CARBON-FREE EUROPE
A TECHNOLOGY-INCLUSIVE CLIMATE INITIATIVE

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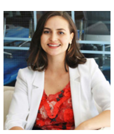
Deployment of Nuclear Energy in the EU and UK Under Different Reactor Cost Assumptions

BEN HALEY
Co-Founder, Evolved Energy Research

KATIE PICKRELL
Principal, Evolved Energy Research



LINDSEY WALTER
Director of International Policy for Third Way's Climate and Energy Program, Co-founder of Carbon-Free Europe

ALAN AHN
Senior Resident Fellow for Third Way's Climate and Energy Program

Overview

In March 2022, Carbon-Free Europe released our original analysis of five different pathways for the EU and UK to reach net-zero emissions by 2050. Our results showed crucial steps Europe must take over the next three decades to implement credible trajectories to carbon neutrality. The analysis reinforced that the feasibility of reaching emissions goals, both for individual countries and the EU as a whole, is greater when net-zero pathways incorporate a wider range of clean technology options. Increased optionality reduces risk and makes it more likely that clean energy will be cost-effective and net-zero goals can actually be achieved.

Nuclear energy emerged in our analysis as an important zero-carbon technology that, when allowed in a net-zero pathway, played a significant role in decarbonizing the power sector and providing heat for hydrogen production. Though we used a single cost assumption for advanced nuclear reactors in the Carbon-Free Europe scenarios, derived from the MIT Energy Initiative study "The Future of Nuclear Energy in a Carbon-Constrained World", the future cost of new nuclear energy in Europe is highly uncertain. Because advanced nuclear reactor technologies have not yet been demonstrated at scale, it's difficult to anticipate their eventual cost—and their cost can likely be influenced by continued investment in R&D and early technology deployment. How much nuclear energy might be economically deployed in Europe if significant reactor cost reductions can be achieved through 2050? And what's the potential for lower-cost nuclear reactors to reduce the total cost of meeting Europe's climate targets?

This sensitivity analysis looks to answer those questions by evaluating how the cost of advanced nuclear reactors influences their economic deployment in Europe. We evaluated the various roles nuclear energy can play in a net-zero European energy system at different reactor cost levels. Our results indicate that under the assumptions used in Carbon-Free Europe's Core scenario, there is an inflection point for nuclear reactor deployment when nuclear electricity costs reach €50/megawatt hour-electric (MWh_e)[1]: at costs below this threshold, nuclear can economically provide a meaningful share of Europe's total electricity generation and hydrogen production, reducing total annual energy system costs by billions of Euros in 2050. This potential upside warrants continued effort from the public and private sectors to drive down costs of advanced nuclear via technology improvements, economies of scale, and improved financing mechanisms.

Topline Takeaways

1. **Deployment of nuclear energy increases significantly when reactor costs drop below €50 per megawatt hour-electric.** Economic deployment of nuclear reactors increases dramatically in our model results when reactor costs drop below €2,000 per kilowatt-thermal (kW_{th}), corresponding to €50/MWh_e nuclear electricity production and €20/MWh_{th} nuclear heat. The total capacity of advanced nuclear reactors deployed in the EU and UK in 2050 jumps from 50 gigawatts-thermal (GW_{th}) to 225 GW_{th} when reactor costs decline from €2,000/kW_{th} to €1,665/kW_{th}.Our modeling indicates very little economic deployment of nuclear if the levelized price of nuclear electricity exceeds €60/MWh_e.

2. **Even with higher reactor costs, nuclear remains competitive in direct heat applications**. At reactor costs above €2,000/kW_{th}, most nuclear energy is used in direct heat applications (primarily high-temperature hydrogen electrolysis), with a smaller portion used to produce electricity. The large step up in deployed reactor capacity when costs reach €1,665/kW_{th} is largely driven by increased cost-competitiveness of nuclear electricity.

3. **At baseline reactor costs, all countries where nuclear is allowed deploy some nuclear capacity.** At a reactor cost of €1,665/kW_{th}, every country where our analysis allows

new nuclear construction adds some advanced reactor capacity by 2050. The degree of nuclear deployment at the country level depends on competition with other sources of zero-carbon electricity: countries with higher-quality renewable resources deploy less nuclear energy than those with limited renewable energy endowment.

4. **Lower reactor costs result in significant energy system costs savings for both the EU and UK.** Reducing the cost of nuclear reactors from €3,000/kW_{th} to our baseline cost of €1,665/kW_{th} reduces total EU and UK energy system costs by over €5B annually in 2050. Further reducing the cost to €1,000/kW_{th} reduces 2050 system costs by over €18B. These annual cost savings can be weighed against the R&D and early-stage deployment investments needed to achieve said reductions.

