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Lucid Insights Report >

Hydrogen Modelling 2.0: De-Risking, De-Scoping, and Lowering the Cost of Achieving Net Zero

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Summary

The Aurora Energy Research (AER) hydrogen study[1] concluded that combining nuclear energy and renewables in the UK energy system can eliminate dependence on fossil fuels, lower emissions, and lower the total cost of achieving UK Net Zero.

This AER model is one of the first energy systems modelling efforts to fully represent the potential for nuclear energy (also known as 'advanced heat sources') to supply clean, flexible generation of power, co-generation of heat, hydrogen and power, and dedicated hydrogen production using high-temperature steam electrolysis, cost-competitively and without emissions. The findings show the transformative potential for these applications to de-risk, de-scope, and lower the cost of achieving Net Zero.

These applications are transformative because they complement the mainstream strategy: deployment of renewables to decarbonise the electricity sector and electrification of energy end uses. This AER model demonstrates a path to full decarbonisation without the requirement for full electrification of end uses by 2050, nor unsustainable dependence on fossil fuels.

These applications of advanced heat sources are complementary to the mainstream decarbonisation strategy in three ways:

1. Flexible advanced heat source generators *complement* renewable electricity dispatch, enabling high renewables penetration without storage or natural gas fired generation.
2. Commodity hydrogen from electrolysis is usually discussed as a use of electricity that competes with electrification of end uses (i.e., 'electricity is better used directly in electrified end uses'). Here instead, power-dense advanced heat sources make hydrogen when the grid does not need electricity, and electricity when it does; making electricity and hydrogen production *complementary*.

3. In parallel, a commodity-only element based on dedicated, large-scale production of hydrogen and hydrogen-enabled synthetic fuels *complements* grid decarbonisation strategies by enabling decarbonisation of existing end uses that are currently impossible to electrify and parts of the system that are lagging in the electrification process.

Combined, these three elements of a complementary strategy substantially reduce major risks discussed below to enable a cost-effective, timely transition to a Net Zero economy.

What is special about Aurora's decarbonisation model?

Three simple yet radical assumptions were made that distinguish this Net Zero model from traditional approaches.

1. All emissions-free generating technologies are treated equally and compete on cost.
2. After 2030, capacity auctions are only available for zero carbon generators. The model assumes an auction model like the offshore wind model, except, in this case, technology neutral in which solar, nuclear, and wind are all able to bid. The capacity market rewards the potential to generate zero carbon power when the grid needs power. The provision of capacity payments and revenue payments is shown to be sufficient for nuclear plants to come online based on those revenues.
3. Nuclear costs and market applications, substantiated by the expert project team, are fully represented in the model. Programmatic cost reduction, as well as innovative delivery and deployment models, deliver low costs. A broad range of nuclear energy services are incorporated into the model, including flexible generation; cogeneration of power, heat, hydrogen, and synthetic fuel; and dedicated large-scale hydrogen production.

The Aurora scenarios suggest strong nuclear pathways reduce reliance on fossil fuels in the hydrogen economy, lower emissions, and lower system costs.

Key insights from the Aurora Hydrogen Study

- Deploying renewables and nuclear for power and hydrogen is required to ensure rapid decarbonisation and reduced reliance on fossil fuels. Cumulative emissions from 2021-2050 can be reduced by 80 $MtCO_2e$, and gas usage in power and H_2 by 8k TWhth in our core scenarios.
- Achieving H_2 volumes required for Net Zero without fossil fuels will be challenging without support for electrolytic H_2 from Renewable Energy Systems (RES) and nuclear. The high share of virtually baseload H_2 demand from transport and industry results in a high dependence on fossil-based blue H_2, comprising over 35% of demand in 2050 in all scenarios that exclude a "Gigafactory" for nuclear derived H_2. Clear support for electrolytic H_2 is required to reduce costs relative to fossil-based blue H_2.
- Including nuclear with co-located electrolysers alongside high RES is economically efficient, reducing total system spending by 6-9% (NPV from 2021-2050). Co-locating electrolysers with nuclear enables nuclear plants to provide additional flexibility to the power grid to match electricity production fluctuations in RES supply by diverting electricity output to or away from electrolysers for H_2 production.
- Novel business models for nuclear energy can provide cost competitive and scalable sources of zero carbon electricity and hydrogen. There are opportunities for existing and new nuclear co-located with H_2 electrolysers to produce cost-competitive electricity and H_2. In addition, a new generation of nuclear reactors (i.e., small modular reactors and Gen IV reactors) can potentially speed up decarbonisation and reduce use of fossil fuels. Utilising new high-temperature nuclear as a source of heat can further increase efficiency of hydrogen production.
- Careful market design and policy are required to get to Net Zero. Absent stabilising market protocols, systems with large volumes of RES and nuclear (but limited fossil fuels) result in many hours of very low power prices. This leads to an increased need for either support payments or new market designs. The continuation of direct support for RES and nuclear (i.e., via Contract-for-Difference (CfDs) or Regulated Asset Base (RABs)) and changes to the Capacity Market (CM) are powerful tools to ensure sufficient low carbon capacity is built. Nuclear can play a key role in decarbonising power and H_2 but clear and vocal policy intentions are critical. Not only for the energy markets themselves, but for the financial market and industry. Only when the Net Zero way forward is confidently clear and unsurprising, will our banking community be able to lower financing costs, and our industrial community be able to perform as we know they can.
- Broader potential benefits of technology mixes should be considered. Deploying RES alongside nuclear can facilitate low carbon systems and those with minimal reliance on fossil fuels are found to have the lowest costs. However, the ability of technologies to drive deeper decarbonisation should be considered such as the potential for nuclear gigafactories for H_2 production to decarbonise hard to abate sectors like aviation and shipping via H_2 directly or H_2 derived synthetic fuels.

