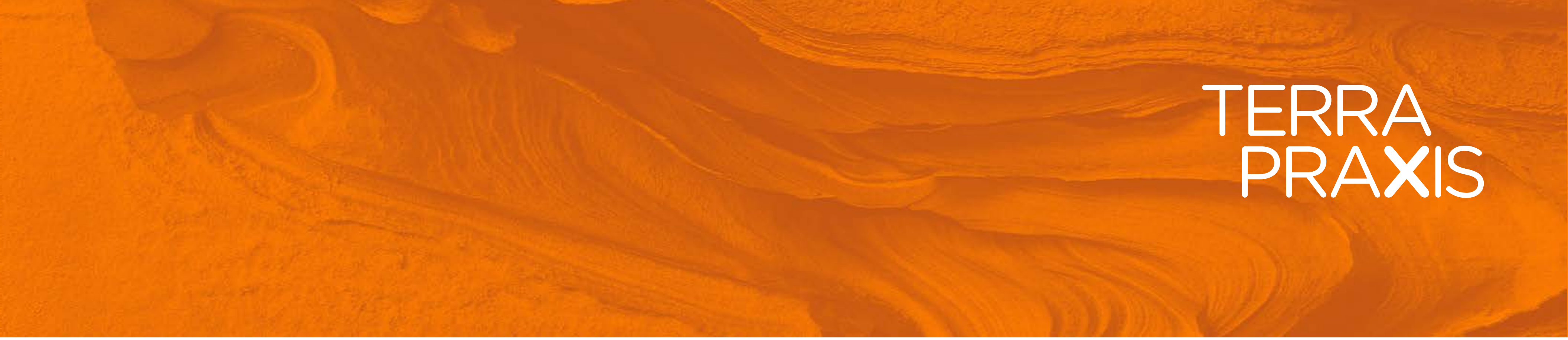


TERRA
PRAXIS

CLIMATE SOLUTION PROFILE/
MISSING LINK TO A LIVABLE CLIMATE

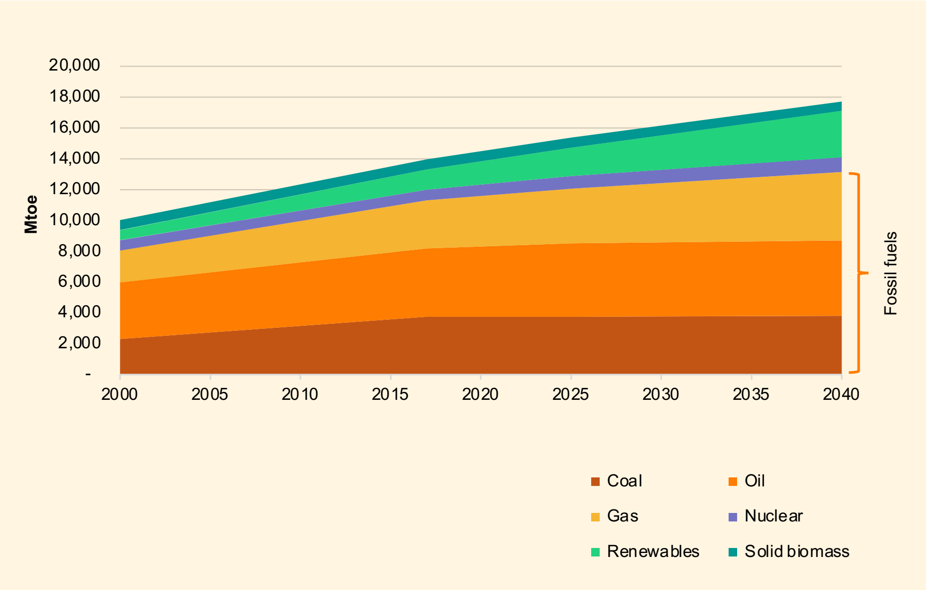
FEBRUARY 2021

The world is far off track when it comes to meeting the Paris Agreement goals of limiting the global temperature increase to 1.5°C by 2050. Current projections, even those that include a vast expansion of renewables generation, show that fossil fuels will still make up the majority of world energy use by mid-century.[1] This puts the world on a trajectory for a high-risk 4°C outcome and could mean substantial areas of the planet becoming uninhabitable. Furthermore, by 2050, three billion people will lack access to electricity, up from 840 million people today.[2]

According to the Intergovernmental Panel on Climate Change (IPCC), in order to meet a 1.5°C pathway with no overshoot, anthropogenic CO_2 emissions must be cut in half by 2030 and reach net zero carbon emissions—"Net Zero"—by 2050. For a 2°C pathway, Net Zero must be reached by 2070.

Current projections show fossil fuels still making up the majority of world energy use by mid-century (Figure 1). Oil and gas use remains high in 'difficult to decarbonize' sectors such as aviation, heavy industry, marine shipping, and non-electricity uses of gas. The lack of practical solutions for these sectors is putting the world on the path to a 4°C outcome.