5. **Renewables build-out in Europe remains robust even in low nuclear cost scenarios.** Some of the cost savings in the low nuclear cost scenario result from avoided renewable power investment. In our modelling, when nuclear reactors cost €1,000/kW_{th}, total new renewable capacity needed in the EU and UK is reduced by 400 GW relative to the €3,000/kW_{th} scenario. This reduction in renewable buildout doesn't take effect until 2040, suggesting that even if advanced nuclear costs decline significantly, rapid buildout of renewable power in the 2020s and 2030s is still a no-regrets action in Europe.

6. **In all reactor cost scenarios, nuclear energy plays a major role in Europe's decarbonised energy system.** In our analysis, nuclear reactors, including existing facilities, generate 17 to 28% of EU and UK electricity in 2050, relative to 25% today. High-temperature electrolysis with nuclear heat produces 20% to 60% of all hydrogen.

7. **Additional real-world constraints could increase the need for nuclear energy to meet climate goals.** All the results presented here correspond to Carbon-Free Europe's Core scenario, which is the least-constrained scenario we evaluated. Real-world policy and implementation constraints on the path to net-zero could further increase the value of nuclear energy.

Introduction

Because advanced nuclear technologies have not yet been deployed at scale, but are expected to dominate new nuclear reactor deployment in the coming decades, long-term forecasts of nuclear reactor costs are highly uncertain. In contrast, renewable energy costs have dropped precipitously over the last decade after being deployed at scale. Comparing nuclear against renewable energy costs today can lead to the conclusion that nuclear energy is likely to be too expensive to compete with renewables in the long term, and that continued investment in nuclear technology advances is therefore a dead end. That conclusion may be premature for two reasons:

1) Non-intermittent electricity generating technologies become relatively more competitive as decarbonisation progresses. At the very high levels of renewable penetration necessary to meet deep decarbonisation targets, constraints—such as declining renewable resource quality, transmission availability, and curtailment— increase the cost and decrease the value of incremental renewable deployment.

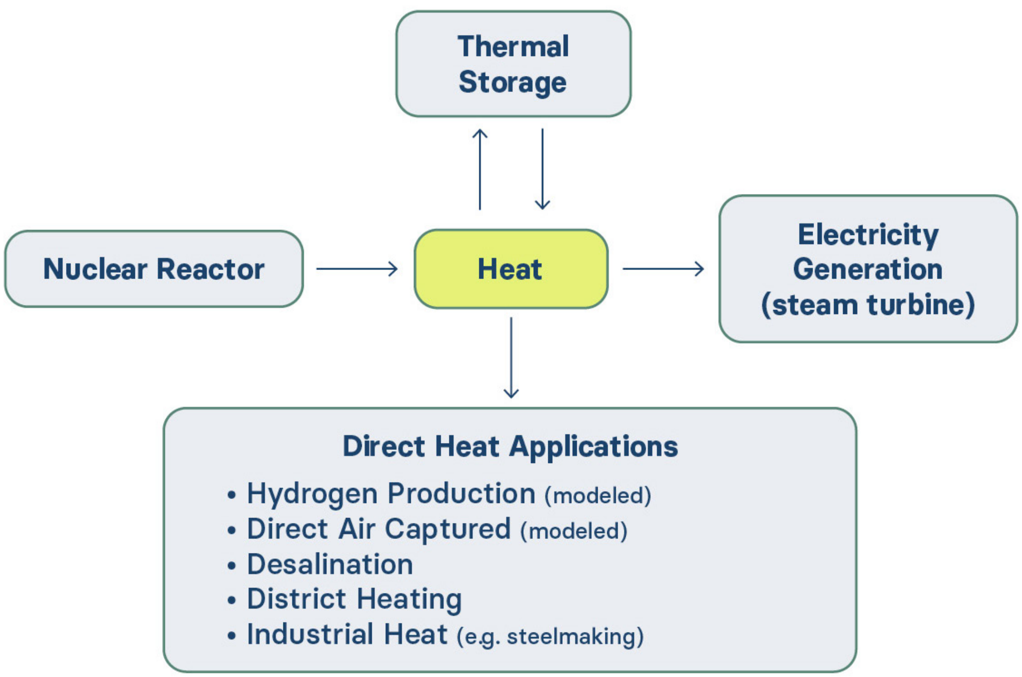
2) Advanced nuclear technology and renewables do not necessarily serve the same function in a net-zero energy system. As a thermal energy source, nuclear provides electric reliability, storage and flexibility, as well as direct heat for industrial uses—services that can be difficult to provide entirely with renewable energy.

In this analysis, we seek to inform the debate not with our own view of future costs, but with a better understanding of an energy system's willingness-to-pay for the services offered by nuclear technology. We do so by evaluating economic deployment of advanced nuclear reactors at a wide range of costs. From these results, we can develop willingness-to-pay curves for individual countries and for Europe as a whole, which can inform economic targets for nuclear deployment. Our results showcase the broad role that nuclear energy could play in electricity generation, hydrogen production, and reducing overall costs in a net-zero energy system.