Aurora recommends 10 ‘least regret’ options to minimise risks to achieving Net Zero

1. **Continued revenue support for low carbon technologies.** To incentivise deployment of low-carbon capacity despite low wholesale market revenues as a result of high penetrations of low marginal cost supply. A level playing field for all technologies is required.
2. **Limit participation of unabated thermal in the CM.** To prevent locking in reliance on new unabated thermal assets (that will remain online for 25 years) by only procuring low carbon alternatives.
3. **Study the role of green H_2 from RES and nuclear to displace fossil fuels.** To apply H_2-only business models for RES and nuclear and create low-cost H_2 without fossil fuels.
4. **Conduct in depth siting and feasibility studies for nuclear and RES deployment.** To ensure target deployment can be met.
5. **Assess infrastructure requirements of decarbonisation pathways.** To assess need, cost, development time, and ecological impact for required infrastructure to be deployed in time for assets to online.
6. **Examine the role existing nuclear can play in green H_2 production.** To consider co-locating electrolysers with existing nuclear to unlock additional revenue whilst also providing power system flexibility.
7. **Explore support for a construction pipeline of small modular reactors.** To enable deployment, costs reductions, and assess feasibility of large-scale deployment.
8. **Explore support options for nuclear business models for power + H_2.** To compete with other low-carbon technologies.
9. **Further investigate the benefits of high-temperature nuclear (Gen IV).** To benefit from high-temperature reactors unlocking very high H_2 conversion efficiencies using waste heat.
10. **Development of clear business models for H_2 and CO_2 infrastructure.** To assess costs and incentivise investment.

Five major innovations for Modelling 2.0

The AER model has made a big step towards implementing five major innovations in energy systems modelling, demonstrating a transformative potential to de-scope, de-risk, and lower the cost of achieving Net Zero.

Following the insights and recommendations in the AER study, LucidCatalyst highlights five innovations, listed below, which could enable an evolution of mainstream energy systems modelling. This evolution—which we have dubbed Modelling 2.0—begins to incorporate both assessments of deployment risk and feasibility, as well as cost and performance metrics for innovative technologies across the whole energy system.

This Insights paper recommends that the AER modelling innovations be generalised to mainstream energy systems modelling. This would lead to a profound shift in the discourse about the feasibility, cost, and risk of achieving Net Zero.

- **Innovation 1. ‘Feasibility guardrails’ are required to de-risk the clean energy transition**

  Recommendation: All Modelling 2.0 Net Zero scenarios should be interrogated for feasibility to anticipate and mitigate risks to the transition. All proposed deployment assumptions should be subject to ‘feasibility guardrails’ related to cost, speed, scale, space, and supplies.

- **Innovation 2. Affordable nuclear is a choice**

  Recommendation: Modelling 2.0 should represent the achievable cost of nuclear supported by evidence from new build programmes from around the world and presume that deployment will be optimised for repeatable low-cost outcomes (see “Figure 1. Pathway to Low Cost” on page 4).

- **Innovation 3. The powerful role of ‘flexgen’—co-producing power, heat, and hydrogen—can address the ‘hard-to-abate’ parts of the energy system**

  Recommendation: Modelling 2.0 should represent the range of advanced heat source applications that can cost-effectively provide a range of services in support of full decarbonisation across the whole energy system.

- **Innovation 4. High-temperature electrolysis should not be overlooked**

  Recommendation: Modelling 2.0 should represent the transformative role of large, low-cost, high-capacity factor, high-temperature electrolysis utilising advanced heat sources, to eliminate risks to the transition related to the needed cost and scale of hydrogen supply.

- **Innovation 5. Dedicated hydrogen production delivers large-scale, low-cost supply**

  Recommendation: Modelling 2.0 should represent the transformative role of large-scale, low-cost 'Gigafactory'-scale hydrogen and synthetic fuels production utilising advanced heat sources manufactured at scale.

By expanding the typical range of assumptions and inputs with the five innovations above, the Aurora model points to a new direction for energy systems modelling—Modelling 2.0.

Modelling 2.0 offers policy makers, developers, investors, and climate hawks more confidence in designing strategies for a more feasible, achievable, and affordable path to achieving Net Zero.