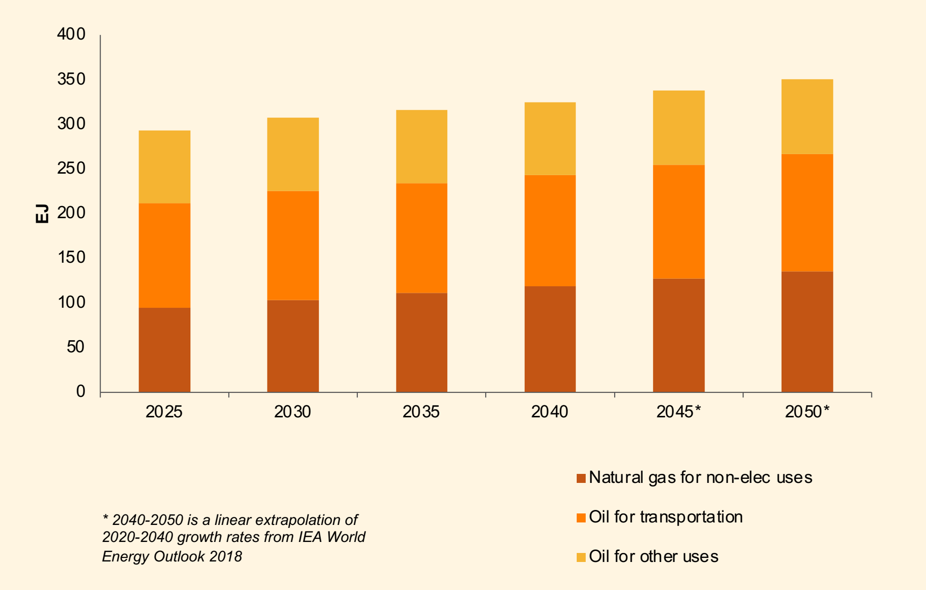
Figure 1. **IEA's stated policies scenario: world energy by source**



Key Findings

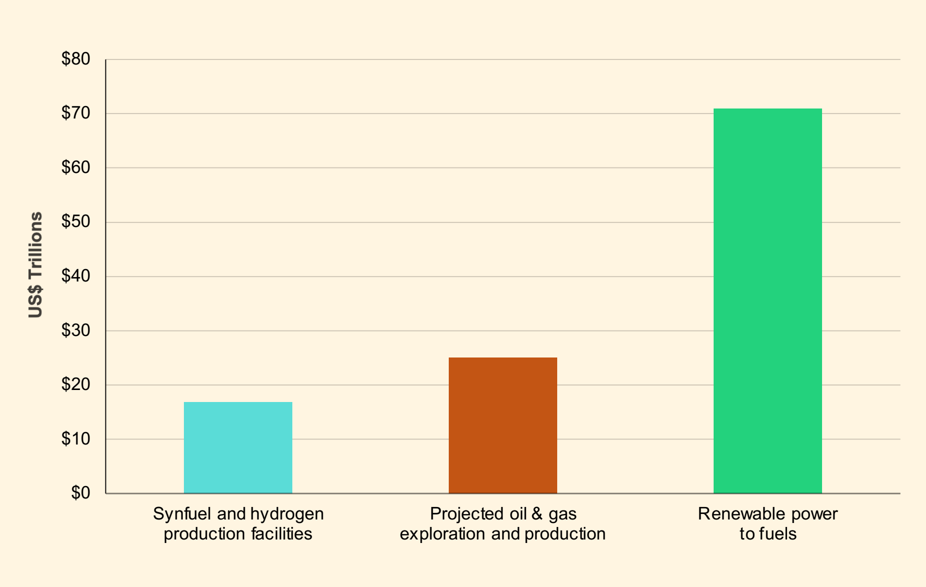
- Massive quantities of clean electricity and hydrogen will be needed to decarbonize the global energy system, particularly the fuels industry and difficult-to-decarbonize sectors. Hydrogen is an energy carrier with remarkably high energy content and is the primary constituent element in a range of emissions-free, synthetic, drop-in fuels. Projected energy use in hard-to-decarbonize sectors is forecast to amount to 350 exajoules by 2050 (Figure 2).
- This report shows how existing industrial capabilities in the oil and gas sectors, combined with a new generation of advanced modular reactors (referred to as *advanced heat sources*), can be re-deployed to fully and cost-competitively decarbonize aviation, shipping, cement, and other industries by mid-century.
- To achieve this, hydrogen-enabled fuels need to be produced, without emissions, at a price that is competitive with the fossil fuels they are replacing. This report shows how advanced heat sources manufactured in high productivity environments, could deliver hydrogen on a large scale for $1.10/kg, with further cost reductions at scale reaching $0.90/kg by 2030.
- These advanced heat sources can be built rapidly and at the required scale using a “Gigafactory” approach to modular construction and manufacturing (Figure 4), or in existing world-class shipyards (Figure 5).
- To replace 100 million barrels of oil per day equivalent requires an investment of $17 trillion, spent over 30 years from 2020 to 2050. This is lower than the $25 trillion investment otherwise required to maintain such fossil fuels flows in future decades, and contrasts with a $70 trillion investment for a similarly sized renewables-to-fuels strategy (Figure 3).

Figure 2. **Energy use in the ‘difficult-to-decarbonize’ sectors**



** 2040-2050 is a linear extrapolation of 2020-2040 growth rates from IEA World Energy Outlook 2018*

Figure 3. **Comparative investment for fuel substitution by 2050**



HYDROGEN-ENABLED FUELS: THE MISSING LINK

While a large portion of the decarbonization challenge can be carried out using electrification (with the electricity generated from zero-carbon sources such as solar, wind, nuclear, and hydro), there are some energy end-uses that electrification is unlikely to serve well in the foreseeable future. Hydrogen-enabled liquid fuels offer a complementary route to address difficult-to-decarbonize sectors within timescales required to avoid catastrophic climate disruption. By adding these scalable clean fuels to existing carbon reduction strategies, we can lower the risk of failing to decarbonize in time.

Hydrogen-enabled synthetic fuels, such as ammonia, can solve density, storage and transport issues associated with hydrogen as an end-use fuel. Ammonia is liquid at close to atmospheric pressure and stores nearly twice as much hydrogen per cubic meter as liquid hydrogen. It can also be used as a clean substitute fuel in diesel generators and engines, including ships and gas turbines with minimal investment in new end-use, storage or transport infrastructure.

Cost-competitive production of drop-in substitute fuels such as ammonia transforms global prospects for a rapid clean energy transition by dramatically reducing the need for additional investment, planning and delivery of new associated infrastructure.

The path to low-cost, clean hydrogen

Less than 1% of the hydrogen used today is ‘clean’—the rest is considered ‘grey’, because it is produced using unabated fossil fuels.[3] The IEA estimates that global hydrogen production currently releases 830 million tonnes of CO_2 per year[4] which makes hydrogen production alone a significant contributor to global warming.