Nuclear Products: Heat and Electricity

To effectively capture the value that nuclear reactors can provide in a net-zero energy system, we model nuclear heat production separately from nuclear electricity generation. As shown in Figure 1 below, a nuclear reactor produces heat, which can then be converted to electricity in a steam turbine, stored via thermal storage for later use, or used in a direct heat application. Nuclear heat has many direct applications; we focus on hydrogen production and direct air capture (DAC) in our modelling, two important heat needs in net-zero energy systems.

FIGURE 1. MODELED USES OF NUCLEAR HEAT

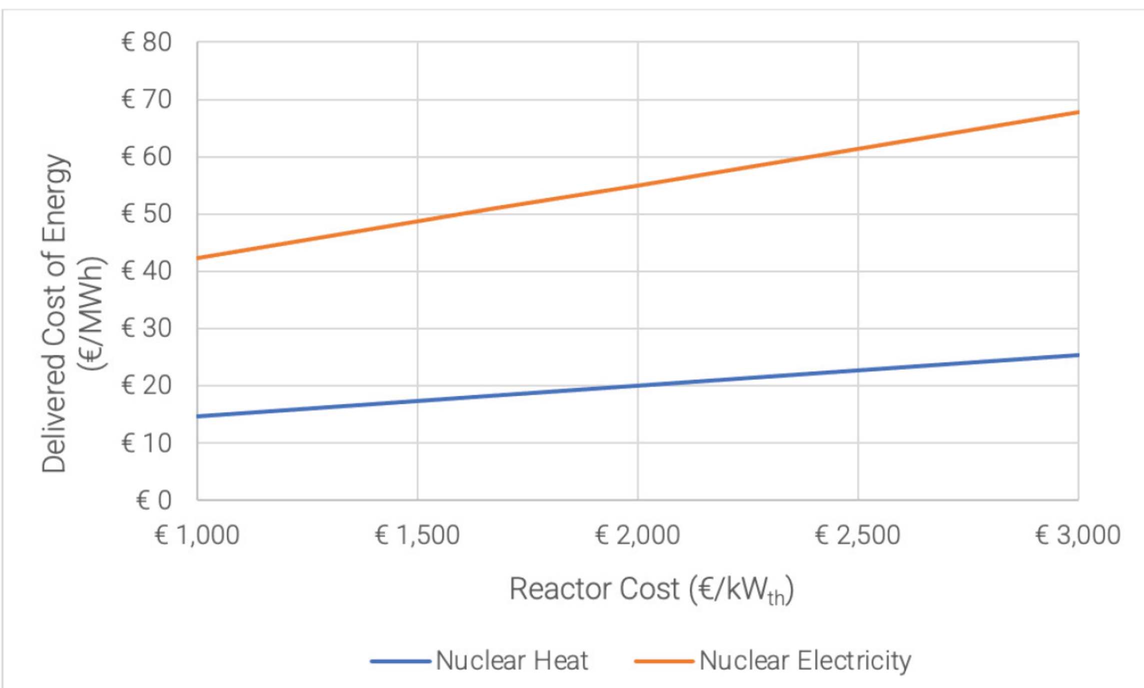


Our analysis optimizes across three nuclear heat applications (electricity generation, electrolytic hydrogen production, and DAC) to determine the highest value use of nuclear heat in every hour. As a result of this approach, the optimal quantity of nuclear reactor capacity and nuclear electricity capacity constructed in our results are not necessarily equal.

Nuclear Costs

Our analysis seeks to understand how nuclear reactor cost reductions could prompt broader economic deployment of nuclear energy through 2050. The all-in cost of nuclear energy depends on many input costs: upfront reactor costs, financing, fuel, operations and maintenance, waste disposal, and plant decommissioning.[2] Forecasting any one of those costs in 2050 is subject to uncertainty. To simplify our analysis, we vary only reactor costs, but we evaluate such a wide range of reactor costs that we effectively capture uncertainty in other cost categories. We use a baseline reactor cost of €1,665/kW_{th},[3] which we vary from €1,000/kW_{th} to 3,000/kW_{th}. We derive the levelized cost of a nuclear reactor's delivered products—heat and electricity—from the reactor's upfront cost, its operational profile,[4] and O&M and fuel costs.[5] Figure 2 shows the linear relationship between nuclear reactor cost and delivered nuclear heat and electricity costs under these assumptions.

