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ADVANCED REACTOR ECONOMICS AND MARKETS

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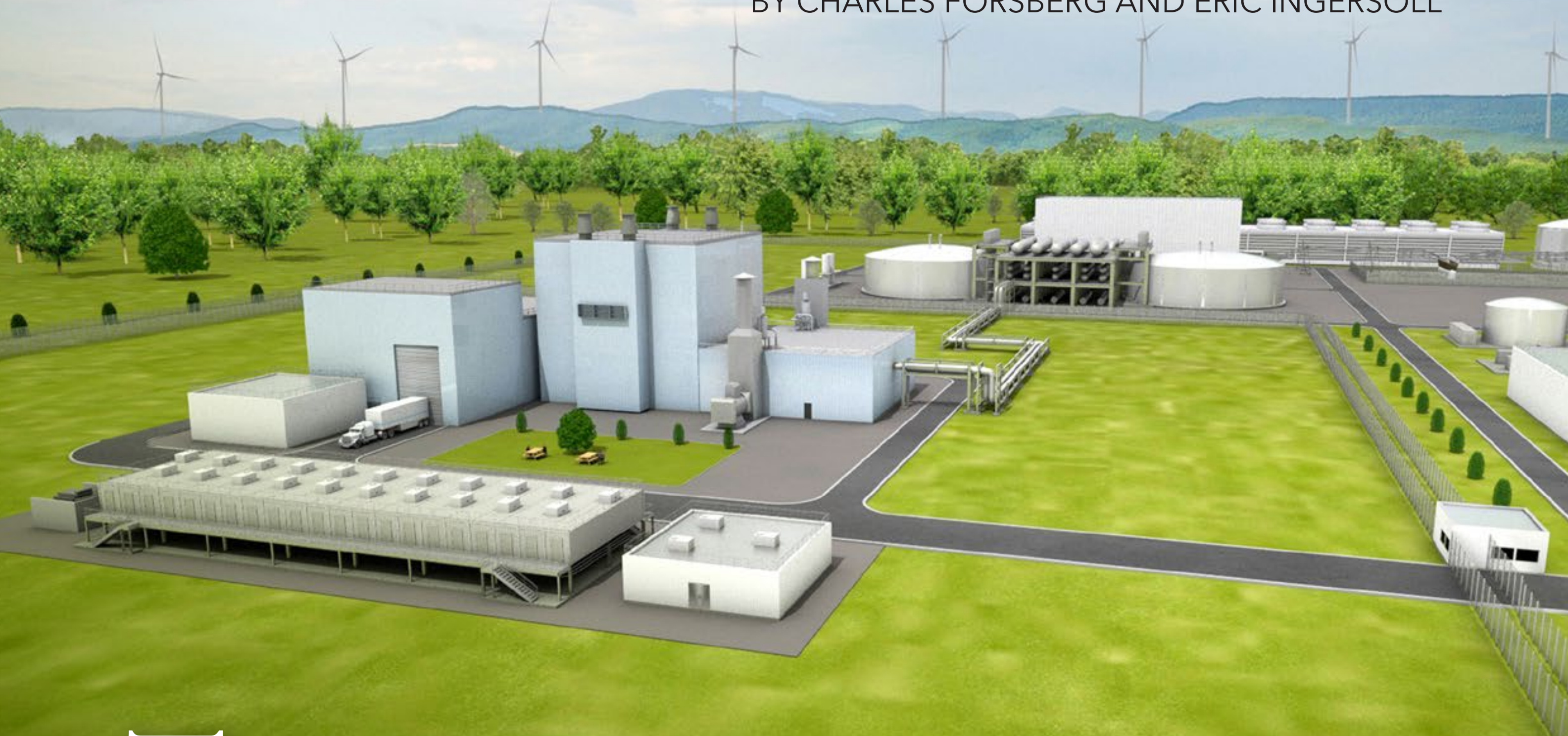

The viability of nuclear power ultimately depends on economics. Safety is a requirement, but it does not determine whether a reactor will be deployed. The most economical reactor maximizes revenue while minimizing costs. The lowest-cost reactor is not necessarily the most economical reactor. Different markets impose different requirements on reactors. If the capital cost of Reactor A is 50 percent more than Reactor B but has characteristics that double the revenue, the most economical reactor is Reactor A.

