Nuclear energy is the single largest source of carbon-free electricity in the U.S.

Nuclear Energy: A Star on Earth

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Although our current perceptions of nuclear energy have been shaped in large part by stories of disaster, the reality is that the next generation of nuclear reactors will be the safest and most efficient ever produced. Further, these SMRs — small modular reactors — can play a critical role in hydrogen production, increasing their value as a ‘dual fuel’ energy source while helping accelerate our transition to a net-zero carbon existence.

In this second installment of our eBook series, we take a closer look at current and near-future reactor technology, and how new and emerging reactor designs can integrate into a larger zero-carbon energy system.

Nuclear Energy: **A Star on Earth**

The consensus that we need to decarbonize our economy has caused nuclear energy to re-enter in the limelight, after a quiet period of 40 years. During that time, the industry vastly improved the performance of machines completed in the 1970s and 1980s but failed to build new reactors.

Nuclear energy already constitutes the largest source of carbon-free electricity globally, and existing plants will run for many decades to come. But with innovation in mind, start-ups and established companies are introducing a score of advanced reactor designs that may help spur adoption.

These advanced reactors create energy the same way as traditional reactors, by splitting atoms to make heat; but they will be built, fueled and operated in an entirely new way, and some of them will do different jobs, meeting new needs in a decarbonized world. Nearly all will produce electricity, but some may provide heat to industry, displacing fossil gas or coal while some will produce hydrogen, which can be a fuel or a storage medium.

Advancements in Reactor Design

All advanced reactors will have the ability to "ramp" — increase or decrease production quickly — to balance variable supply from renewable energy with demand, which also varies but on a different schedule. These reactors will be the indispensable partner that can produce clean energy regardless of the season or weather. They are one of only two generating technologies that can do this; the other is fossil fuel generation with carbon capture, an approach that drawn early attention but has not garnered much interest from utility companies, who face a variety of technical and regulatory difficulties.

Numerous studies have found that firm, dispatchable electricity sources are an essential complement to a power grid based on intermittent renewable energy. **A study published in *Joule*** found that "firm low-carbon resources consistently lower decarbonized electricity system costs," and the "availability of firm low-carbon resources reduces costs 10 percent to 62 percent in zero-CO2 cases."

Many of the new reactor designs will depart from the standard recipe now in use: uranium in ceramic pellets, wrapped in a special metal alloy and submersed in "light water" — e.g., ordinary water, although considerably more pure than what comes out of your tap. Light-water reactors were an easy path for the industry to follow in the 1950s, piggybacking on the U.S. Navy's then-new submarine propulsion program, and some of the new types are still light water but designed for ease of manufacturing and installation, with less steel and concrete needed for construction, simplified safety systems that are less costly to build and maintain, and smoother refueling procedures.

A note on terminology

The buzzword in new nuclear is “small modular reactor” (SMR). The term is useful but very broad, as it does not describe a technology. An SMR can be a light-water reactor, or it can use sodium, molten salt or inert gas to move heat out of the core to a place where it can be put to work. SMRs can use fuel in conventional ceramic form, in a coating of silicon carbide, or even dissolved in salt.

What SMR actually describes is, to borrow a term from the computer industry, “form factor.” An SMR is a reactor that is built in a factory and shipped intact, or in a small number of pieces. It then is installed at the power plant site, not built.

Among the advantages: fabrication in factories is easier and less expensive than building in the field. While the factory is building the reactors, construction workers can pour the concrete and erect the buildings. Putting these tasks in parallel, rather than arranging them consecutively, shrinks the construction time saving money.

Similarly, fabricating the reactor vessel in a traditional, large nuclear plant is a bottleneck because very few foundries have the equipment needed for objects that large. Shrinking the reactor vessel multiplies the number of foundries that can do the work.

Smaller plants have other advantages:

- They can be used to add capacity in smaller increments, as demand grows.
- They can be installed on smaller grids. A big reactor on a small or weak grid would threaten stability if it tripped offline and could create shortages when shut down for scheduled refueling or maintenance.
- They may work well as drop-in replacements for decades-old coal plants, which already have cooling water, grid access and workforces with transferrable skills. An SMR or two may approximate the power output of the old coal units.
- They can be built in countries with strong industrial bases and exported more easily to developing countries that have a rising demand for energy but lack construction expertise.
- They can be located close to load so that they can deliver heat directly to customers for industrial use or space heating.

Advanced reactors…will be built, fueled, and operated in an entirely new way, **meeting new needs in a decarbonized world…**

Light Water Nears Deployment

Three advanced light-water designs show substantial progress toward near-term deployment:

1. **NuScale Power,** in which the modules are wrapped in something resembling a thermos bottle. In case of malfunction, the system breaks the vacuum layer and heat flows into a giant tank of room-temperature water that surrounds the bottle. The system does not require emergency water beyond what already is present, no electrical power and no operator action. The Nuclear Regulatory Commission (NRC) has approved basic design. The modules generate 77 megawatts each and customers can order four, six and eight or 12.
2. **GE-Hitachi's BWRX-300** incorporates many features already approved by the NRC, with 90 percent of the components already in use in the industry. The reactor is 80 percent smaller than previous designs but uses 90 percent less steel and concrete. It relies on natural force — not mechanical systems — for core cooling in an emergency.
3. **Holtec's SMR-160** incorporates many passive safety systems. Holtec is a major manufacturer of nuclear components, including dry casks for spent fuel storage.

