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Variable Electricity with Base-load Reactor Operations

Fluoride-salt-cooled High-temperature Reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage

In this century man will transition to a low-carbon energy future—either in first half of the century because of concerns about global climate and ocean pH (acidity) changes or in the second half of the century because of depletion of fossil resources in a world of 10 billion people. Since the caveman discovered fire, our energy policy has been to have a storable supply of a carbon fuel (wood, whale oil, coal, natural gas) that we light on fire to provide variable light and heat. The technology may have changed from the wood cooking fire to the natural-gas-fired turbine but the essentials have not—a storable carbon-based fuel coupled to a low-cost method to convert fuel to heat and light as needed.

In a low-carbon world, the energy sources are nuclear and renewables (wind and solar). The defining characteristics of these technologies are (1) high capital and low operating costs requiring full capacity operation for economic energy production and (2) output does not match the variable energy needs by man. This challenge suggests a need to develop new nuclear technologies to meet the variable energy needs for low-carbon world while improving economics.

To address the above challenge, we have been developing a Fluoride-salt-cooled High-temperature Reactor (FHR) with a Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES). The goals are to (1) improve nuclear power plant economics by 50 to 100% relative to a base-load nuclear power plant, (2) develop the enabling technology for a zero-carbon nuclear renewables electricity grid by providing dispatchable power, and (3) eliminate major fuel failures and hence eliminate the potential for major offsite radionuclide releases in a beyond design basis accident. Figure 1 shows the capabilities of a modular FHR when coupled to the electricity grid. FHR produces base-load electricity with peak electricity produced by a topping cycle using auxiliary natural gas or stored heat---or further into the future using hydrogen. The FIRES heat storage capability enables the FHR to replace energy storage technologies such as batteries and pumped storage—a storage requirement for a grid with significant non-dispatchable solar or wind generating systems.

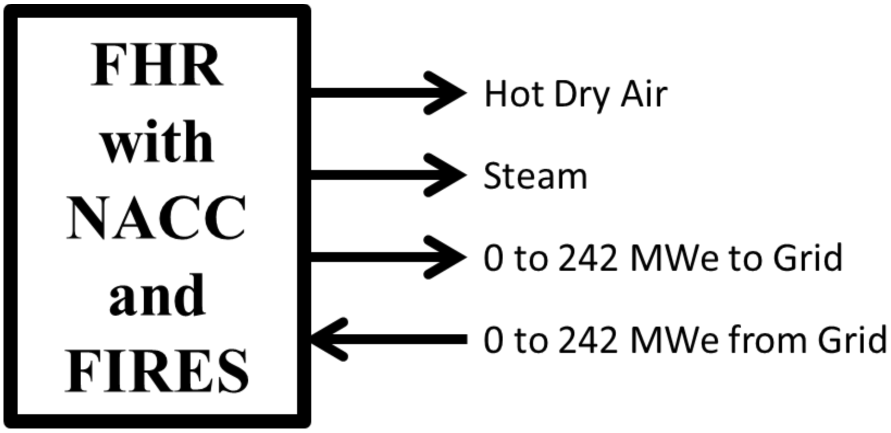

Fig. 1. Capability of Modular FHR with NACC and FIRES with Base-load FHR Operation

The concept of the FHR is about a decade old [1]. An Integrated Research Project led by the author at the Massachusetts Institute of Technology (MIT) and including the University of California at Berkeley (UCB), and the University of Wisconsin (UW) has completed a three year study (analysis and experiments) to develop the concept and develop a pathway to commercialization [2-5]. Since the FHR inception there has been growing interest at universities and national laboratories—and a decision by the Chinese Academy of Science to build a 10 MWt test reactor by 2020.

Description of FHR with NACC and FIRES

The FHR is a new class of reactors (Fig. 2) with characteristics different from light-water reactors (LWRs). The fuel is the graphite-matrix coated-particle fuel used by high-temperature gas-cooled reactors (HTGRs) resulting in similar reactor core and fuel cycle designs—except the power density is greater because liquids are better coolants than gases. The coolant is a clean fluoride salt mixture. The coolant salts were originally developed for the molten salt reactor (MSR) where the fuel is dissolved in the coolant. Current coolant-boundary materials limitations imply maximum coolant temperatures of about 700°C. New materials are being developed that may allow exit coolant temperatures of 800°C or more. The power cycle is similar to that used in natural-gas-fired plants.