The most important factor is an efficient supply chain, including on-site construction practices. This is the basis for the low capital cost of light water reactors from China and South Korea. The design of the reactor can significantly affect capital cost through its impact on the supply chain. The question is, how can advanced reactors boost revenue and reduce costs?

MARKETS

From the customer's perspective, a nuclear reactor is a black box that provides a continuous supply of heat. What separates one reactor type from another reactor type is the temperature of the delivered heat. Table 1 shows the four classes of reactors by the temperature of delivered heat. Salt reactors include the fluoride salt–cooled high-temperature reactor (FHR), with solid fuel and clean salt; the molten salt reactor (MSR), with fuel dissolved in the salt; and proposed fusion reactors, with clean salt blankets. The most important feature of advanced reactors is that they deliver heat at higher temperatures. The question is, what is the value of higher-temperature heat?

TABLE 1. Temperatures of Delivered Heat from Different Reactors

Coolant	Inlet Temp. (°C)	Exit Temp. (°C)	Avg. Temp. (°C)
Water	270	290	280
Sodium	450	550	500
Helium	350	750	550
Salt	600	700	650

Higher-temperature heat opens up many heat markets, including industrial sectors that use large quantities of higher-temperature heat than can be provided by LWRs. The chemical industry alone requires about 100,000 MW of heat. The Next Generation Nuclear Plant program to develop high-temperature reactors was based on this market. That program was ultimately canceled because fracking dramatically reduced the cost of natural gas; the program was a victim of bad timing. However, the goal of a low-carbon economy makes nuclear energy competitive in that market if the reactor can provide high-temperature heat. There are also two newer and larger markets for high-temperature heat: variable electricity and hydrogen production.

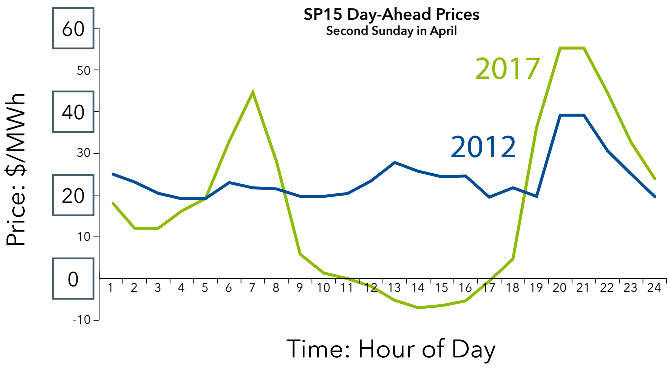

Fig. 1. Wholesale price of California electricity over a one-day period.

VARIABLE ELECTRICITY

Historically, nuclear reactors have been primarily used for baseload electricity. That is a consequence of the existence of fossil fuels. Nuclear plants have high capital costs and low operating costs, while fossil-fuel plants have low capital costs and high operating costs. Today those fossil plants are gas turbines. The different economics of nuclear and fossil resulted in baseload nuclear plants, with variable electricity from fossil-fuel plants.

The addition of non-dispatchable wind and solar provides electricity to the grid based on weather patterns, independent of the demand for electricity. The effects of wind and solar have been seen in places such as California, where wholesale electricity prices collapse at times of high solar and wind output and increase at other times. Figure 1 shows California electricity prices on a spring day in 2012 and 2017. The 2012 prices were set by fossil fuel power plants. The dramatic variations in electricity prices in 2017 were a consequence of the large-scale addition of subsidized solar. Today, gas turbines provide dispatchable electricity to meet the variable demand for electricity. The question is, what replaces the gas turbine in a low-carbon world?

Multiple developers of advanced reactors are proposing options to add heat storage to enable baseload

LEFT: TerraPower and GE Hitachi Nuclear Energy jointly developed the sodium-cooled Natrium reactor with the turbine hall, nitrate heat storage tanks, and cooling towers separated from the reactor at the back of the site.