To displace global oil and gas within 30 years, emissions-free hydrogen-based fuels must offer equivalent energy performance at a comparable, or lower, price than oil and gas today.[5] These drop-in substitutes have to be relatively cheap to make it easy for end users to switch. Figure 6 shows the hydrogen production price needed to make a synthetic fuel that is cost competitive with the range of normal oil prices. The diagonal lines are the approximate cost of ammonia and synthetic hydrocarbons with two different cost assumptions for the input CO_2. To produce these synfuels at competitive costs requires hydrogen costs below $1.50/kg. The cost of renewable hydrogen today, if produced at scale by dedicated projects, and which is well over $3/kg, is not even on this chart.

Figure 4. **Refinery-scale hydrogen Gigafactory**

Figure 5. **Shipyard manufactured hydrogen production facility**

HYDROGEN COST DRIVERS

According to Bloomberg New Energy Finance (BNEF),[6] renewable electricity derived hydrogen will be too expensive for cost-competitive synthetic fuels until as late as mid-century; preventing this option from playing a significant role. High-volume manufactured, high-temperature, advanced heat sources have the potential to produce at the lowest delivered cost to all major markets within the 2030-2050 critical window required to contribute to deep decarbonization (Figure 8).

To achieve the lowest cost renewable-hydrogen, it is possible to co-locate wind and solar projects, in the best combined wind and solar resources, to deliver high capacity factors and hydrogen at around $2/kg within the 2030 timeframe. However, most of these locations are remote from populations and markets. Adding transportation costs from remote locations, for example, Australia to Japan, increases costs from $2/kg to $3.3/kg. This raises the cost beyond the threshold of economic competitiveness ($0.90/kg), which this report describes as essential to achieving large-scale substitution of fossil fuels.

Capacity factor is the biggest driver of hydrogen production cost (Figure 7). With other factors held constant, a move from 90% capacity factor to 20% capacity factor can almost triple the cost of hydrogen. Moving from 90% capacity factor to 40% capacity factor doubles the cost.

New advanced heat sources combine location-independent high capacity factors with power density to reliably produce large amounts of electricity and high-temperature steam. These attributes are uniquely suited to support the production of low-cost hydrogen at global scale.

However, to enable low-cost, large-scale geographically-independent hydrogen production, the delivery model for advanced heat sources must be radically transformed in order to dramatically lower capital expenditures and operating costs. Furthermore, the reduction of financial risk associated with delivery of projects requires building projects faster, at lower cost, with simpler and more streamlined operations.[7] Under these conditions, advanced heat sources can make hydrogen-based carbon-neutral fuels at low enough cost and large enough scale to offer a realistic near-term alternative to fossil hydrocarbons (Figure 8).

Figure 6. **Oil price 'guardrails' of the hydrogen economy**

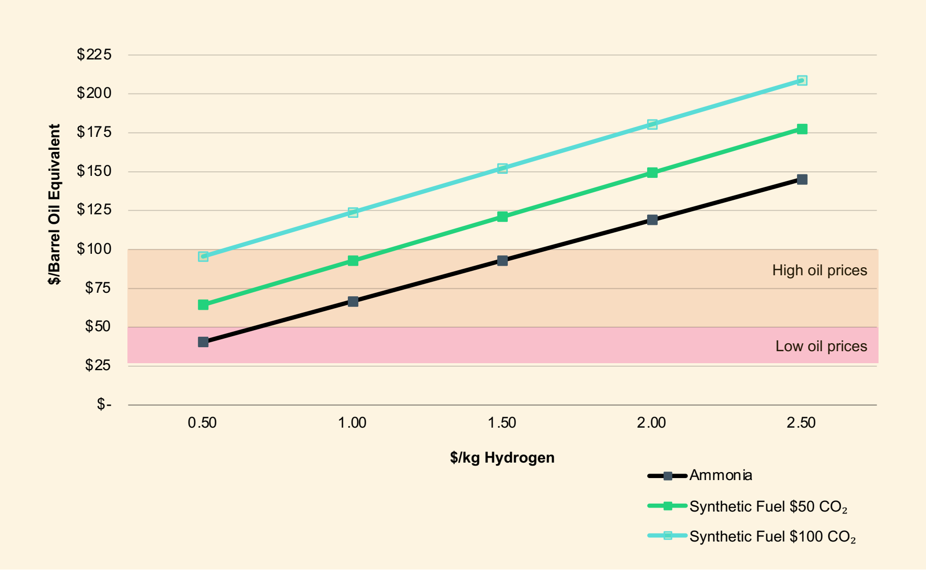
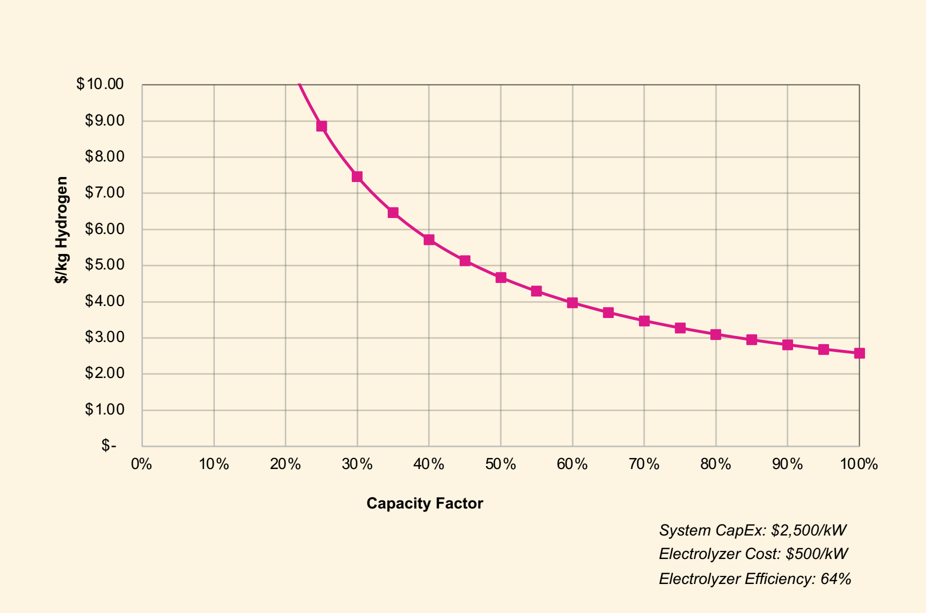