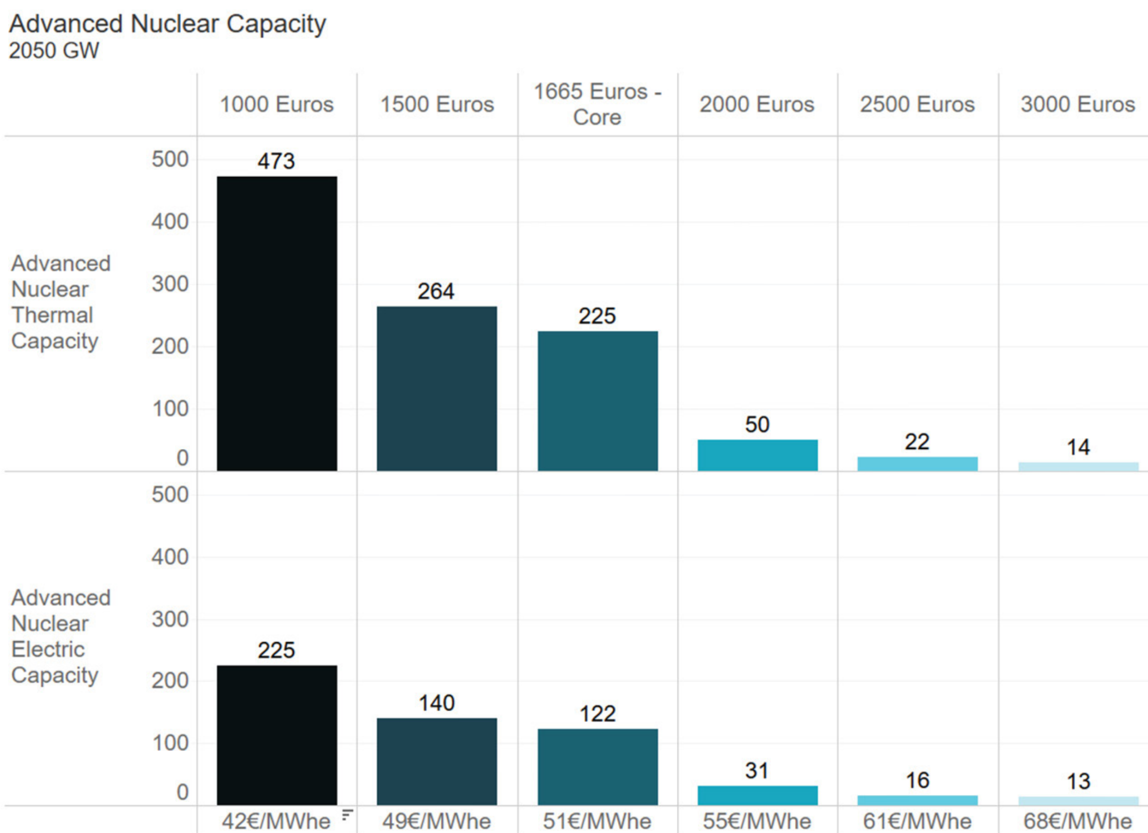
FIGURE 2. RELATIONSHIP BETWEEN REACTOR COST AND DELIVERED COST OF NUCLEAR ENERGY



Results: Deployment

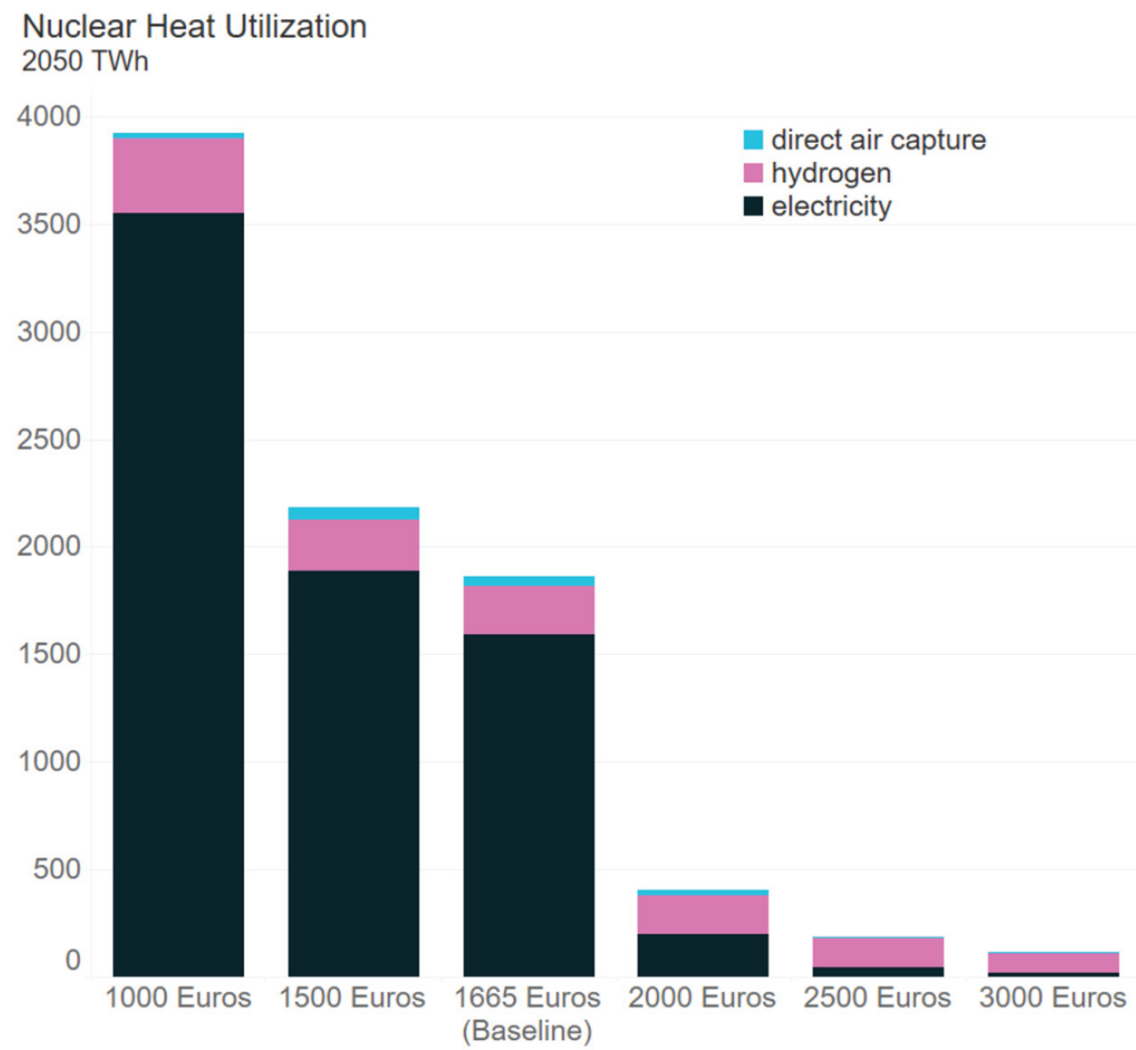
Figure 3 shows deployment of advanced nuclear reactors and nuclear electric generation across the spectrum of modelled reactor costs. Reactor deployment increases significantly when costs drop below €2,000/kW_{th}, accelerating from 50 GW_{th} to 225 GW_{th}. At the low end of our modelled cost range, our optimization constructs almost 500 GW_{th} of reactor capacity and 225 GW_e of new electricity capacity.