Participating Organisations

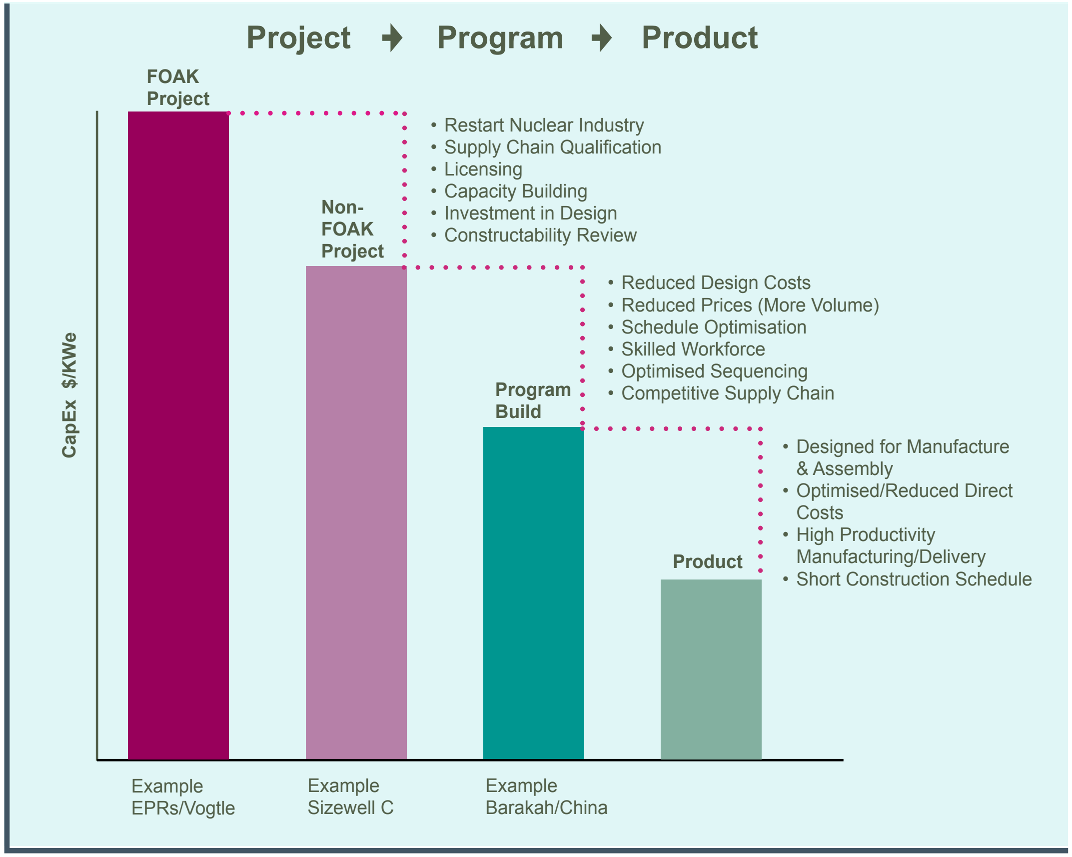
The Aurora Energy Research hydrogen study was authored by Aurora Energy Research, commissioned by Urenco, with inputs provided by LucidCatalyst, the International Atomic Energy Agency (IAEA), and EDF.

Authored by:

Commissioned by:

Additional inputs from:

Figure 1. **Pathway to Low Cost**



Five Innovations for Modelling 2.0

As discussed above, this Insights paper describes how the AER modelling innovations can be generalised to mainstream energy systems modelling. This next section describes in detail why and how the application of these innovations in mainstream energy systems modelling would lead to a profound shift in the discourse about the feasibility, cost, and risk of achieving Net Zero.

Modelling 2.0 Innovation 1: 'Feasibility guardrails' to de-risk the transition

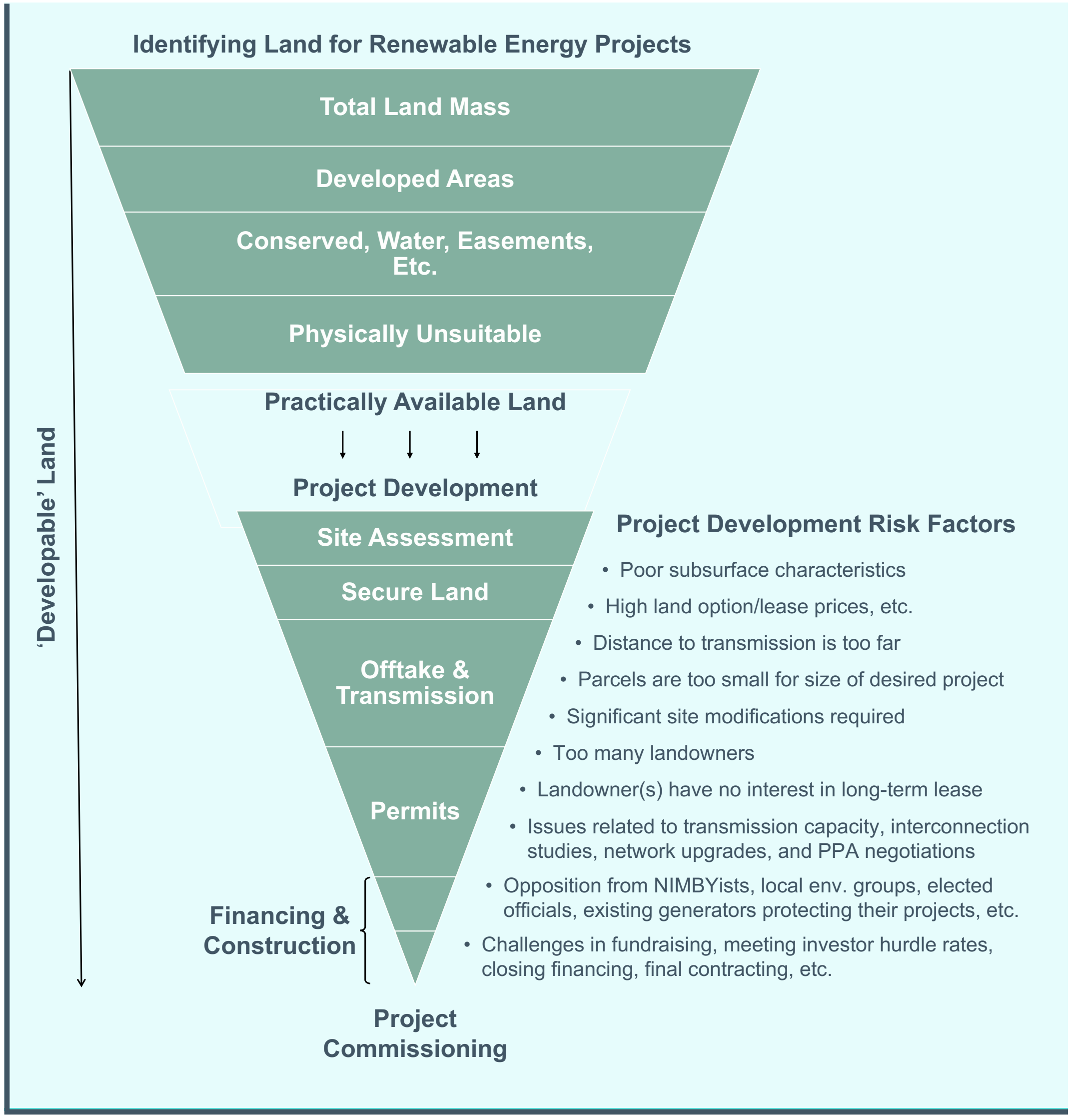
Recommendation 1: All Modelling 2.0 Net Zero scenarios should be interrogated for feasibility to anticipate and mitigate risks to the transition. All proposed deployment assumptions should be subject to 'feasibility guardrails' related to cost, speed, scale, space, and supplies.