Figure 7. **Relationship between capacity factor and cost of hydrogen**



System CapEx: $2,500/kW
Electrolyzer Cost: $500/kW
Electrolyzer Efficiency: 64%

RE-DEPLOYING OIL AND GAS CAPABILITY FOR CLEAN HYDROGEN/SYNFUELS PRODUCTION

The oil and gas industry is already at scale, and already supplies cost competitive energy. It now has the capital, supply chains, and business models to integrate the technologies, develop the projects, produce the products, and distribute them to customers.

To achieve the lowest potential cost of hydrogen necessary for market penetration by 2030, such existing capability must combine with the world-class manufacturing prowess used in shipyard and factory settings. In addition to meeting demanding cost targets, these shipyard and refinery-scale manufacturing facilities can rapidly deliver sufficient hydrogen and synthetic fuels production at the scale and pace needed to fully decarbonize oil and gas markets by 2050 (Figure 12).

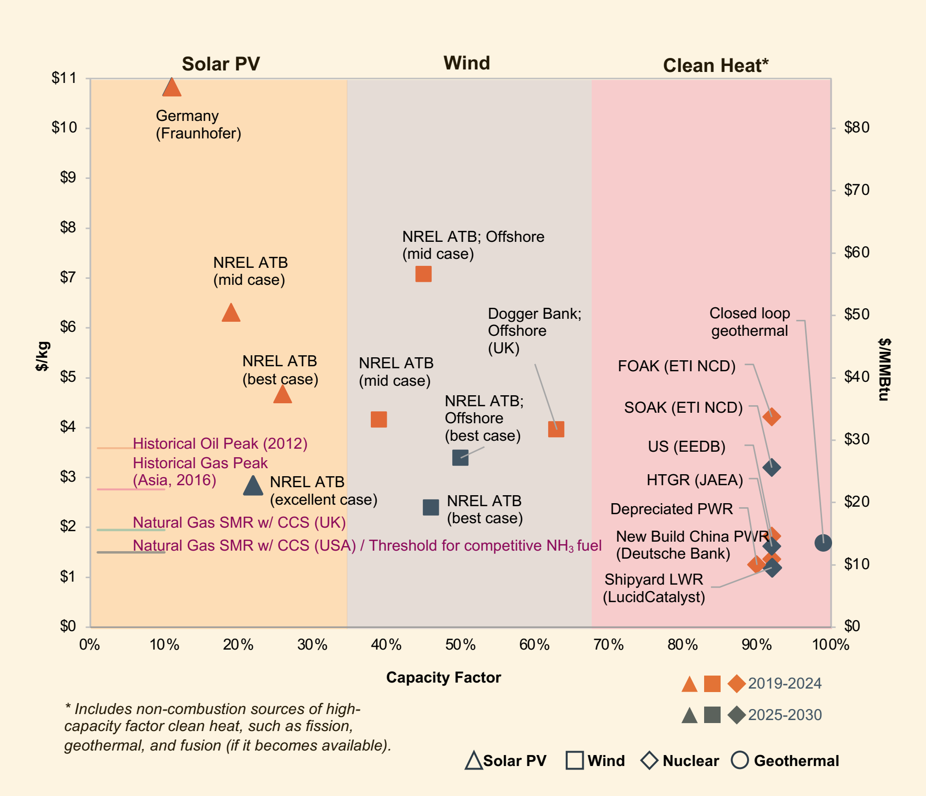
Next, we describe two delivery and deployment models to achieve the target costs and scale of production needed: (1) the Gigafactory, and (2) the shipyard manufactured production platform.

Hydrogen Gigafactory

A hydrogen Gigafactory (Figure 4) is a refinery-scale hydrogen production facility. It includes a highly productive factory-based system for the fabrication, installation, and automated operations of the hydrogen and synthetic fuels production infrastructure.

- Simplified heat source designs and factory setting minimize installation labor costs and enable the application of fast, high-quality manufacturing techniques.
- Streamlined licensing is enabled by reusable designs and repeatable processes in a standardized factory, managed by fixed teams, operating continuously.
- Low-cost hydrogen (less than $1/kg) can be fed directly into existing gas pipeline infrastructure or used for other applications, such as synthetic fuels production.
- Hydrogen Gigafactories can be sited on former coastal refinery and industrial sites. For example, just 12 Gigafactories placed on former refinery sites could supply current UK oil and gas demand (see Figure 14 for map illustrating land use requirements).

Figure 8. **Cost of hydrogen production from different energy technologies in the real world now and in 2030**



** Includes non-combustion sources of high-capacity factor clean heat, such as fission, geothermal, and fusion (if it becomes available).*

Sources: Unless otherwise indicated, capital and operating costs and capacity factors for solar and wind were sourced from the National Renewable Energy Laboratory's Annual Technology Baseline (NREL ATB). Nuclear costs and capacity factors were sourced from "The ETI Nuclear Cost Drivers Project: Full Technical Report," (by LucidCatalyst) September 2020, as well as the NREL ATB. Sources for the range in electrolyzer costs included publications from McKinsey, Bloomberg New Energy Finance, the IEA, NREL, and Idaho National Laboratory.