While water is well understood, reactors that use it produce heat at relatively low temperatures, around 300 degrees C. When reaching outlet temperatures higher than that, the steam pressure becomes harder to manage, so some reactor designers have moved away from water. X-energy uses helium gas to move heat out of the core, and uranium fuel wrapped in heat-resistant layers of graphite and other non-metallic materials to achieve an outlet temperature of 565 degrees C. Higher temperature means better thermal efficiency, i.e., more kilowatt-hours produced per calorie of heat generated. And it can make higher-temperature steam for use in chemical processing or other industries.

GE-Hitachi and Terrapower, a company backed by Bill Gates, took a different approach: a reactor with the fuel dissolved in molten salt. Salt can reach very high temperatures, over 600 degrees C, at low pressure, which makes it considerably easier to build the vessel, piping and heat exchangers.

Their reactor is designed to push its heat into a giant salt tank, which functions as a battery. Heat from the tank can be used to boil water into steam and spin a standard, industrial-grade turbine at a pace that the grid demands. The reactor runs at a steady 345 megawatts, but the turbines can produce anywhere from 100 to 500 megawatts. The plant could store heat during sunny times and ramp up quickly when

A reactor could split its output between two products: **electric current for the grid,** and **hydrogen production.** The result would be a **fully employed reactor.**

the sun goes down, a period when demand typically increases sharply as people return home from work.

The GE-Hitachi/Terrapower reactor, called Natrium, operates with high-energy neutrons that can release energy by splitting uranium as well as other kinds of atoms, some of which would otherwise be considered nuclear waste.

High-temperature heat from a gas-graphite reactor or a reactor that uses molten metal or molten salt as a coolant can substitute for fossil gas, coal or oil used in industry. And when converting heat to electricity, the efficiency is higher when the temperature is higher.

The Hydrogen Connection

High-temperature reactors also may be used to produce hydrogen. Water can be split to make hydrogen using plain old electricity from any source, but the amount of electricity needed declines sharply as temperature rises — and the water used is generally in the form of steam.

Hydrogen can be blended with methane, the main ingredient of fossil gas, and burned in plants that were built to run on 100-percent fossil gas. With modifications, those plants may be able to burn pure hydrogen. Because pure hydrogen fuel has no carbon in it, there is no production of carbon dioxide; in fact, the only byproduct is very pure water.

A reactor could split its output between two products: electricity and hydrogen. Hydrogen storage is well-demonstrated so production could run around the clock while hydrogen is saved for burning at peak hours. The result would be a fully employed reactor and a peaking unit that is fossil-free.

Hydrogen also can reduce carbon emissions through a variety of industrial uses. In metallurgy, it binds with the excess oxygen found in iron, a major step in converting iron to steel. Today, that job is uses carbon monoxide, produced by the partial burning of coal. The carbon monoxide molecule absorbs another oxygen atom from the iron, converting the molecule to carbon dioxide. Steelmaking is a major source of carbon dioxide.

Hydrogen also can be used to bind to sulfur so it can be removed from valuable chemicals. Today, that hydrogen is obtained by breaking up a methane molecule, which consists of four hydrogen atoms and one carbon atom. In the process, the carbon atom becomes carbon dioxide. Iron and steel production contribute about 11 percent of global carbon dioxide emissions.

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Additional Benefits

Advanced reactors have another favorable characteristic that is sometimes overlooked: they are “black start” machines, which refers to the ability of a generator to start up without outside help.

Black start machines are a key tool in grid resiliency. Today’s reactors need grid power — and a lot of it — to run their coolant pumps and other key equipment before they can make steam and turn a generator. The same is true of many fossil plants. As a result, when a blackout hits, the generators must be started from the edges of the affected areas, moving inward. Imagine a parking lot filled with cars whose dead batteries can only be fixed by jump-starting the ones at the edges and then moving inward.

Most of the new machines are designed to stay safe without an outside supply of electricity, through passive shut-down cooling — so many do not have massive reactor coolant pumps like the older models. As a result, they can start up with just a little push from an industrial-grade diesel generator. Diesels not required for safety are less expensive to buy and maintain, helping make these reactors more competitive.

Advanced reactors have another feature that will help them compete better: They all were designed after terrorism became a concern, and thus their layout takes security into account. They will not need armies of security guards, as some current plants require. Many of the new designs are located mostly underground, which is a way to ensure heat dissipation in case of mechanical failure, with the side benefit of reducing the plant’s profile and vulnerability.

Changes in fuel are coming to the existing fleet of reactors and to their advanced younger cousins, to allow the plants to run longer between pauses for re-fueling. Todays’ reactors and many of the new models work by splitting atoms of a type of uranium called U-235. That type is rare in nature, making up less than 1 percent of the uranium in natural ore, but through a process called “enrichment,” the proportion can be raised, generally to around 5 percent for the current fleet.

But operators today are looking to move to enrichments of up to 10 percent, and some of the new designs call for enrichments approaching 20 percent, which is the limit for civil uranium; above that level, proliferation becomes a concern. Some advanced reactors can run for more than two years on the more highly enriched fuel. Others can be refueled during operations, as fossil plants are, so shut downs are less frequent.

And reactors that use high-energy neutrons, common to several advanced designs, can split the dominant type of uranium, U-238, which makes up more than 99 percent of natural supplies. The United States has vast supplies of highly purified U-238, a byproduct left over from decades of enrichment, which may now have fuel value.

The question regarding nuclear power is not about whether we should rely on it, but rather, how we should rely on it. These advancements are the answer. With new and improved technologies offering safer, more efficient, and better performing options, nuclear has the power to meet needs in a variety of industries, accelerating the path to decarbonization.

Future eBooks in this series will explore how the elements of a carbon-free energy system, including wind, solar and nuclear, can come together to solve our climate problems in North America and demonstrate a path forward for the rest of the world.

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