The sequencing and time sensitivity of the Net Zero challenge, which will involve a massive, simultaneous infrastructure build-out in every country over the next 28 years (to 2050), presents an unprecedented logistical challenge. The challenge is not only to build enough clean electricity generation infrastructure, but to build the infrastructure needed to electrify or fully decarbonise other sectors such as heat, industry, and transport.

Currently, 75% of primary energy use is outside the power sector. The amount of generation capacity required to develop emissions-free substitute fuels and to decarbonise other carbon-intensive sectors of the economy will require a staggering amount of emissions-free energy.

The scale of investment required, necessary deployment rates, public acceptance, willingness to bear the incremental costs, and available land for development will be major hurdles to the energy transition. In many locations, deployment rates for renewables are far below what is necessary to achieve 2050 decarbonisation targets. Advocates for renewables-led strategies point to this shortfall and say we need to redouble our efforts. But it would be prudent to consider that these current sluggish levels of deployment may be evidence of how difficult large-scale renewables deployment is becoming, even though we are just at the beginning of the build-up needed for the energy transition. If it is difficult now, at the beginning, it is only going to get more difficult due to the best sites being taken, lack of transmission, escalation of development risks and cost, and growing public opposition.

Figure 2. **Project Development Pipeline**



A view of project risk shown in Figure 3, illustrates the hurdles that all projects must successfully navigate. Note also the "S-curve" illustration depicting the notion of project deployment challenges increasing as more and more sites and projects deploy. Although the trajectory may look like a hockey stick curve at the beginning, it is likely to flatten out into an S-curve as various pressures on project development increase over time, and risks to project development compound.

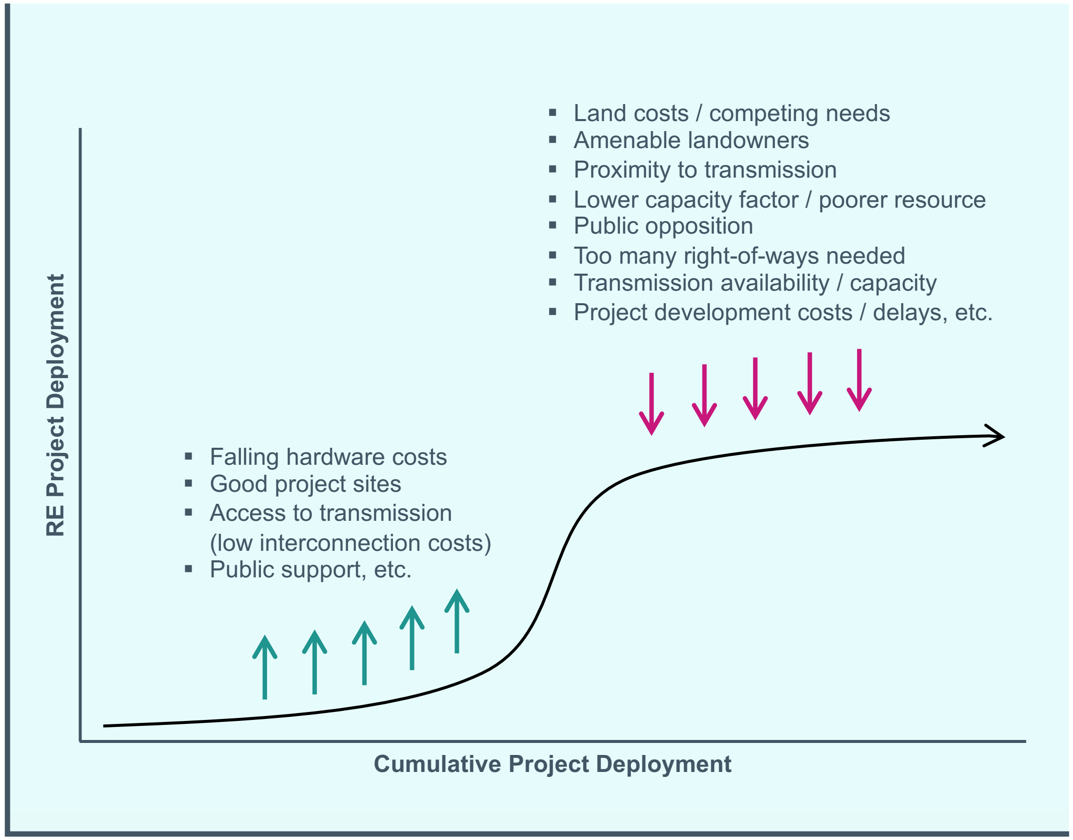
Many potential projects do not make it all the way through the project development process, which means that to commission a gigawatt of solar, several gigawatts must make it to late-stage development status. This will necessarily require more developers overall, more development capital, and more human resources dedicated to other parts of the development process (e.g., permitting, interconnection studies, engineers, financiers, etc.) (see Figure 2).