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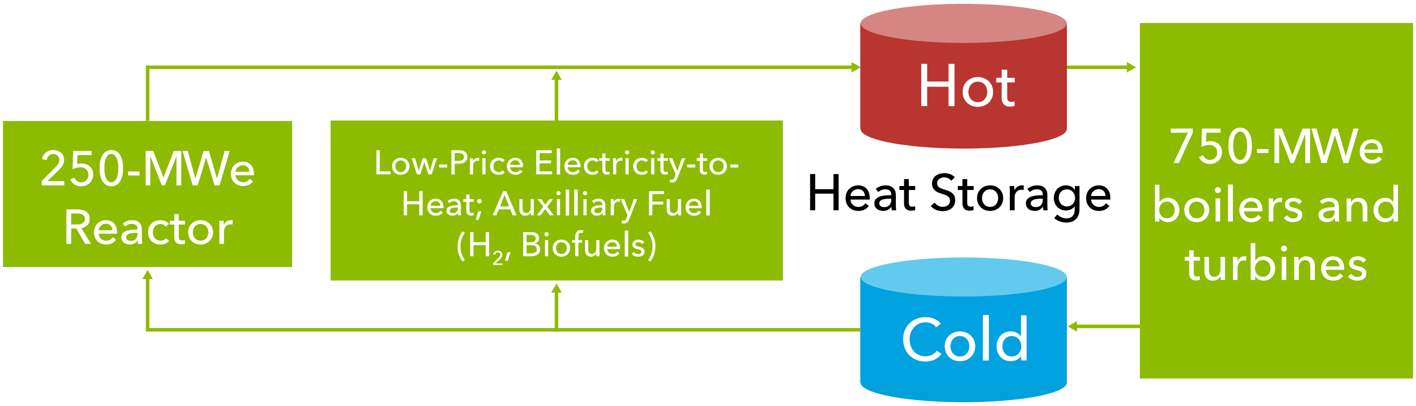

Fig. 2. Intermediate salt loop with storage between the reactor and power cycle.

reactors to provide variable electricity to the grid (Fig. 2). The reactors include the TerraPower/GE Hitachi Nuclear Energy jointly developed sodium-cooled Natrium reactor (see image on page 38), the Moltex MSR, and the Kairos Power KP-FHR. In these three cases, the heat storage material is a sodium potassium nitrate salt—the same salt used in concentrated solar power plants for heat storage. The reactor is not directly coupled to the to the power block. Instead, the reactor receives cold salt, heats the salt, and sends it to a hot-salt storage tank. The salt loop is the intermediate loop between the reactor and the power cycle. The power cycle takes hot salt and produces steam that produces electricity.

The reactor is sized to match average electricity demand. The power block, with steam boilers and turbines, is sized to match peak electricity demand. The relative size of peak power output versus the reactor depends on the local electricity market. For example, the Moltex reactor has a peak power output about three times higher than the reactor output, based on the U.K. electricity grid that has large quantities of offshore wind. The power block can change power levels much faster than a nuclear reactor because heat input into the power cycle is controlled by the hot-salt pump speed, not the rate at which the reactor can change its power output. The power cycle can be designed to respond to changing electricity demand faster than a gas turbine. The goal is to maximize revenue by selling electricity when the price is high.

In these plants with storage, there are large incentives to drive down the capital costs of the power block below those of gas turbines. The power block is built to nonnuclear standards because it is not coupled to the reactor. The power cycle is designed to minimize capital costs because the power block capacity factor may be 30 percent, while the reactor capacity factor is 90 percent.

If there is very low-price electricity, the power plant buys electricity to heat more nitrate salt. If the peak demand extends for a long period of time and heat storage becomes depleted, a low-cost furnace burning natural gas, or in the future, hydrogen or biofuels, provides added heat. A recent workshop examined this redesign of nuclear energy in detail (Forsberg, Sabharwall, and Sowder, 2020).

The near-term heat storage material for high-temperature reactors is nitrate salt stored in large hot and cold storage tanks. This heat storage system is used in concentrated solar power plants at the gigawatt-hour heat-storage scale for two reasons. First, on partly cloudy days, the power output may go up and down a dozen times as clouds pass over the solar farm. Storage provides constant heat to the power block. Second, more recently, salt storage enables solar plants to produce electricity after the sun goes down. The heat-storage capital costs are \$20–\$30/kWh of heat—an order of magnitude less than battery or pumped hydro storage.