Shipyard-manufactured fuel production platform

Floating offshore fuel production platforms are ubiquitous in the oil and gas sector. These platforms are fabricated by world-class shipyards that produce high-quality, cost-competitive platforms on schedule, and in high volumes. Leveraging existing world-class shipyard manufacturing infrastructure for offshore hydrogen and synthetic fuels production could enable costs that are low enough to scale emissions-free synthetic, drop-in fuels globally within the necessary timeframe.

Is this scale and rate of deployment achievable in the real world? Compelling evidence suggests that it is. The industry delivering this transition would need to deploy 14,000 platforms in the 30 years between now and 2050 (Figure 11). This equates to annual additions of more than the current global nuclear fleet capacity—approximately 560 production platforms each year from 2025 to 2050. The world's shipyards produce between 1,500 and 3,500 ships per year and are currently operating at only about 50% capacity. Furthermore, many of the products currently being made in these shipyards are production platforms for the oil and gas industry, such as the Petronas FPLNG Dua (which is significantly more complex than the production platforms proposed in this report). It is also likely that in addition to utilizing excess capacity, the shipyard manufacturing capacity now dedicated to oil and gas infrastructure would be reallocated for synthetic fuels production platforms.

In the last five years there has been a substantial consolidation of shipyard capacity, with a number of smaller and less efficient shipyards closing down. As of 2019, there were 281 active shipyards in the world. As shown in Figure 12, the full substitution of the oil and gas industry by clean synthetic fuels can be accomplished from the dedicated production of 64 large shipyards (Figure 10). **This supply of clean fuel and hydrogen would completely eliminate the CO_2 emissions from the global oil and gas industry for a lower investment otherwise required to maintain the equivalent flow of oil and gas** (Figure 3).

Dramatic cost reduction can be achieved through design standardization and manufacture in a highly controlled, highly productive environment. World-class shipyards are the most productive manufacturing environments in the world. They routinely develop, maintain, and follow strict quality control and quality assurance programs (not unlike the nuclear and aerospace industries). Best-in-class shipyards have made substantial investments in technology, automation, and supply chain tracking that lowers costs and enables high-quality repeat builds.

Production platforms can be sited near a suitable diversity of markets, including developing countries, and produce a variety of products including abundant low cost electricity, hydrogen, ammonia, synthetic hydrocarbons and fresh water. Figure 9 shows an ammonia production platform offloading refrigerated liquid ammonia to a smaller transport bunker for delivery to ships and other users.

Figure 9. **Shipyard manufactured offshore ammonia production platform**

Multi-product platform sited offshore

Offshore siting of multi-product platforms offers a number of advantages:

- Platforms can be designed to meet market demand for emissions-free electricity, ammonia, synthetic aviation fuel, and desalinated water. These products can be produced in combination in the desired quantities.
- Multiple products (power, fuels, and fresh water) can be supplied to large coastal cities without requiring major additional investments in terrestrial infrastructure projects.
- Multi-product platforms can variably serve electrical power production or hydrogen-fuels production, making them complementary with solar power.
- Offshore siting eliminates land use challenges and siting issues associated with proximity to population centers.
- Safety concerns are greatly alleviated as the reactors are surrounded by coolant (i.e., ocean water).
- With approximately 6,000 offshore oil and gas platforms[8] and 440 reactors[9] operating globally today, the necessary legal, regulatory, and financial infrastructure already exists, including well-established precedents for regulating reactors at sea. Production platforms would be fueled in-situ and would not be moved around whilst operating, simplifying regulatory issues.

Even without globally or regionally harmonized regulation and licensing regimes, these production platforms could deliver clean energy products at massive scale that could then be used in multiple countries. Only a small number of countries would need to be ready to build and license production platforms of this kind, but the supply of clean abundant fuels could be utilized anywhere in the world.

COST REDUCTION FROM SHIPYARD MANUFACTURING

Recent experience in the United States and Europe implies that nuclear energy is too expensive and slow to be relied upon to make a meaningful contribution to tackling climate change. However, extensive research into the drivers of nuclear construction cost demonstrates there is a credible—and well-proven—path for nuclear energy to become competitive alongside renewables.[10] Global experience and numerous studies provide evidence that commitment to proven best practices around design standardization, combined with timely and effective programmatic sequencing, can deliver highly competitive nuclear new build. In addition, new delivery and deployment models (as outlined above), combined with sustained access to finance, can accelerate even more rapid and cost-effective deployment of advanced technologies, ultimately moving towards ultra-low cost mass production.

Figure 13 shows this evolution in cost reduction from first-of-a-kind and first-in-a-generation (FOAK); to the costs associated with series builds (US/Japan BE); to the cost savings from manufacturing in shipyards (LWR Shipyard); to the costs associated with advanced heat source technology manufactured in shipyards (Advanced Shipyard); and finally with mass production (Mass Production).

By moving to the low-cost, high-productivity shipyard manufacturing environment, it is possible to eliminate whole categories of costs (e.g., everything related to concrete). These estimates are based on detailed assessments of plants designed for shipyard manufacturing. The costs of these shipyard manufacturing processes are well-understood, enabling cost projections with high confidence.