The magnitude of the Net Zero project development challenges highlights the need for energy models to expand beyond simple cost optimisation. Diverse technology inclusive transition plans can reduce Net Zero programme risk by deploying a portfolio of solutions that are not all exposed to the same risks. Even if consumption is reduced as the energy transition progresses, we have less than 30 years to reduce carbon emissions to Net Zero. Assuming that fossil fuels would be fully replaced by renewables it would mean we need about 10-times as much renewable energy in the next 28 years as has been built in the last 20 years. This big picture shows that we will need all available CO_2-free alternatives to achieve Net Zero—renewables and advanced heat sources.

Energy models, upon which all energy transition targets are based, highlight the types of generation capacity that we need to deploy by mid-century. These models offer critical guidance about the scale of the energy infrastructure needed. However, nearly all energy models are optimised on generation cost alone. This means that if a renewables strategy alone is just a few dollars per MWh cheaper, the models recommend decarbonisation with mostly renewables. They do not consider other factors, particularly those related to deployment feasibility (reflecting various socio-political, cultural, commercial, and financial factors). This creates a widening gap between energy models and the real world of project development.

The danger is that policymakers may expect that all energy models realistically characterise deployment feasibility. Consequently, unrealistic policy targets will not successfully weather real world implementation challenges.

Figure 3. **The Project Development S-Curve**



Beyond cost, energy systems Modelling 2.0 should evaluate the feasibility of deploying new infrastructure, including assessments of space requirements and site availability; associated infrastructure requirements, such as transmission or pipelines, and those associated system costs; the achievable rate of deployment, including the number of projects needed in the pipeline to deliver the required build outcome; and supply chain requirements in terms of materials, finance, and human resources.

Modelling 2.0 Innovation 2: Affordable nuclear is a choice

Recommendation 2: Modelling 2.0 should represent the achievable cost of nuclear supported by evidence from new build programmes from around the world, and presume that deployment will be optimised for repeatable, low-cost outcomes.

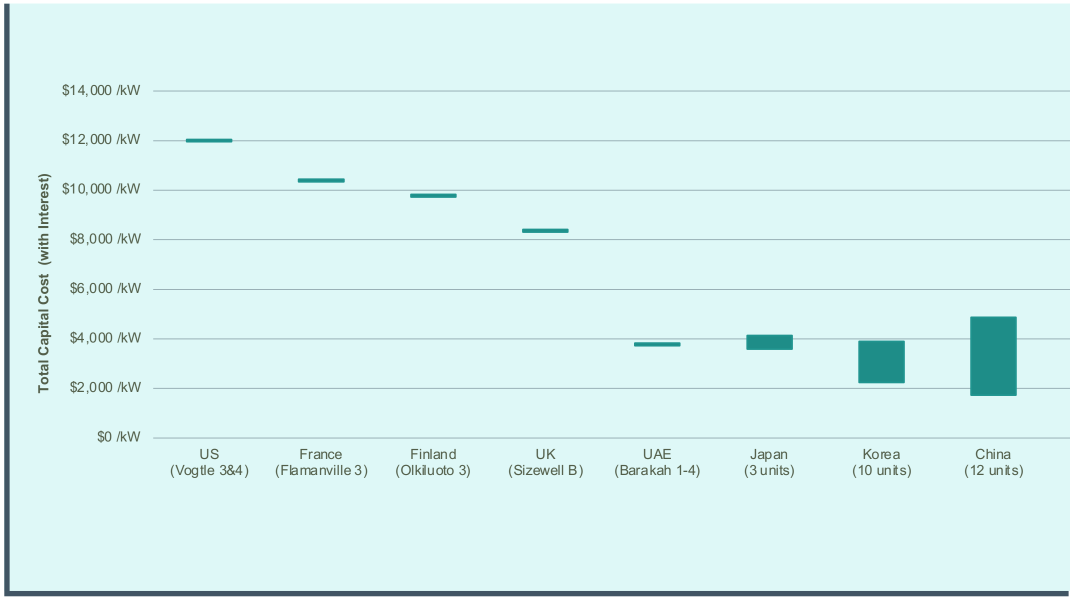
To make a meaningful contribution towards clean, reliable, and economical future energy systems, nuclear power plants must be cost- and risk-competitive with other low-carbon technologies, within near-term timeframes. Most nuclear being built globally today is low-cost (the majority being delivered for less than $4,000/kW).[2] Recent new builds in the US and Western Europe are expensive outliers (Figure 4). Firstly, they are expensive in absolute and relative terms: the cost per MW installed, along with the size of the plant, makes them among the most expensive power plants of any type. Secondly, all these projects in the West have been delivered over-budget and late, making nuclear new build a risky investment, which in turn increases the cost of borrowing money for new projects. However, the experience with programme builds in Asia has been very different. Many new build projects there are highly cost-competitive with both fossil fuels and renewables.