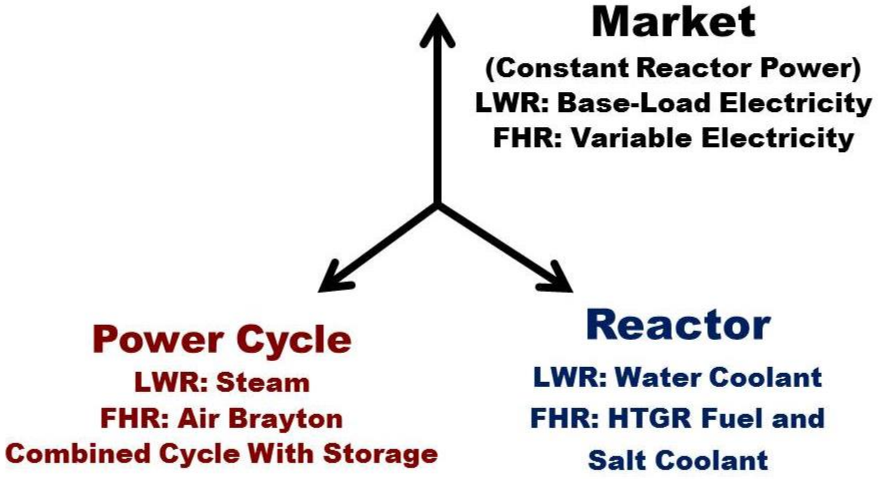

Fig. 2. Comparison of the LWR and FHR

The fluoride salt coolants were originally developed for the U.S. Aircraft Nuclear Propulsion in the late 1950s. The goal was to develop a nuclear-powered jet bomber. These fluoride salts have low nuclear cross sections with melting points of 350 to 500°C and boiling points in excess of 1200°C—properties for efficient transfer of heat from a reactor to a jet engine. Since then there have been two developments. The first development was high-temperature graphite-matrix coated-particle fuels for HTGRs that are compatible with liquid salt coolants. The second has been a half-century of improvements in utility gas turbines that now make it feasible to couple a nuclear reactor (the FHR) to NACC. The utility gas turbine combined cycle technology for a commercially viable FHR did not exist 15 years ago. Figure 3 shows a modular FHR with NACC.

It is the coupling of high-temperature nuclear reactor and gas turbine technologies that result in the transformational characteristics of an FHR with NACC and FIRES.