Figure 10. **Shipyard starts and cumulative operating shipyards**

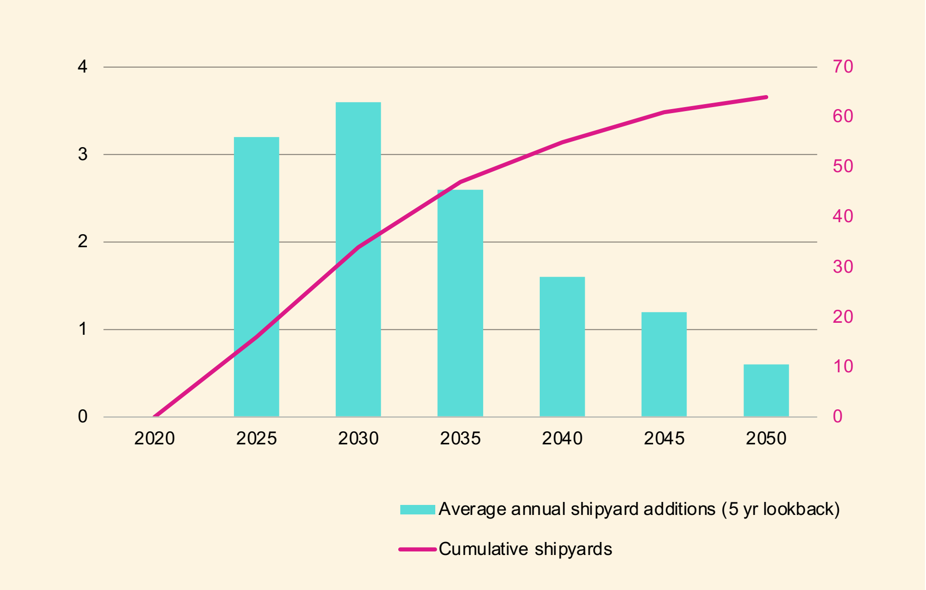
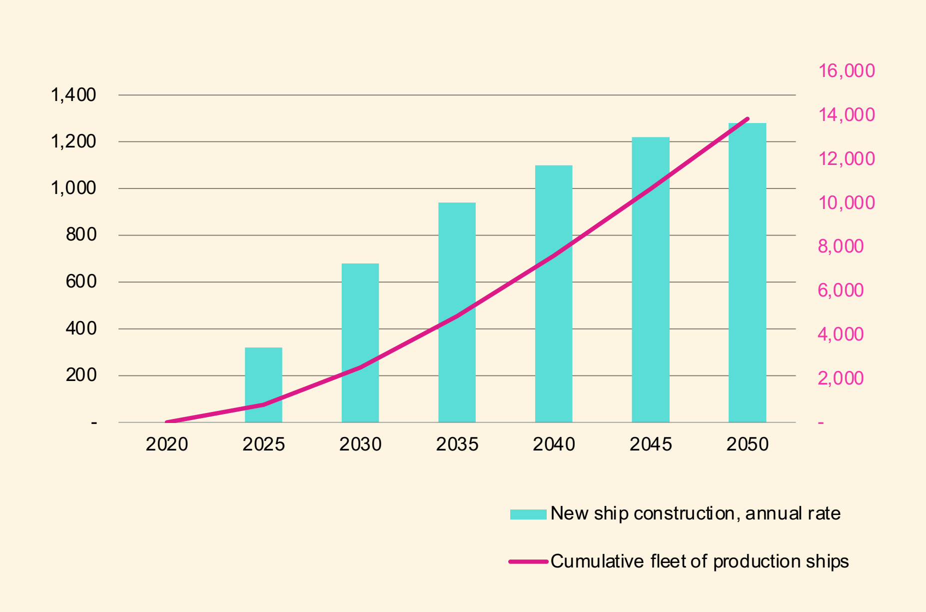


Figure 11. **Additions and cumulative production facilities**



SCALE: A REALITY CHECK

Different generating technologies have radically different energy production per unit area. This is a function of power density and capacity factor, as shown in the table below. Therefore, the geographic area required to produce hydrogen from wind and solar is far larger than from advanced heat sources. The power density differential matters. While solar PV has a power density of 50 MW per km^2, offshore wind can deliver only 2 MW per km^2. This calculation includes the space between the turbines, to be more realistic. In contrast, advanced heat sources have a power density of 2,080 MW per km^2: about 500-times greater than solar PV and 1,200-times greater than offshore wind. Table 1 shows the calculations to determine the area required for two illustrative high-income, land-limited countries which have dense populations and high per capita energy use—the UK and Japan (Figure 14).

The enormous scale required for low-power-density renewables to substantially replace energy-dense fossil fuels will result in qualitatively different landscape impacts, local opposition, and competition for land. These impacts are a significant source of risk to decarbonization pathways that rely on renewables to substitute for a significant percentage of energy production.

Table 1. **Calculations of energy production and hydrogen production for wind, solar, and advanced heat sources for the UK and Japan**

	Solar PV	Offshore Wind	Adv. Heat Sources
Power Density (MW/km^2)	50	2.3	2,080
Capacity Factor	12%	50%	90%
Specific Annual Energy Production (GWh/km^2/year)	52.6	9.1	16,399
Specific Annual Hydrogen Production (Tonnes/km^2/year)	968	167	466,979

Calculation Sources: PV calculated from the list of the largest photovoltaic power stations, Wikipedia; Andrew ZP Smith, ORCID: 0000-0003-3289-2237; "UK offshore wind capacity factors" (note that the power weighted average capacity factor for UK offshore wind is 40% but newer projects are expected to have higher capacity factors, therefore, we used 50%); Advanced Heat Source is the average of Hinkley Units A, B, C (2,427 MWe/km^2) and Hanbit Nuclear Power Station in South Korea (1,733 MWe/km^2). Note that offshore production platforms and the onshore Gigafactory would both have higher power density.

Figure 12. **Fuel substitution in difficult-to-decarbonize sectors from ultra-cheap hydrogen generated by advanced heat sources from 2020-2050**