The reason for the high-cost outcomes in Europe and the United States is that these First-of-a-Kind plants represent a major investment in licensing and building a plant for the first time, and establishing first-in-a-generation skills and capability in human capital. Significant productivity improvements and cost effectiveness can be gained in subsequent projects with respect to the project governance, workforce, supply chain, regulators, and the project delivery chain, in general illustrating the effect that experienced leadership, design standardisation, and mature capability can have in reducing cost, delays, and risks.

For example, South Korea has executed a fleet build approach combined with good project management, construction execution, and technology innovation, which has delivered new nuclear power plants domestically and even in newcomer countries like the UAE at significantly lower costs than those recently experienced in Europe and the United States.[3]

The conclusion is that low-cost nuclear is a choice, just like low-cost renewables—albeit both require long-term investment and policy commitment. There are well-defined actions and best practices that can deliver low-cost, competitive outcomes for nuclear

Figure 4. **Total Capital Costs for Historical and Ongoing Nuclear Projects in Database**



technologies, including advanced heat sources, as have been applied successfully elsewhere, as well as in historic nuclear new build programmes in the United States and Europe, as well as to other low-carbon technologies, such as offshore wind in the UK.

A highly focused, deliberate program can drive down costs and improve efficiency of the construction process over time through consistent, rational implementation of best practices, regardless of location, assuming there is a strong commitment from the major stakeholders. A large body of literature on the cost of megaprojects, across a variety of sectors besides nuclear, validates these points.

In addition to the adoption of best project management and execution practices, new technologies may further reduce cost and risk even for GW-scale conventional light water reactors. For example, the 2018 MIT Future of Nuclear study recommends the use of seismic isolation to reduce the need for site specific design changes, and advanced construction materials, such as high-strength reinforcing steel and ultra-high performance concrete, to reduce the installation cost of concrete structures.

Even more radical cost reductions could come from new delivery models anchored in industries that already deliver large, low-cost, high-quality, highly-regulated and complex machines.[4] Shipyards, aircraft factories, and auto manufacturing plants are good examples.

Learning from these other industries demonstrates that steep, near-term cost reduction is achievable by shifting from traditional 'stick-built' construction projects to high productivity manufacturing environments such as a shipyard or factory. Moving from traditional construction to a highly integrated manufacturing, assembly, and installation process on one site could enable high quality, repeatable processes, with quality assurance designed into every step of the process. For example, thanks to the standardisation of design and suppliers, the aerospace industry has achieved extraordinary cost reduction and safety improvements over the decades, making flying cheap, safe, and convenient.

The UK nuclear sector needs to shift its mindset from "one-off white elephant projects"—each with a unique design and delivered by a unique and novel supply chain and inexperienced workforce. Plans and delivery should be based on a few standardised and replicated designs delivered by a consistent network of experienced suppliers.

Modelling 2.0 Innovation 3: 'Flexgen' power, heat, hydrogen

Recommendation 3: Modelling 2.0 should represent the range of nuclear applications that can cost-effectively provide a range of services in support of full decarbonisation across the whole energy system.

We must decarbonise every sector of the economy, not just the electricity sector. Cogeneration of power and heat enables a highly economical production of multiple energy services. The flexible cogeneration plant modelled in the AER study, capable of producing hydrogen, heat, and power, enables the attractive economics of dedicated hydrogen production with the provision of valuable grid services, improving the overall economic performance of the plant as well as lowering the cost of energy to the system.

The next generation of advanced reactors are being designed for this kind of flexible cogeneration ('flexgen'). A helpful feature of some advanced designs is the separation of the heat source (reactor) from the power island via a thermal energy storage system. This system allows the reactor to operate continuously at full capacity while the power island responsively dispatches to the grid based on daily demand and price variations.[5]

This kind of system can operate flexibly, much like hydro or fossil gas plants, cost-effectively supporting higher penetrations of variable renewable energy at lower overall costs and emissions.

In addition, flexible generators of hydrogen, heat, and electricity can replace the need for large-scale energy storage otherwise required when deploying variable renewables. By being able to switch from making hydrogen most of the time, to generating electricity to the grid during a seasonal lull in wind and solar, for example, the energy system benefits from lower overall costs, reduced dependence on fossil fuel gas plants or diesel generators, and therefore lower emissions.

Flexible advanced heat sources—in combination with wind, solar, and hydro—can therefore make a substantial contribution towards reliable, responsive, affordable, clean energy systems supplying clean dispatchable generating capacity.

Modelling 2.0 Innovation 4: High-Temperature Steam Electrolysis (HTSE)

Recommendation 4: Modelling 2.0 should represent the transformative role of large, low-cost high-capacity factor, high-temperature electrolysis utilising nuclear as a high-temperature heat source, to eliminate risks to the transition related to needed cost and scale of hydrogen supply.

The AER model explores the effect of hydrogen production benefiting from high-temperature steam electrolysis (HTSE) production efficiencies, which produce as much as 30% more hydrogen for the same electrical input, even when using 'low-temperature' nuclear.

Larger plant sizes also enable dramatic cost reductions in the electrolyser plant, particularly for high temperature electrolysers. The high-capacity factor available from the nuclear reactor results in optimal utilisation of the electrolyser facility, and is therefore a major contributor towards lowering costs. In addition, keeping the system hot when not in use is easy for a nuclear plant, enabling operational flexibility and efficiency.