Equally important, heat storage is more efficient than battery or pumped hydro storage. This provides an additional competitive advantage. The U.S. Energy Information Administration (EIA) reported that the average round trip electricity-to-electricity efficiency of utility battery systems is 82 percent, and pumped hydro storage is 79 percent. The round-trip efficiency for real utility electricity storage systems is significantly below the generally advertised efficiency for energy storage systems. The losses occur in the multiple energy conversion steps. In a battery, alternating current is converted to direct current that then charges the battery. The process is reversed to send electricity from the battery to the grid.

In pumped hydro storage, electricity powers a pump that moves water uphill. The water is discharged through a turbine that powers a generator to produce electricity. All those energy conversion processes have inefficiencies that lower round-trip efficiency. In an advanced high-temperature nuclear reactor, the nitrate salt is the intermediate loop that would exist in any case. Heat normally goes from the reactor to the power cycle. Adding heat storage in the intermediate loop does not involve an energy conversion step with its associated inefficiencies. There are some small heat losses, but those are less than 1 percent. The efficiency penalty of adding storage is small relative to batteries and pumped hydro storage.

Today, gas turbines are the enabling technology for large-scale wind and solar. In a low-carbon world, nuclear energy with heat storage replaces the gas turbine and thus becomes the enabling technology for wind and solar (Ingersoll et al., July 2020). The EIA has estimated the levelized cost of electricity for solar at $31.30/MWh, onshore wind at $31.45/MWh, and offshore wind at $115.04/MWh in good locations. However, wind and solar can provide electricity less than half the time, because the sun sets and there can be days with no wind. The majority of the time, electricity is provided by gas turbines.

The levelized cost of storage using batteries is $121.86/MWh—far higher than the cost of making electricity. Furthermore, batteries are good for only two to six hours and thus are unable to provide backup for multiple days of cloudy weather or a week of low-wind conditions. Large-scale wind or solar requires gas turbines or a replacement for the gas turbine, such as nuclear with heat storage.

This system with heat storage is applicable to all reactors. Lower-temperature LWRs use hot oil storage rather than nitrate salt heat storage. However, the economics favor higher-temperature reactors, given similar costs to produce heat from the reactor, for the following reasons:

- High-temperature reactors require an intermediate loop that in many cases can serve two functions—separating the reactor from the power block, and heat storage. In an LWR, the heat must be transferred to a low-pressure oil system to the heat storage system and back. There are inefficiencies associated with those heat exchangers.
- Higher temperatures allow a larger hot-cold temperature swing of the heat storage system. This reduces the size and cost of the heat storage system for any given heat storage capacity, but with efficiency tradeoffs.
- Higher temperatures allow the use of simplified superheated steam cycles that have much lower capital costs than the saturated steam cycles of LWRs. The higher-temperature steam avoids moist steam in the turbines and systems to remove moisture from the steam.

There are growing economic incentives to couple heat storage to LWRs, and that may happen. However, heat storage economics will be much better with higher-temperature reactors, everything else being equal. In a low-carbon electricity grid, this system could produce more than half of the total electricity, assuming large-scale wind and solar production at times of good wind and solar conditions.

HYDROGEN PRODUCTION

The second market is hydrogen production. Today, industry consumes about 10 million tons per year. In a low-carbon world, hydrogen production could be more than 20 percent of total energy consumed by the customer. This market has three segments. The first market segment is where hydrogen is used as a chemical reagent, and there are no substitutes if you want the final product. Today that market includes fertilizer production and converting crude oil into low-sulfur gasoline, diesel fuel, and jet fuel. In a low-carbon future, hydrogen will likely replace coke in the production of steel and will be used to upgrade biofuels into drop-in replacements for gasoline, diesel fuel, and jet fuel. A drop-in replacement fuel does not require any changes in the engine. The second market segment is to replace natural gas—particularly for smaller users where fossil fuels with carbon capture are prohibitively expensive and electric heat is about six times as expensive as natural gas. The third market segment is as a future transport fuel where there are competing options.

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The question is how to produce hydrogen. In this context, hydrogen is different from electricity. Hydrogen is cheap to store using the same underground facilities used for natural gas storage. We store up to 20 percent of a year's natural gas production to meet peak winter demand. There is no need to match hydrogen production with demand on a second-to-second or even month-to-month basis since storage provides an assured supply. Second, a single pipeline can ship tens of gigawatts versus electricity transmission lines that are limited to a few gigawatts. However, transcontinental shipment is more expensive for hydrogen than for natural gas because the volumetric energy density of hydrogen is several times smaller than that of natural gas. That drives toward a system with regional hydrogen production. Today in Texas we have such hydrogen storage facilities and pipelines that connect refineries, chemical plants, and hydrogen production facilities.