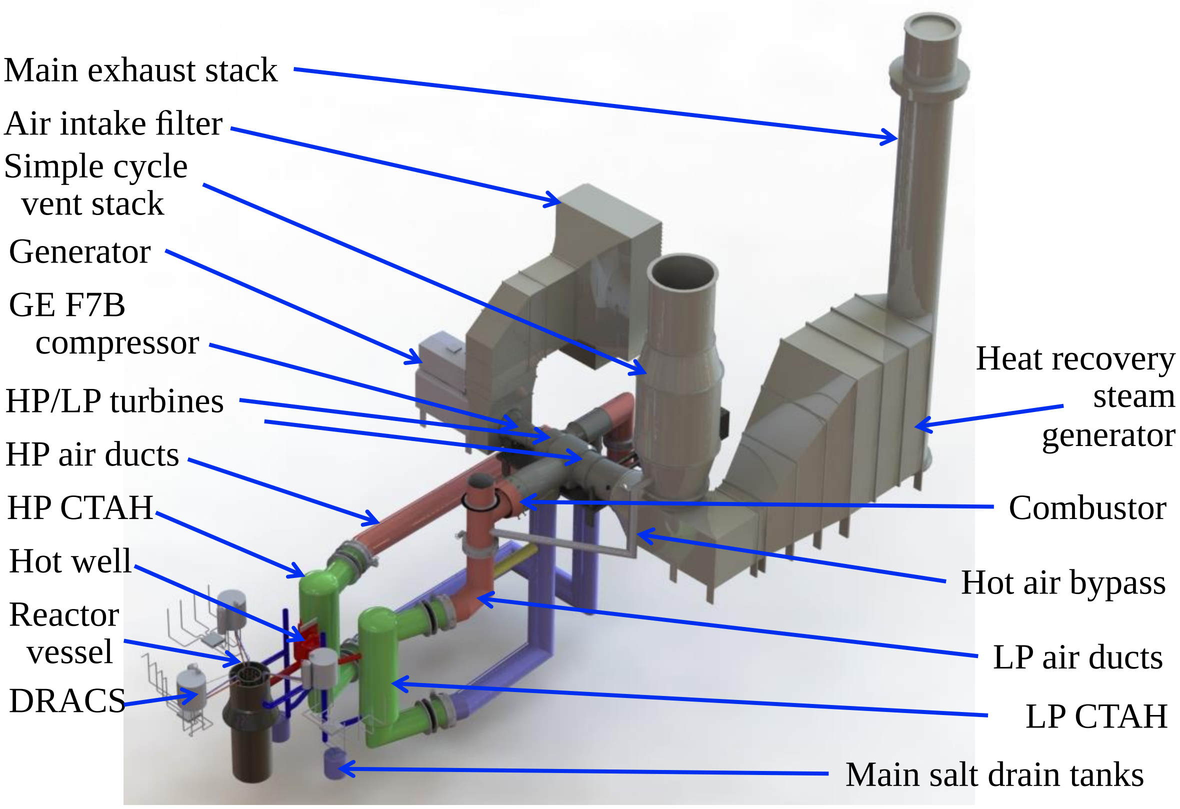

Fig. 3. Mk1 PB-FHR plant layout, showing coupling to NACC power conversion

MIT, UCB, and UW have developed a FHR path forward including a commercialization strategy [2], an FHR point design—a Mark-1 pebble-bed FHR (Mk1 PB-FHR) [3], and a test reactor strategy [4]. Figure 3 shows the Mk1 PB-FHR and its NACC power conversion system, while Table 1 lists some of the design parameters. The pebble-bed fuel is similar to that originally developed in Germany and now used in China for their HTGRs but the pebble size has been reduced to 3-cm diameter spheres to enable a higher power density. Like the HTGR pebble bed reactors, the pebbles flow through the reactor core to allow online refueling. The coolant is flibe ($^7Li_2BeF_4$), the same coolant proposed for many molten-salt reactors (MSRs) except in an FHR it is clean salt to minimize corrosion and radiation doses in coolant piping. Fixed-fuel FHR designs are also an option and several different designs have been developed with small and large power outputs.

Table 1. Mk1 PB-FHR System Design

Parameter	**Value**
Reactor Design	
Thermal power[1]	236 MWt
Core inlet temperature	600°C
Core bulk-average outlet temperature	700°C
Primary coolant mass flow rate (100%power)	976 kg/sec
Primary coolant volumetric flow rate (100% power)	0.54 m^3/sec
Power Conversion	
Gas turbine model number	GE 7FB
Nominal ambient temperature	15°C
Elevation	Sea level
Compression ratio	18.52
Compressor outlet pressure	18.58 bar
Compressor outlet temperature	418.7°C
Compressor outlet mass flow[2]	418.5 kg/sec
Coiled tube air heater outlet temperature	670°C
Base load net electrical power output	100 MWe
Base load thermal efficiency	42.5 %
Co-firing turbine inlet temperature	1065°C
Co-firing net electrical power output	241.8 MWe
Co-firing efficiency (gas-to-peak-power)	66.4 %

The Mk1 PB-FHR is coupled to an air-Brayton combined cycle—similar to natural gas combined cycle plants. This specific NACC is based on the General Electric® 7FB natural-gas-fired combined cycle plant. The NACC design based on the GE turbine determines the reactor size. Larger reactors can be built by coupling multiple NACCs to a single reactor. The GE 7FB compressor is unmodified, but the turbine is redesigned to introduce external air heating and reheat. Air is filtered, compressed, and heated by high-temperature salt using a coiled-tube air heater (CTAH). The power cycle is shown in Fig. 4. The high-pressure compressed-air exit temperature after nuclear heating is 670°C. The hot compressed air is then expanded through a turbine to lower pressure, reheated in a second CTAH to 670°C, and sent through a

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[1] Power output chosen to couple to GE-7FB gas turbine and first reactor size of commercial interest above FHR test reactor. The power plant would contain up to 12 modular reactors built in groups of four.

[2] Total flow is 440.4 kg/s; GE-7FB design uses excess for turbine blade cooling

second turbine. The warm, near atmospheric-pressure exhaust gas from the air Brayton cycle is sent to a heat recovery steam generator (HRSG) where the warm air is used to generate steam that can provide additional power via a steam Rankine bottoming cycle or be sold to offsite users.