Figure 5 shows the findings from a range of studies conducted over the past decade by several institutions including the Imperial College London, US Department of Energy, the US National Renewable Energy Laboratory, and Idaho National Laboratory.[6]

These studies show projected capital cost of a range of sizes of high temperature steam electrolysis coupled to high temperature heat, and Figure 6 illustrates the reduction in the expected costs for 500MWe class high-temperature electrolyser plants as the program evolved from conceptual to detailed engineering.

Several companies are now demonstrating and commercialising this high-temperature steam electrolysis technology.[7]

Modelling 2.0 Innovation 5: Dedicated large-scale hydrogen production

Recommendation 5: Modelling 2.0 should represent the transformative role of large-scale, low-cost 'Gigafactory'-scale hydrogen and synthetic fuels production utilising advanced heat sources manufactured at scale.

The AER report describes the need for dedicated, large-scale hydrogen production as a key enabler to reduce overall costs to the clean energy transition, as well as lowering emissions and dependence on fossil fuels.

Large-scale, highly automated factories are the way in which low-cost, high-volume products are made in all sectors of the global economy. The emergence of Gigafactories that are designed to be replicated quickly in new locations adds rapid global expansion to the high-volume, low-cost manufacturing model. This is the dominant model in manufacturing of electric cars, PV, batteries, and numerous other sectors, and demonstrates the transformative effect of this model in each of these sectors. The hydrogen Gigafactory is a direct application of this model to serial production and installation of advanced heat sources in a refinery-scale hydrogen/fuels production facility.

Hydrogen Gigafactory

The AER model assesses the economic entry of a Hydrogen Gigafactory for large-scale dedicated hydrogen production. The Hydrogen Gigafactory is a refinery-scale hydrogen production facility, sized to be large, but limited in this case to a maximum production capacity of one-tenth of UK hydrogen demand in 2050.

The Gigafactory model enables a highly integrated manufacturing, assembly, installation and production process on one site. This enables high-quality, repeatable processes, with quality assurance designed into every step of the process. This approach 'brings the factory to the project'—replacing the traditional construction model with a highly productive manufacturing model. Capital and operating

Figure 5. **Projected Capital Cost of Large-Scale High-Temperature Steam Electrolysis Coupled to High-Temperature Heat**

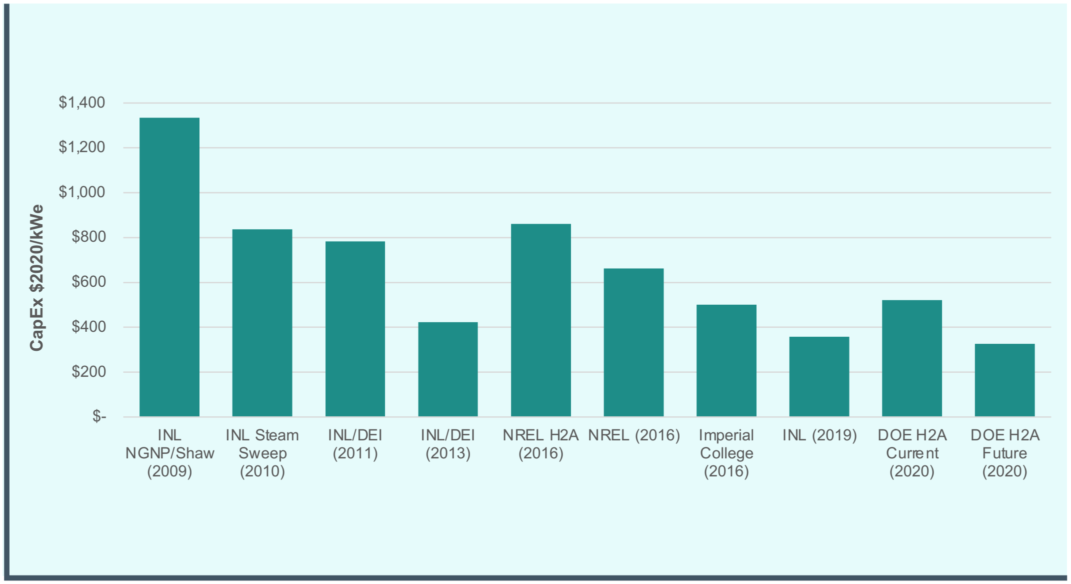


Figure 6. **Evolution of Projected Capital Cost of Large-Scale, High-Temperature Steam Electrolysis**

costs are radically reduced by streamlining manufacturing, operations, and maintenance. This is enabled by a move away from the traditional utilities-based electricity model to a commodities-based model.

The buildings shown on the left (Figure 7) provide the manufactured components, including modular manufacture of dozens of advanced heat sources, shown in the middle).

When completed, these supply gigawatts of heat and power required for large-scale hydrogen and synfuels production (Figure 7). After completion, the manufacturing facilities can continue to produce components for other sites. Manufactured components can also be moved by barge to other coastal refinery sites.

At full production rate, the factory is designed to produce twelve 600MWth reactors per year, equivalent to approximately 3GW of hydrogen production. The hydrogen produced by the Gigafactory is either supplied directly to the gas networks or to a synthetic fuels plant on an adjacent site. The Gigafactory, sized to be equivalent to a medium-sized refinery in terms of output, enabled by storable, transportable commodities production, is large enough to justify the capital investment required for a highly automated, modern factory.