FIGURE 3. 2050 DEPLOYMENTS OF ADVANCED NUCLEAR REACTORS AND ELECTRIC GENERATION



While both nuclear reactors and nuclear electric generators are deployed more widely as reactor costs decline, electricity generation capacity is more sensitive to reactor cost than direct heat applications. Figure 4 below further illustrates this trend: as reactor deployment accelerates at costs below €2,000/kW_{th}, most of the incremental heat production is directed to electricity. In contrast, nuclear is a competitive source for direct heat used in hydrogen production and DAC even at relatively high reactor costs. Some nuclear electricity generation is also economical at high reactor costs, but the number of hours when nuclear electricity is cost-competitive grows substantially as reactor costs decline.

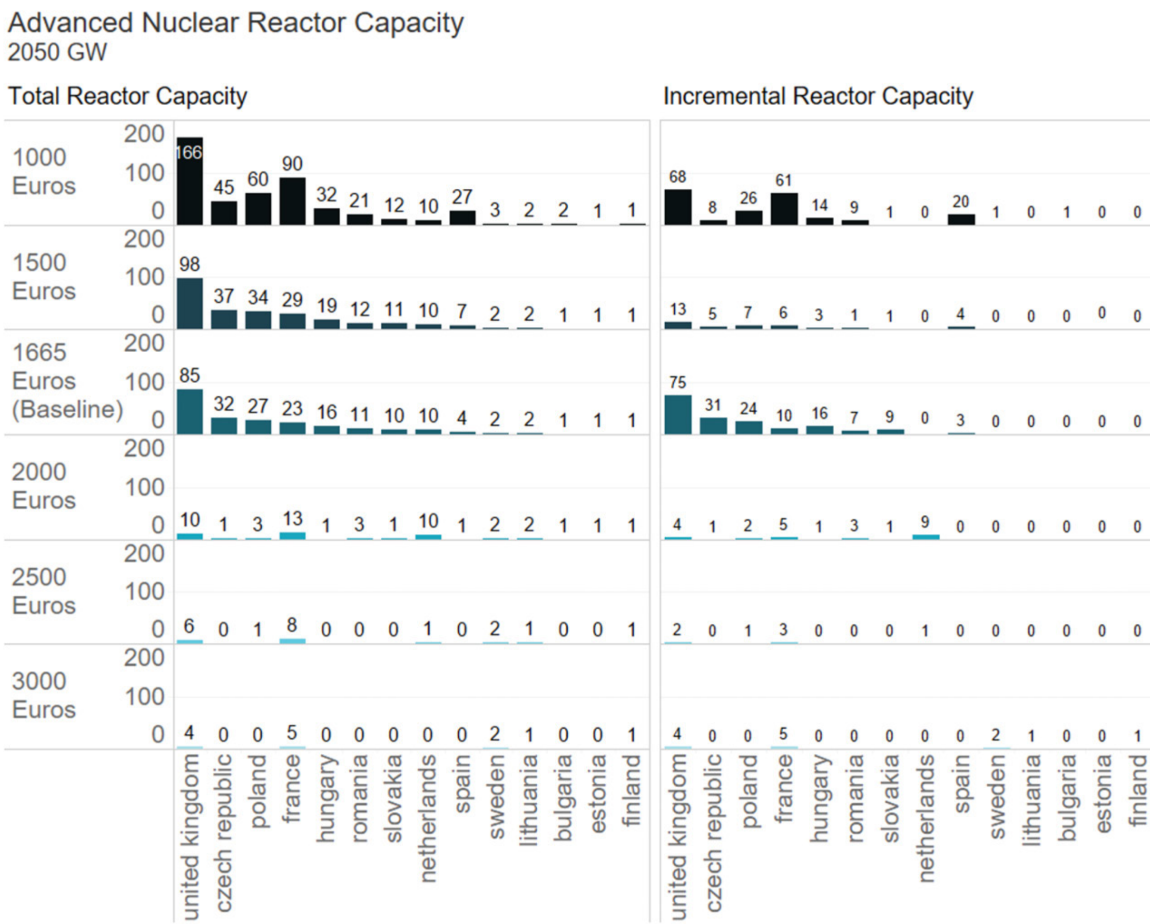
FIGURE 4. 2050 NUCLEAR HEAT UTILIZATION: ALLOCATION TO ELECTRICITY, HYDROGEN PRODUCTION, AND DIRECT AIR CAPTURE