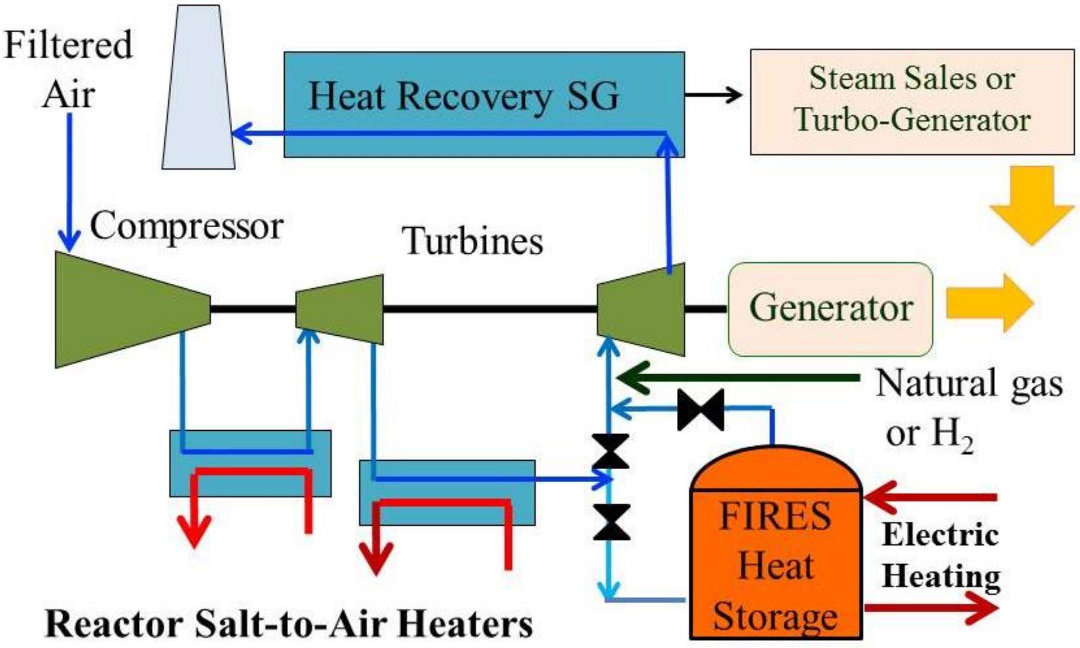

Fig. 4. Simplified Schematic of NACC and FIRES

The base-load efficiency is 42.5%. The cooling water requirements are 40% per unit of electricity compared to a light water reactor (LWR) because of the higher base-load efficiency and because all combined cycle plants reject much of their heat as warm air from the HRSG.

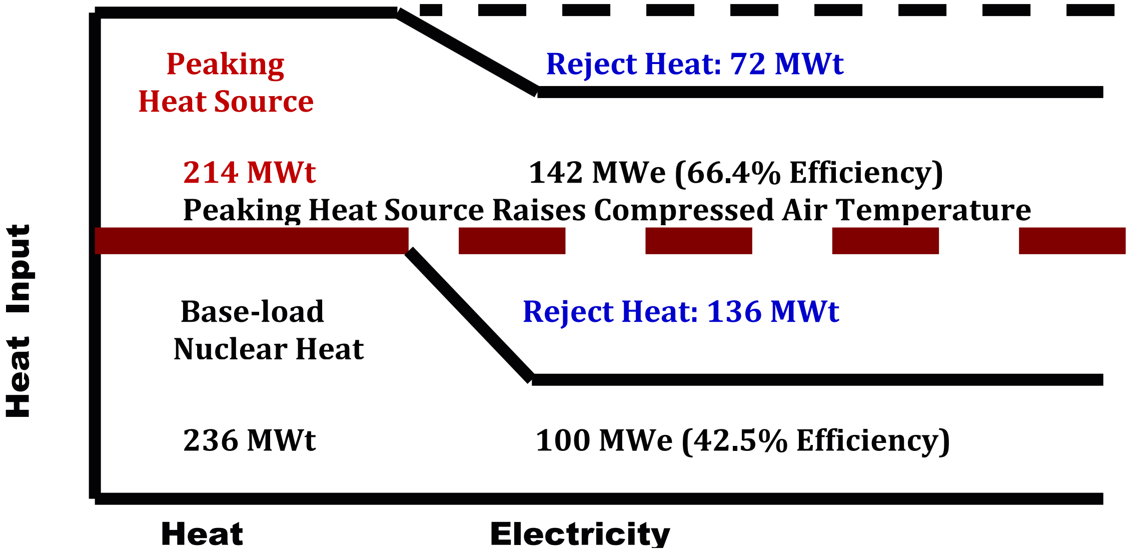

Fig. 5. Heat and Electricity Balance for NACC

The NACC enables the production of additional electricity by injecting supplemental natural gas, stored heat, biofuels, or hydrogen before the last set of turbine stages to raise the compressed air temperature. NACC operates at lower temperatures than natural gas combined cycle plants so compressed nuclear-preheated air temperatures can be raised without exceeding existing gas turbine temperature limits. Because natural gas is a peaking fuel above the "low-temperature" nuclear heat, the incremental natural gas to electricity efficiency is 66.4%--above the best stand-alone natural gas combined cycle plants with 60% efficiency. Figure 5 shows the heat balance for base-load and peak electricity production

The stored heat option involves heating firebrick inside a prestress concrete pressure vessel with electricity to high temperatures at times of low electricity prices; that is, below the price of natural gas. When peak power is needed, compressed air after nuclear heating and before entering the second turbine would be routed through the firebrick, heated to higher temperatures and sent to the second turbine. The efficiency of converting electricity to heat is 100%. The efficiency of converting auxiliary heat (natural gas or stored heat) to electricity in our current design is 66%. This implies a round trip efficiency of electricity to heat to electricity of ~66%. Improvements in gas turbines in the next decade are expected to raise that efficiency to 70%. FIRES would only be added to NACC in electricity grids where there are significant quantities of electricity at prices less than the price of natural gas. As discussed later, these conditions are expected in any power grid with significant installed wind or solar capacity.