The Hydrogen Gigafactory technology is proposed as a next generation refinery to be located on brownfield sites, such as large coastal oil and gas refineries in the UK. For countries developing such facilities, the Gigafactory provides three important benefits: affordable decarbonisation; the potential to export carbon neutral synthetic fuels; and a world-class domestic supply chain capability for advanced heat sources. It can deliver large quantities of very low-cost synfuels, enabled by ultra-low-cost hydrogen at the target cost of less than $1/kg (Figure 8).

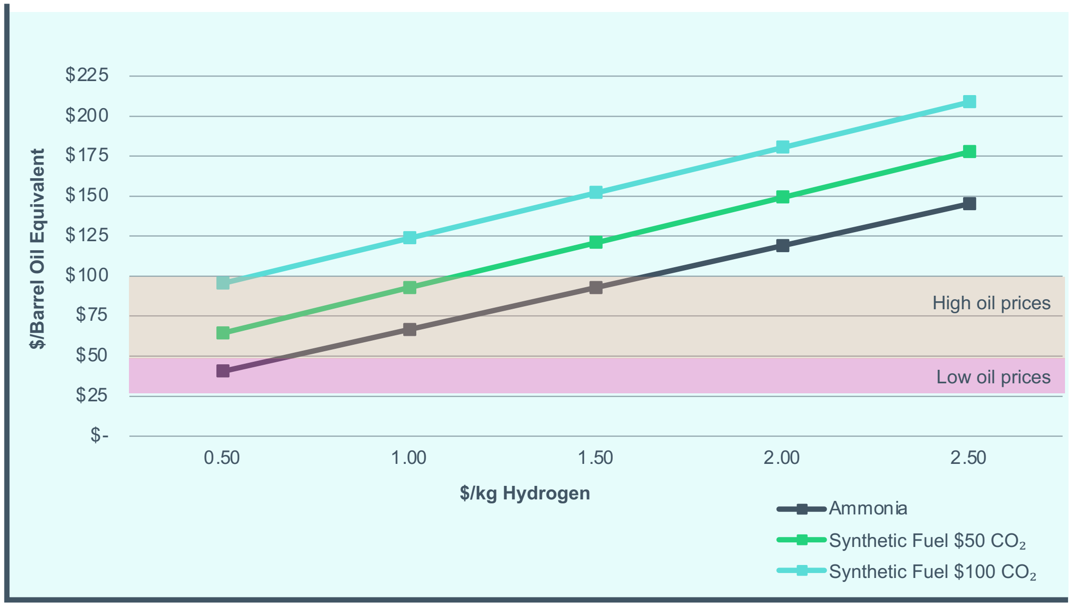
Synthetic liquid fuels

The Gigafactory is designed to incorporate production of cost-competitive drop-in substitute fuels, targeting sectors that cannot be easily electrified in the near term. For example, shipping and aviation. Synthetic fuel production requiring CO_2 reformers, Fischer-Tropsch reactor and fuel finishing systems increases plant capex by £600/kWe over the equivalent hydrogen Gigafactory to produce synthetic liquid fuel.[8]

While not specifically used in AER model runs, production cost estimates for liquid synthetic fuel plants run between 3.0 p/kWh and 3.5 p/kWh. When available, this undercuts the cost of conventional fossil-based aviation fuel (circa 5 p/kWh) throughout. The implied marginal cost of abatement is therefore negative.

Figure 7. **Hydrogen Gigafactory**

Figure 8. **Guardrails of the Hydrogen Economy**



Endnotes

1 Aurora Energy Research, "Decarbonising Hydrogen in a Net Zero Economy," 27 September 2021.

2 Ingersoll, E.; Gogan, K.; Herter, J.; Foss, A. "ETI Nuclear Cost Drivers Project – Full Technical Report," September 2020, funded by the Energy Technologies Institute and released by Energy Systems Catapult with the support of authors at LucidCatalyst.

3 Ibid

4 LucidCatalyst (2020), "Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals," September 2020.

5 Ingersoll, E.; Gogan, K.; Herter, J.; Foss, A. (LucidCatalyst). "Cost and Performance Requirements for Flexible Advanced Nuclear Plants in Future U.S. Power Markets." Report for the ORNL Resource team supporting ARPA-E's MEITNER Program, July 2020.

6 "Of all the reviewed hydrogen production methods, HTSE systems are the closest to commercialization within current LWRs." from Talbot, P.W., Boardman, R.D. (INL), et al, "Light Water Reactor Sustainability Program Evaluation of Hybrid Flexible Plant Operation and Generation Applications in Regulated and Deregulated Markets Using HERON, INL/EXT-20-60968 Rev. 0," Idaho National Laboratories 2020 report. Dec. 2020, p. 26.

7 Press release: "Haldor Topsoe to build large-scale SOEC electrolyzer manufacturing facility to meet customer needs for green hydrogen production," Mar. 4, 2021.

8 LucidCatalyst's forthcoming report for the Electric Power Research Institute (EPRI) presents the detailed techno-economic analysis for this concept. Capital estimates are derived from Idaho National Laboratory technoeconomic analysis of hydrogen, ammonia, and other commodity production.

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LucidCatalyst is a highly specialised international consultancy offering thought leadership, strategy development and techno-economic expertise. Our mission is to multiply and accelerate zero carbon technology options available for large-scale, affordable, market-based decarbonisation of the global economy over a wide range of future scenarios.

We work to transform the energy space, helping companies gain competitive advantage from this change by engaging in a broad range of the stakeholders who can benefit from and enable these changes. We help large companies create new ventures and help startup companies accelerate growth. We are deep technical, market, policy, communication and commercial analysts, with extensive experience in starting new businesses and advising companies on entering new markets.