Results: Country-Level Deployment

In our Carbon-Free Europe analysis, 14 of the 28 European countries we model are allowed to add new nuclear capacity, based on existing national nuclear policy. All 14 of those countries build some new nuclear reactor capacity under baseline cost assumptions (€1,665/ kW_{th} reactor cost), but country-level sensitivity to reactor cost depends on the domestic availability of other zero-carbon resources. Figure 5 shows the total and incremental capacity of nuclear reactors deployed in each country by 2050 under each reactor cost assumption.

FIGURE 5. TOTAL AND INCREMENTAL 2050 ADVANCED NUCLEAR REACTOR CAPACITY BY COUNTRY

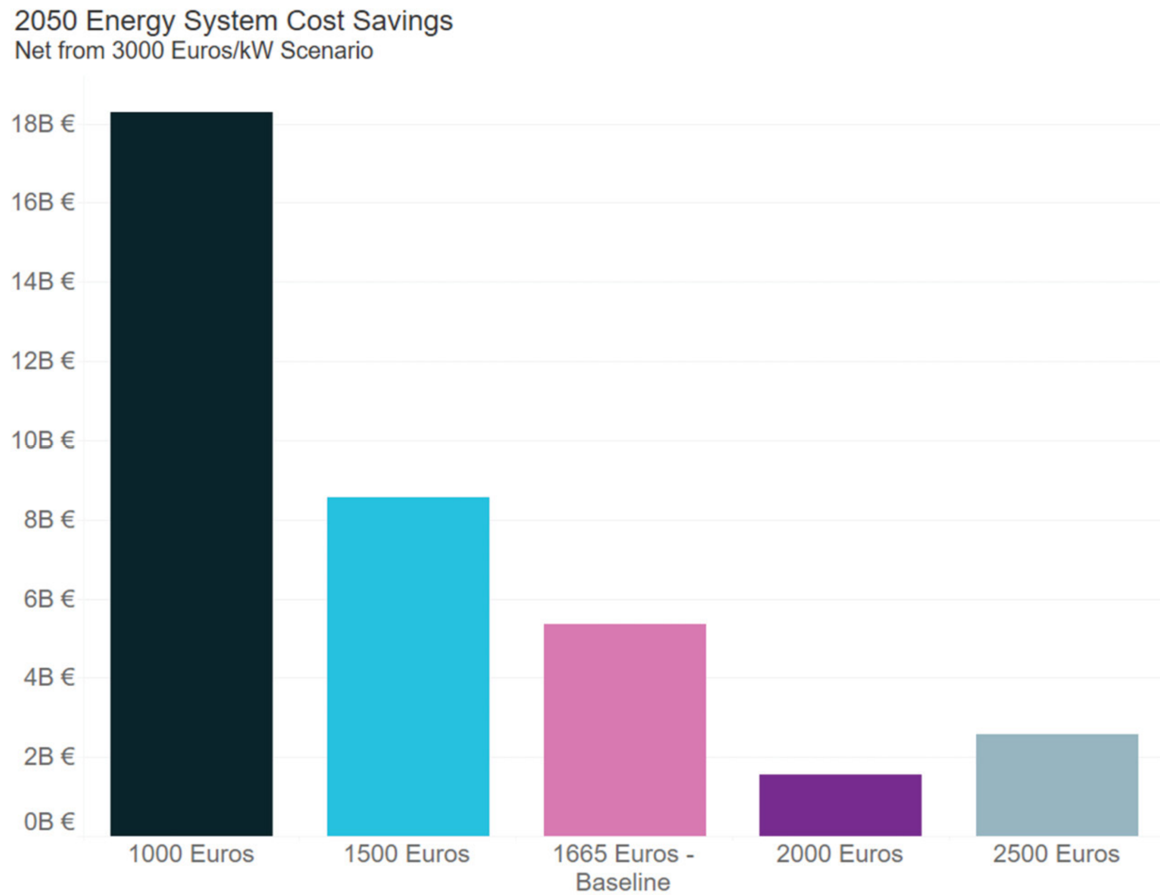


In Northern Europe where high-quality offshore wind is abundant, nuclear heat is used primarily to produce hydrogen even at the lowest reactor costs modelled, so reactor deployment does not expand to start providing electricity in any of our scenarios. In Spain and France, where nuclear electricity competes with solar, onshore wind, and offshore wind, nuclear deployment does not accelerate greatly until reactor costs reach €1,000/kW_{th}. In Eastern Europe, where renewables are less abundant, reactor deployment ramps up at €1,665/kW_{th}.