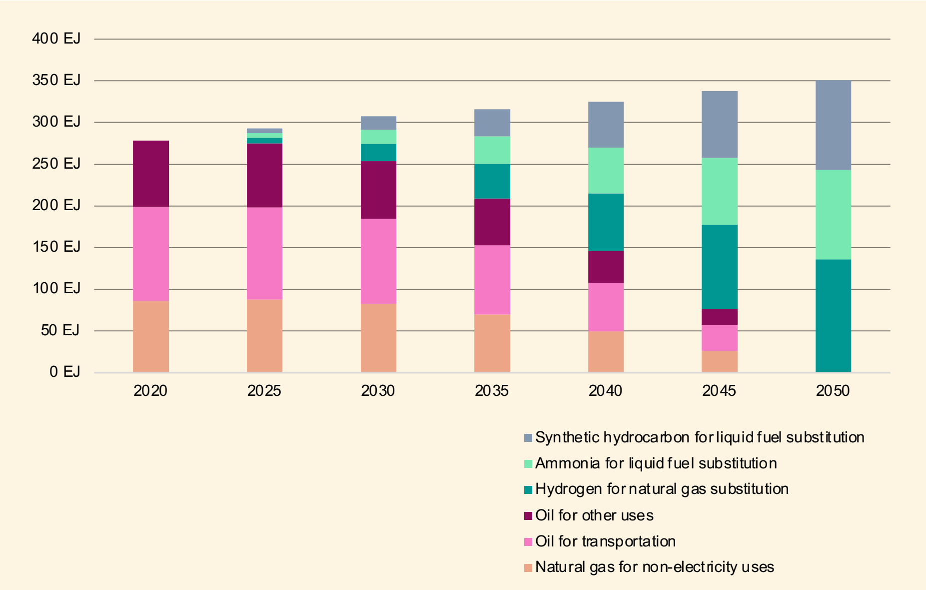


Figure 13. **Evolution of cost reduction from first-of-a-kind construction to mass manufactured products**

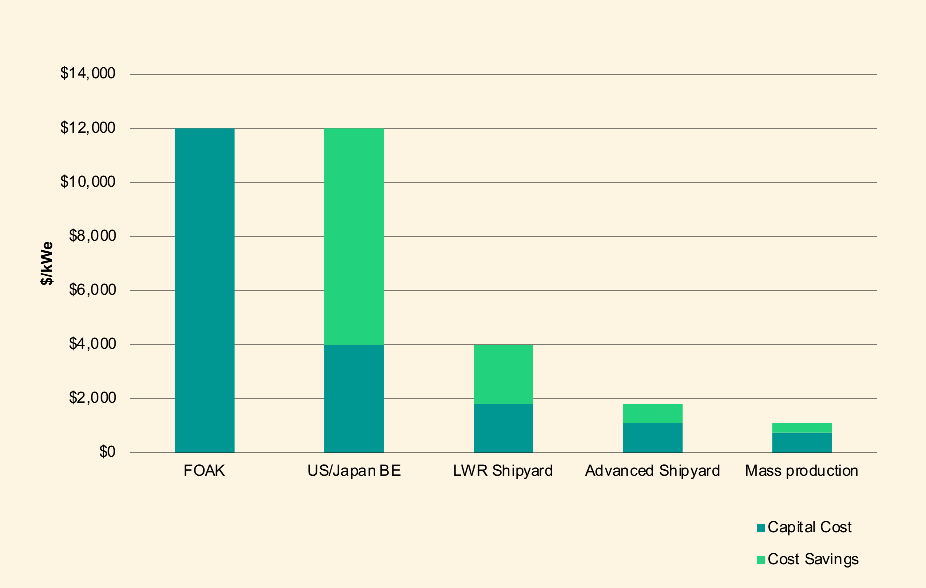
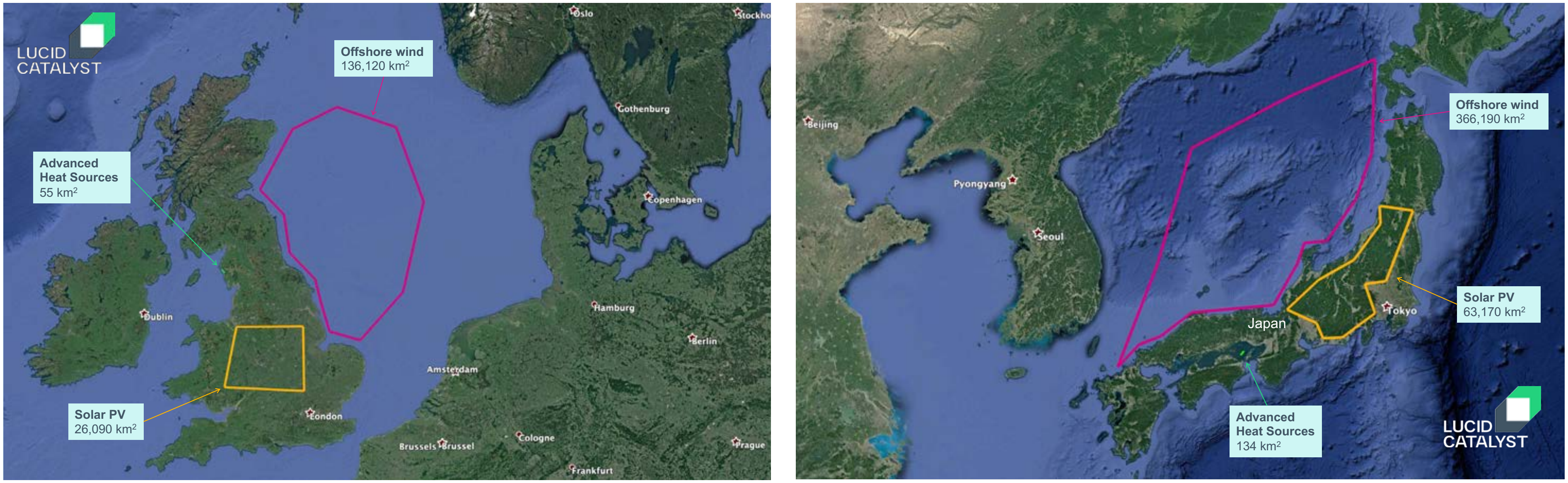


Figure 14. **Area that would be required to supply UK's (left) and Japan's (right) current oil consumption with hydrogen from wind, solar, or advanced heat sources**



Hydrogen production geographic area requirements case studies

Figure 14, showing two maps, represents in colored outlines the total area that would be required for each resource if used to generate enough hydrogen to supply current oil consumption in the UK and Japan, respectively.