Nuclear energy is potentially competitive in this market. Hydrogen can be made by electrolysis of water or steam. High-temperature electrolysis (HTE) is the most efficient technology where nuclear plants can provide electricity and steam—an intrinsic advantage of nuclear energy to provide hydrogen versus electrolysis of liquid water. However, hydrogen plants, from the electrolysis cells to the compressors, are capital intensive. The hydrogen plant capacity factor must be high, as shown in Fig. 3, to produce cheap hydrogen. The higher efficiency of HTE and the requirement for high capacity factors provide an economic competitive advantage to coupling nuclear reactors to hydrogen production plants, compared to wind or solar with their lower capacity factors. Nuclear plants have capacity factors of about 90 percent, versus wind, near 40 percent, and solar, near 25 percent.

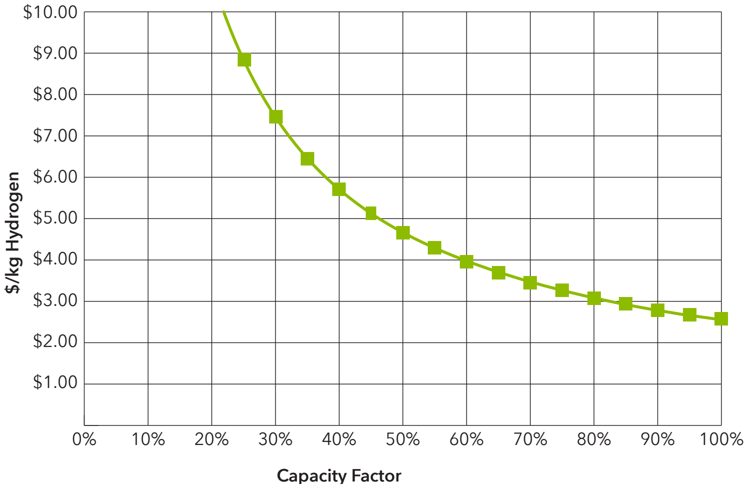

Fig. 3. Cost of hydrogen vs. capacity factor. Graph: LucidCatalyst

While such a system can use LWRs, there are major economic advantages of higher-temperature advanced reactors. The efficiency of HTE systems increases with higher-temperature steam. The higher efficiency of electricity production means that less heat must be generated per unit of hydrogen.

The primary competition for low-carbon hydrogen production is steam-methane reforming of natural gas with carbon capture and sequestration, an expensive process for fossil power plants because of the cost to separate carbon dioxide from the stack gas. However, there are some steam-methane reforming processes that produce a relatively pure carbon dioxide off-gas. If such plants are located over good sequestration sites, hydrogen from natural gas may be economical. However, the high cost of transcontinental hydrogen transport means that such hydrogen will likely be limited to locations such as Texas, where it will be a local resource like hydroelectricity.

The other unique hydrogen characteristic is that it is economically feasible to ship 20 or 30 gigawatts of hydrogen via pipeline—the same scale of energy transport as in natural gas pipelines. A large electricity transmission line can move 1 or 2 gigawatts. We have the option to build very large nuclear hydrogen production complexes on the same energy scale as oil refineries. This creates a new nuclear plant model: Site a modular nuclear reactor fabrication plant next door to a hydrogen plant. Use shipyard cranes to lift and move reactors from the fabrication plant to the hydrogen plant. If the need comes to refurbish a reactor, bring it back by crane to the fabrication plant. This scenario would change nuclear energy into a factory operation, where the site's hydrogen production capacity could grow over 20 years and the fabrication plant would produce replacement reactors.

Such mega facilities (Fig. 4) would favor advanced reactors for other reasons, some of which are described in the next section. Cooling options, such as dry cooling for the power cycle, are much cheaper if the heat rejection temperature from the power cycle is higher. A hydrogen factory with tens of gigawatts of electricity production requires large power plant cooling capability—most likely ocean cooling or dry air cooling.