Much of the FIRES heat storage technology is being developed by General Electric® and its partners for an adiabatic compressed air energy storage (CAES) system called Adele (German abbreviation). The first prototype storage system is expected to be operational by 2018 with 90 MWe peak power and storing 360 MWh. When the price of electricity is low the air is (1) adiabatically compressed to 70 bars with an exit temperature of 600°C, (2) cooled to 40°C by flowing the hot compressed air through firebrick in a prestress concrete pressure vessel, and (3) stored as cool compressed air in underground salt caverns. At times of high electricity prices the compressed air from the underground cavern goes through the firebrick, is reheated, and sent through a turbine to produce electricity with the air exhausted to the atmosphere. The expected round-trip storage efficiency is 70%. The Adele project is integrating firebrick heat storage into a gas turbine system. For NACC using FIRES there are differences, (1) the peak pressure would be about a third of the Adele project, (2) the firebrick is heated to higher temperatures, and (3) electricity is used to heat the firebrick at times of low electricity prices to higher temperatures. The technology for heat storage integration into NACC is partly under development.

The plant can operate in multiple modes while the reactor remains at full power.

- *Base-load electricity (nuclear).* The reactor runs at full power. No supplemental fuel is injected. The Brayton and Rankine (HRSG) cycles produce electricity for sale.
- *Peak electricity (nuclear plus auxiliary heat).* The reactor runs at full power. Supplemental natural gas is injected after nuclear heating of air to maximize electricity production. The natural gas provides an extra 142 MWe for every 100 MWe of base-load electricity.
- *Electricity and steam (nuclear).* The Brayton cycle produces electricity for sale, and the HRSG steam is directed to the industrial steam distribution system for process heat sales.

There are differences between steam sales to industrial customers using NACC compared to steam sales from other reactors. Because heat from the reactor is transferred to the HRSG via an air stream, there is no concern about contamination of the steam and thus no steam isolation heat exchanger—a requirement for LWRs selling process steam. That implies no expensive steam isolation heat exchanger for offsite sales of steam or the associated temperature losses. There is almost no cost for the capability to sell steam to industrial customers. There are two types of industrial steam sales.

- *Variable sales*. Many industrial facilities have their own steam boilers and would turn them down if they could buy steam that cost less than the fuel costs for producing their own steam. This creates the option to sell steam at times of low electricity prices to boost reactor revenue while selling steam at prices below the cost of steam generated by industrial facilities using natural gas.

- *Base-load sales*. There is the classical cogeneration strategy of selling electricity and steam. The historical limitation for using nuclear reactors to provide steam to industrial users was the need for backup sources of steam if the reactor was shut down for any reason. With NACC there is the option to add natural gas burners with fresh air to assure hot air for continued operation of the HRSG if the reactor and gas turbine shut down. This is a feature found in some existing natural-gas-fired and waste-gas-fired combined-cycle plants used to provide electricity and steam in refineries and chemical plants. If the turbine has problems, steam generation continues.

The FHR with NACC can be used to provide spinning reserve and other grid services. Stand-alone natural-gas-fired combined cycle plants operating at part load have the ability to rapidly increase their power level if required to meet the demands of the electrical grid. However, part load operation implies inefficient use of natural gas. The alternative is a cold start but it takes considerable time to start up a gas turbine and connect it to the grid. With an operating base-load FHR plant, these problems are avoided because the peaking power is on top of an operating base-load nuclear plant. The power maneuvering capabilities are also enhanced because unlike a natural-gas-fired turbine, there is no need to control the air to fuel ratio to assure combustion—the hot gas is above natural gas auto-ignition temperatures

It is the properties of fluoride salt coolants that enable coupling to a NACC. In modern gas turbines the front-end compressor heats the air to between 400 and 500°C. The temperatures of LWRs and sodium-cooled reactors are too low to couple to NACC. Current designs of HTRGs can't couple to NACC because the return helium gas temperature is typically 350°C to enable cooling of the steel reactor pressure vessel, a temperature below the outlet temperature of air from the compressor. In contrast, the temperature range of the FHR couples to a gas turbine—a direct consequence of these coolants being explicitly developed to couple a nuclear reactor to a jet engine. If the economics favor larger FHRs, multiple turbines would be coupled to a single reactor—similar to some LWRs that have multiple steam turbines. The FHR is a new class of reactors where the market defines the power cycle and the power cycle defines the requirements for the reactor.

Economics

The economics of a reactor depend upon the costs versus the revenue. Traditional nuclear power plants are designed for base-load operation where there is no capability to increase revenue by increasing electricity production at times of high prices. The FHR with NACC and FIRES enables base-load operation of the reactor with variable electricity to the grid—a capability that increases revenue relative to a traditional nuclear power plant.