The UK is a high-income country with high energy use per capita and high population density. The area required to supply the UK's current oil consumption with hydrogen from solar would be 26,090 km². To produce the same amount of hydrogen instead with offshore wind would require an area of 136,120 km²—which would take up most of the North Sea. The pink outline shows the size of a single continuous wind farm to produce this much hydrogen. If the UK were to produce the same amount of hydrogen for liquid fuels substitution using Gigafactories or production platforms with advanced heat sources, the land area required is dramatically smaller—only 55 km²—illustrated by the barely visible green shape.

Japan is a particularly striking example as its mountainous and densely-populated territory has very little land available for the large solar farms that would be required for solar-generated hydrogen, and onshore wind faces similar geographical constraints. As Figure 14 shows, the solar task is simply not viable—the area required for solar-generated hydrogen to supply Japan's current consumption of oil-based liquid fuels would be 63,170 km².

Japan's offshore wind resources are limited by the extent of the shallow continental shelf. Even floating offshore wind turbines must be anchored to the seabed, so water thousands of meters deep will never be suitable.

We do not map a projection for global comparisons, because in practice the hydrogen production locations would be in multiple locations. We have to assume that if countries are planning massive investments in clean energy that they will want—as far as possible—to control those investments.

However, the numbers are striking. For example, if solar PV were to replace all global oil using hydrogen, 770,900 km²—an area similar to the size of Turkey—would have to be covered with solar panels.

If offshore wind were to replace global oil with hydrogen, an even larger area of 8,380,000 km² would be required—about the size of Brazil (8,460,000 km²).

If the production platforms described in this report, powered by advanced heat sources, were to do the same job—only 3,414 km² would be needed, equal to a square of 58 kilometers per side.

CONCLUSION

Given the scale and urgency of the required clean transition combined with the growth of the global energy system, all zero-carbon hydrogen production options should be pursued. The potential of advanced heat sources to power the production of large-scale, very low-cost hydrogen and hydrogen-based fuels could transform global prospects for near-term decarbonization and prosperity. This report sets out a pathway to decarbonize a substantial portion of the global energy system, for which there is currently no viable alternative.

While it sounds daunting to achieve the scale of production needed, the scalability and power density of advanced heat sources are a major benefit. By moving to a manufacturing model with modular designs, it is possible to deliver hundreds of units in multiple markets around the world each year.

The clean energy from these units, **combined with aggressive renewables deployment**, gives us a much better chance of achieving the Paris goals of limiting warming to 1.5°C **in the very limited time** available.

Maximizing the opportunity requires action without delay

Act now. This study shows how scalable, cost-effective hydrogen can be produced in the near term. For too long, risks associated with advanced heat sources have been considered outside of the context of risks with other technologies. In addition, all clean energy investments should be reviewed with due consideration of the risks of failing to decarbonize. This report is a call to action for leaders to put risks into context and make informed, evidence-based, and outcomes-focused decisions having properly evaluated the alternatives. To facilitate such informed decision-making, Government and industry should immediately issue requests for information and seek quotes for shipyard manufactured plants and begin commissioning refinery-scale clean fuels production now.

Shipyards are masters of cost, scale, and engineering integration. We must vigorously invite their capable participation. Their tightly-integrated design and manufacturing processes—combined with onsite steel mills and long-term supply chain relationships—offer exactly the needed heavy manufacturing components and equipment. They offer consistently accurate costing and scheduling. Their advanced manufacturing facilities are certified to meet world-class standards. They regularly deliver complex, highly regulated products.

Policy making. Domestic and global zero-CO_2 hydrogen market development along with existing and emerging global and domestic zero-carbon hydrogen policy initiatives should be technology inclusive. They should be focused on key outcomes related to cost and scale of production, creation of zero-carbon hydrogen markets, and increased market share for zero-carbon fuels.

Access to finance. In the same way that investors must take a portfolio approach to investments in order to reduce exposure to risk, global efforts to limit climate change should be spread across a portfolio of technology options. Consistent, technology-inclusive access to finance is critical to realizing this.

Industry mobilization. Government and industry need to proactively collaborate to demonstrate determination and capability towards affordable decarbonization and prosperity. This should include demonstration of hydrogen projects at conventional plants, as well as active participation in national and international efforts to accelerate cost-effective commercialization of innovative technologies, delivery and deployment models.

Add to climate and energy modeling. Surprisingly, advanced heat source technology is not included by significant energy modeling programs active across the globe today. We recommend that policy makers consider adding this demonstrated technology option into modeling where it is currently missing.

ENDNOTES

1. BP Statistical Review of World Energy 2019; DNV GL Energy Transition Outlook 2019; IEA. “World Energy Outlook 2019,” November 2019; IEA (2019), “World Energy Model,” IEA, Paris, 2019.
2. Sustainable Energy for All 2019
3. Anouti, Yahya, Raed Kombargi, Shihab Elborai, and Ramzi Hage. “The Dawn of Green Hydrogen.” Abu Dhabi, 2020.
4. IEA. “The Future of Hydrogen: Seizing today’s opportunities,” (IEA 2019).
5. Kirsty Gogan and Eric Ingersoll, “We Need More of Our Climate Solutions to Be Impossible™ Burgers,” Business Green, December 2, 2019.
6. Bloomberg New Energy Finance (2020). Hydrogen Economy Outlook. Key Messages. March 30, 2020.
7. OECD-NEA. “Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders,” 2020.
8. Bull, Ann Scarborough, and Milton S. Love. “Worldwide Oil and Gas Platform Decommissioning: A Review of Practices and Reefing Options.” Ocean and Coastal Management. Elsevier Ltd, February 1, 2019.
9. Tiseo, Ian. “Number of Operable Nuclear Power Plants by Country 2020.” Statista, September 2, 2020.
10. Energy Technologies Institute “Nuclear Cost Drivers Study,” LucidCatalyst, 2018.

This profile summarizes our substantially longer, more detailed, thought leadership study, “Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals,” September 2020, available at terrapraxis.org.

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