Fig. 4. Rendering of a hydrogen "gigafactory." Image: LucidCatalyst

NUCLEAR PLANT COSTS

The other challenge is to lower nuclear plant capital costs (Buongiorno et al., 2018; Ingersoll et al., Sep. 2020). This is a three-part challenge. First, in the United States, most large projects of any type go over budget and behind schedule. The U.S. has lost the ability to efficiently manage large projects. In contrast, China has this capability. The reason is simple: people learn by doing. Most large construction projects in the world in the past 20 years have occurred in China; thus, China has most of the people capable of efficiently managing large construction projects.

Also, in the past 40 years, there has been no increase in U.S. construction labor productivity. There have been significant gains in productivity on the factory floor and, as usual, the never-ending spectacular gains in agricultural productivity, where corn yields have gone from 20 to 180 bushels per acre—making everyone else look like laggards. Last, the Nuclear Regulatory Commission has historically made licensing extremely expensive with long delays. This leads to several conclusions: minimize field construction, maximize factory assembly, and have simple and robust safety strategies to simplify licensing.

Advanced reactors have the potential for lower costs than LWRs because of several intrinsic characteristics. The most obvious is higher-temperature operation that results in higher efficiency of converting heat to electricity, as efficiency goes from about 35 percent for LWRs to somewhere between 40 and 50 percent for advanced reactors. Less heat is generated per unit of electricity produced. There is less reactor, turbine, generator, condenser, and cooling tower per unit of output—less on-site construction.

Second, the high LWR primary system pressure results in high-pressure safety systems, from emergency core cooling systems to the large leak-tight containment buildings capable of withstanding high condensing steam pressures in the event of an accident. The high pressures are created by the use of pressurized water as a coolant. Salt and sodium reactors operate at low pressures, and high-temperature gas-cooled reactors (HTGRs) use a safety strategy where depressurization does not require a high-pressure containment to hold in helium. Eliminating these high-pressure, field-fabricated systems significantly reduces field labor and total costs.

Third, the primary accident initiator in all reactors is decay heat. The fission reactions in the reactor can be shut down, but the decay heat can't be turned off. If the reactor core overheats, fuel is destroyed and radionuclides are released. Advanced reactors operate at higher temperatures, and thus there is a larger temperature drop between the reactor core and the environment to safely remove decay heat in an accident by all heat transfer methods, including conduction and convection. That creates options for smaller, simpler passive decay-heat removal systems. The extreme case is the HTGR, where the safety case is simple—to conduct decay heat from fuel to the environment.

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OBSERVATIONS

What we did not discuss are fuel cycles or reactor size. Fuel cycles receive a great deal of attention, but the cost of fuel is small relative to the capital cost of reactors. The cost structure provides many options to ensure long-term supplies of fissile materials. Those characteristics are not neatly defined by reactor type and technology. Advances in construction technologies, factory fabrication, streamlined regulation, and other changes apply to all reactor types.

None of the above advantages ensure the success of advanced reactors. Water-cooled reactors have the advantage of a massive experience base. China and South Korea are building large LWRs at low prices. Separate from the technology, a development team led by a driven leader often determines the choice of technology in many industries. Pressurized water reactors are the dominant reactor type today because Admiral Hyman Rickover was determined to make nuclear submarines with unlimited travel distance underwater. One suspects that without Admiral Rickover, the low-enriched uranium thermal-spectrum sodium reactor might have become the early winner, because the temperature of the heat output of the fossil fuel steam cycles of the 1950s and 1960s matched what the customer wanted. Several such reactors were built in the early years of atomic power. However, the learning curve of experience made the LWR the preferred technology.

Everyone has their favorite technology. I (Charles Forsberg) have a bias for the fluoride salt–cooled high-temperature reactor, partly because salt reactors deliver average higher-temperature heat than other reactors, and partly because the FHR is the stepping-stone to both MSRs and fusion reactors with salt blankets—but also because I am one of the three original developers of the concept. An FHR uses a clean salt coolant with solid fuel—the simplest reactor that one can build that uses high-temperature liquid salt coolants. Others can make strong arguments for other technologies. Separate from those differences, advanced reactors as a class have fundamental advantages that translate into meeting new market requirements and reducing costs. However, the advanced reactors that get built will be determined by those that are best able to execute the development and deployment of those technologies. ⌘

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