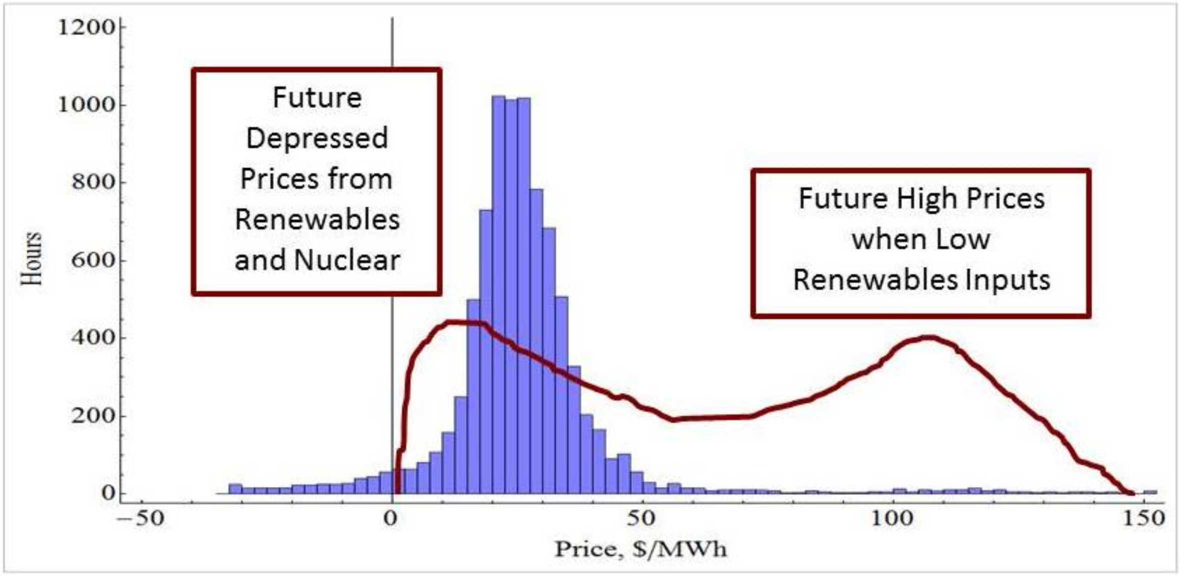

Fig. 6. Distribution of Electrical Prices (bar chart), by Duration, Averaged Over CAISO (California) Hubs (July 2011-June 2012) and Notational Price Curve (Red Line) for Future Low-Carbon Grid.

In deregulated markets the price of electricity varies with time. Figure 6 (blue bars) shows the 2012 California electricity prices in terms of price of electricity versus the number of hours per year electricity could have been bought at that price. The price of electricity goes from negative prices to high prices. Negative prices occur at times of low demand. Nuclear and coal plants remain on line at times of negative prices and pay the grid to take their electricity to avoid shutting down and thus unable to produce electricity at times of high demand and high prices that may occur a few hours later. FHR revenue can be maximized by increased production of electricity at times of high prices and minimizing electricity sales at times of low prices.

To provide an estimate of the economic benefits of the FHR, we examined the FHR with NACC but without FIRES. To estimate FHR revenue we used the 2012 hourly wholesale prices of electricity on the Texas and California grid and average 2012 natural gas prices ($ 3.52/million BTU). With this price date we calculated for each hour of the year the revenue for (1) base-load electricity and (2) peak electricity using nuclear heat and auxiliary natural gas. For each hour of the year we chose to operate the plant in the mode that provides the most revenue for that hour and totaled the revenue for the year. This was the net revenue after subtracting for the cost of the natural gas. Auxiliary natural gas was not used when the cost of the gas exceeded the additional revenue from peak power operations. It is assumed that the nuclear reactor operates at full capacity. At times of high electricity prices the plant used natural gas to maximize electricity production and thus revenue. At times of very low or negative prices, only base-load electricity is produced. Table 2 shows the relative revenue compared to base-load electricity production.

Table 2. 2012 Net Revenue for Mk1 NACC plant in Texas or California: M$/y (%)

Allowed Operating Modes	Texas	California
Base-load Electricity (Nuclear)	21.9 (100)	26.6 (100)
Base-load and Peak Electricity (Nuclear plus Natural Gas)	31.2 (142)	44.4 (167)

The results show dramatic increases in plant revenue for plants with multiple operating modes versus operating the reactor only to produce base-load electricity. For example, if the Mk1 plant operated in two modes (base-load and peak electricity with auxiliary natural gas), the plant revenue after subtracting natural gas costs in California in 2012 would have been 167% of a base-load nuclear plant. There is the option to reduce power levels or vent hot air from NACC when electricity prices are negative to reduce loses at these times. If there are industrial customers for steam, HRSG steam can be sold when the revenue from steam sales would be greater than from electricity sales. If one assumes at such times steam is sold at 90% of the cost of natural gas, FHR revenue would be about double a base-load nuclear plant.