Results: System Costs

The impact of nuclear technology costs on total energy system costs depends on the extent of nuclear deployment as well as the magnitude of nuclear technology's cost advantage over alternative solutions. In this case, nuclear technology primarily displaces renewable electricity (for electricity and hydrogen production), gas power plants (for reliability), battery storage, and low-temperature electrolysis. The cost advantage of nuclear technology at the examined reactor costs over these alternative solutions is shown in Figure 6 below.

FIGURE 6. 2050 ENERGY SYSTEM COST SAVINGS BY COST SCENARIO



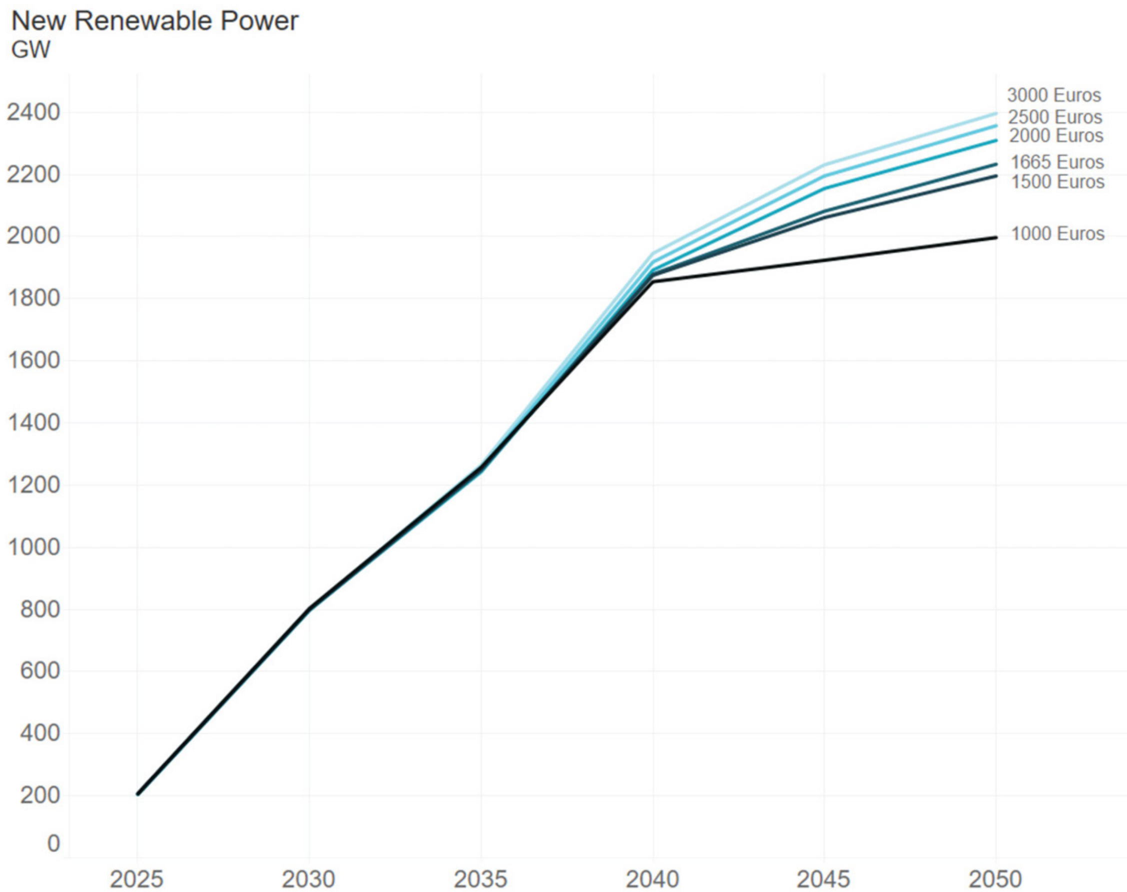
Note: We use 2050 energy system cost savings as the metric in this figure, but assumed nuclear reactor costs have impacts in all modeled years and the model optimizes using the NPV of costs across all modeled years. This explains the discontinuity between energy system cost savings with reactor costs at 2000 Euros and savings at 2500 Euros.