Because NACC is more efficient in converting natural gas to electricity than a stand-alone natural gas plant, it has the lowest operating costs in terms of converting natural gas to electricity. Consequently it is dispatched in peak power mode before any stand-alone natural gas plant comes on line. In California that implies operating 77% of the time with auxiliary natural gas. In Texas it implies operating 80% of the time with auxiliary natural gas. After dispatch of an FHR with NACC producing peak electricity, the next power plants that would be dispatched as electricity demand grows would be the combined cycle plants with 60% efficiency in converting natural gas to electricity. Those plants would then determine the market price of electricity. As the electricity demand further increases, simple air-Brayton natural gas plants would come on line at 40% efficiency and set the prices of electricity. In a free market the FHR and the gas plants are paid the same for their electricity and pay the same for the natural gas. The higher efficiency implies more net revenue (revenue minus cost of natural gas) for the FHR. At natural gas prices similar to Japan and Europe (3 times U.S. prices), net revenue would be double a base-load plant.

The other half of the economics is the reactor costs. Several groups have estimated FHR capital costs to be less than those of LWRs based on higher efficiency, a low pressure system and the characteristics of the salt as a heat transfer fluid. However, no FHR has been built and there has been no regulatory review. At this time a reasonable conclusion is that the costs will be similar to other types of nuclear plants.

The free market price distribution for electricity has major implications for a low-carbon grid with nuclear and renewables. The addition of a small amount of solar is beneficial because the electricity is added at times of peak demand. However, as additional solar is added, it drives down the price of electricity during the mid-day at times of high solar input. Each owner of a solar power system will sell electricity at whatever price exists above zero. This implies that when somewhere between 10 to 15% of the total yearly electricity demand is met by solar in California, the output from solar systems during midday for parts of the year starting in June will exceed demand, the price of electricity will collapse to near zero, and the revenue to power plants at those times will collapse to near zero. Each incremental addition of solar will lower the revenue for existing solar and other electricity producers at times of good solar conditions. The same effect occurs as one adds wind capacity but wind input is more random.

Recent studies [6, 7] have estimated this effect in the European market. If wind grows from providing 0% to 30% of all electricity, the average yearly price for wind energy in the market would drop from 73 €/MWe (first wind farm) to 18€/MWe (30% of all electricity generated). There would be 1000 hours per year when wind would provide the total electricity demand, the price of electricity would be near zero, and 28% of all wind energy would be sold in the market for prices near zero. The revenue collapse at times of high wind conditions implies greater subsidies are required to add wind capacity as wind capacity increases.

Shown in Figure 6 in red is a notational price curve if one adds significant non-dispatchable renewables. It is the collapse of electricity prices and revenue at times of high wind or solar input that limits the use of renewables. This occurs by the time solar provides 10% of the total electricity to the grid, wind provides 20% of the total electricity to the grid and nuclear provides 70% of the electricity to the grid. Base-load electricity is about 70% of the total demand for electricity.

The addition of renewables has other implications. It implies substantially higher electricity prices at times of low solar or wind input. Backup electricity generating plants will not be built that operate a limited number of hours per year unless there is a significant increase in electricity prices during those times. In a free market, the addition of renewables may result in locking in added fossil fuel plants because they are the most economic choice to provide backup power because of their low capital costs. This is happening in Germany. State of California [8] and Google [9] studies came to similar conclusions.

The FHR with NACC and FIRES addresses this challenge by buying electricity when the price is low and providing electricity at times of high prices. The FHR with FIRES raises the electricity price when prices are depressed by large solar or wind generation by creating added demand and lowers the electricity price when there is little solar or wind generation. The characteristics of the FHR with NACC and FIRES make it potentially the economic enabling technology for (1) the larger-scale use of nuclear and renewables and (2) a zero-carbon electricity grid.

Future Zero-Carbon Grids

The world will transition to a low carbon grid in this century. The FHR with NACC and FIRES can be used to produce variable zero-carbon electricity using hydrogen, biofuels or stored high-temperature heat. Hydrogen made from electrolysis or biofuels can substitute for natural gas. Alternatively, high-temperature stored heat may be used for peak electricity production using FIRES is fundamentally different than batteries or pumped storage.

First, with traditional storage systems (pumped storage, batteries, etc.) the electricity charging rate is close to the discharge rate. FIRES uses low-capital-cost resistance heating to enable fast charging rates to buy large quantities of low-priced electricity when available—such as for two or three hours in the middle of the day in a grid with large PV output. Low-priced electricity is whenever the price of electricity is less than the price of whatever combustable fuel is used for peak electricity production.

Second, an FHR with NACC and FIRES addresses the capacity challenge. Storage (MWh) by itself does not enable use of renewables. One also needs electricity generating capacity (MW) because conventional storage systems will become fully discharged if there are multiple days of low solar or wind conditions. Heat storage embedded in NACC provides storage with backup generating capacity using natural gas, biofuels or ultimately hydrogen.

Third, the FHR with NACC and FIRES addresses the seasonal storage challenge. There are seasonal variations in electricity demand. The two zero-carbon seasonal storage media are hydrogen and heat. Hydrogen can be made via electrolysis, stored in underground reservoirs like natural gas and burned to produce electricity. Seasonal heat storage is possible using techniques such as nuclear geothermal heat storage. The challenges are (1) the round trip efficiency is less than 50% implying expensive energy and (2) high capital costs. The FHR with NACC and FIRES addresses this several ways.