By 2050, reducing the cost of nuclear reactors from €3,000/kW_{th} to our baseline cost of €1,665/kW_{th} reduces total EU and UK energy system costs annually by over €5B. Further reducing the cost to €1,000/kW_{th} reduces overall energy system costs annually by over €18B. These system cost reductions imply that investment in advanced nuclear R&D and early-stage deployment is a high-value undertaking in Europe if it drives down the cost of nuclear reactors.

Results: Other System Impacts

One of the principal benefits of nuclear development is to provide a zero-carbon energy resource in areas that may face constraints to siting renewables. Our analysis shows that low-cost nuclear displaces a significant amount of otherwise-needed renewable power, reducing total new renewable capacity in 2050 by one-sixth (400 GW) compared to the highest cost scenario. This impact, however, isn’t realized until the 2040s, showing the continued need to develop renewables at unprecedented scales (while also maintaining Europe’s existing nuclear fleet).

FIGURE 7. NEW RENEWABLE CAPACITY ADDED 2025 – 2050 UNDER VARYING NUCLEAR REACTOR COST ASSUMPTIONS



The ultimate contribution that nuclear energy makes to electricity generation and hydrogen production in 2050 is shown below by cost scenario. Under the most optimistic cost projections, nuclear (including existing facilities) exceeds the overall share of electricity generation it makes up today (25% in 2020).[6] Nuclear heat becomes critical to hydrogen production in many scenarios, with high-temperature electrolysis representing 60% of hydrogen production under the lowest reactor cost scenario.

FIGURE 8. 2050 SHARE OF PRODUCTION AND GENERATION FOR ELECTRICITY AND HYDROGEN

Conclusions

With a breakthrough in costs (€1,000/kW_{th} reactor costs, corresponding with €15/MWh_{th} for heat and €42/MWh_{e} for electricity), nuclear energy in 2050 exceeds the generation share seen in Europe today, reduces the necessary renewable build by 400 GWs, and is used to produce greater than 60% of Europe's hydrogen. Costs below €1,665/kW_{th} (€20/MWh_{th} for heat or €50/MWh_{e} for electricity) are necessary to see significant economic deployment. These costs can potentially be achieved through technology improvements, economies of scale, and improved financing mechanisms.

Carbon-Free Europe's analysis evaluated five net-zero pathways: a relatively unconstrained Core pathway,[7] and four additional pathways designed to explore how different policy and implementation constraints impact the route to carbon neutrality. This sensitivity analysis of nuclear reactor costs simulates economic deployment of nuclear only under the Core pathway assumptions. Even at higher costs, nuclear technology may be valuable to mitigate risks to decarbonisation represented in our other modelled pathways: the pace of demand transformation (Slow Demand Transformation), limited ability to construct new transmission lines and pipelines (Domestic Preference), or difficulty siting new renewable power (Limited Renewable Siting).

ENDNOTES

1. Throughout this report, we cite cost and capacity figures for both nuclear reactors and nuclear electricity generators. Nuclear thermal energy capacity and heat production are quantified in GW_{th} and MWh_{th}, while nuclear electric capacity and electricity production are denoted as GW_e and MWh_e.

2. Each of these cost types contributes to the delivered cost of nuclear energy and represents an area to target for potential cost reduction.

3. This broad range of reactor costs is not intended to represent a forecast; rather, it is designed to identify inflection points in nuclear energy deployment.

4. We assume that new nuclear reactors can operate up to a 95% capacity factor.

5. Nuclear O&M and fuel costs are from MIT's study "The Future of Nuclear Energy in a Carbon-Constrained World". Our analysis does not explicitly include nuclear waste disposal or decommissioning costs. While those costs are non-negligible contributors to the total cost of nuclear energy, they are smaller than the range of reactor costs we evaluate by an order of magnitude, so would not impact the conclusions of this analysis. Decommissioning costs are large in absolute terms but are heavily discounted relative to upfront reactor costs, because they are paid at the end of a nuclear facility's long lifetime.

   These reactor costs represent Nth of a kind installed costs: they do not include R&D or early technology deployment investments incurred on the path to achieving cost reductions. The cost of "buying down" advanced nuclear technology costs is outside the scope of our analysis but can be weighed against the reductions in total energy system costs we attribute to nuclear deployment at each reactor cost level.

6. As electricity demand grows rapidly on the path to net-zero, new nuclear capacity is required to maintain nuclear power's current share of total electricity generation.

7. This pathway achieves emissions targets with high levels of electrification (in transport, buildings, and industry), improvements in energy efficiency, and significant deployment of all available clean energy technologies. Clean energy technologies have central cost and availability assumptions. Parts of heavy industry that cannot be electrified are decarbonised with hydrogen (iron and steel) and carbon capture (cement). Residual fossil emissions in industry and transportation are offset by a modest amount of direct air capture.