- *Heat.* Heat storage for the daily variation in demand is met by FIRES. Heat storage is more efficient than hydrogen storage—66% today with a pathway to 70% round-trip efficiency. Heat storage times are limited by the cost of the FIRES pressure vessel. It is not cost effective for seasonal storage.

- *Reactor Operations*. Reactor downtime for maintenance is chosen to minimize seasonal storage challenges. This is an option because nuclear power is dispatchable—one choses when to do maintenance to reduce seasonal storage challenges in a zero-carbon grid.

- *Hydrogen*. Hydrogen storage is used for seasonal demand (beyond daily demand) when required. On a large scale NACC is the most efficient method to convert a combustible fuel into electricity because the combustible fuel is a topping cycle above a “low-temperature” 700°C FHR bottoming cycle—a major economic advantage when burning a premium fuel.

- *Storage requirements*. Seasonal energy storage requirements depend upon where one is located. The total amount of required seasonal stored energy in the mid-latitudes (United States) in a zero-carbon electricity grid is substantially less for a system containing significant nuclear energy than for systems dominated by wind or solar [10]. There are several reasons for this.

    - Nuclear. About 70% of energy demand is base-load, a demand that matches traditional nuclear power and reduces seasonal energy storage requirements in a zero-carbon world.
    - Solar. Solar input peaks in June and is a minimum in January. Seasonal storage requirements with solar sharply increase with latitude due to low winter solar input.
    - Wind. In the U.S., economic wind is Great Plains wind. Cold weather implies low wind velocities. In the U.S., peak output is in the spring but this is location dependent.

Figure 7 shows the capabilities of a fleet of FHRs that meet base-load demand to meet peak demand. This is while the reactor operates at full capacity to make efficient use of the capital intensive assets.

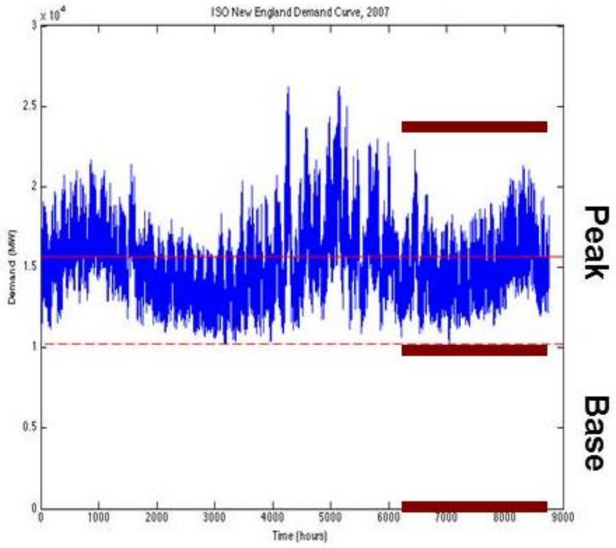

Fig. 7. New England Power Demand and FHR Capabilities to Meet that Demand

Conclusions

No new reactor will be developed unless there is a compelling case for its development—near term and long term. For the LWR, that compelling case was the need for a nuclear submarine that could stay underwater for months. The technology was transferable to commercial power plants because submarines and utility fossil plants used steam power cycles. For the FHR that compelling case is based on: (1) increased net revenue relative to nuclear power plants that sell electricity at constant output to the grid (economics) and (2) the enabling technology for a zero-carbon nuclear renewable grid by providing the variable electricity on demand including storage to replace traditional fossil power plants (environmental). In the near-term the fuel for that peaking capability would be natural gas or stored heat in markets where electricity prices go below the price of natural gas. In the long-term the peaking fuel could also include hydrogen and biofuels.

When the LWR was being developed, the nation had regulated utilities and the competition was from fossil fuels where costs were dominated by fuel operating costs. Evaluating nuclear plant economics using levelized cost of electricity was the appropriate model because nuclear power plants were to replace base-load fossil power plants in electricity production. Today we have deregulated markets and increased renewables that are leading to increased daily swings in electricity prices. Future electricity prices are projected to drop significantly at times of good solar or wind conditions (revenue collapse) and increase significantly when there are low solar and wind conditions [11]. Changes in the electricity markets require that nuclear economics be evaluated on net revenue—revenue minus costs. Market changes create large economic incentives for a different type of nuclear power—a nuclear power system such as the FHR with NACC and FIRES designed to provide variable power to the electricity grid.

The FHR with NACC and FIRES is an enabling technology for large-scale use of renewables because of the capability (Fig. 1) to buy electricity at times of low prices and sell electricity at times of high prices. Without that capability, any non dispatchable energy source used on a large scale faces revenue collapse during times of high wind or solar output. Unlike traditional storage systems (batteries, etc.), no backup gas-turbine generating capacity is required.

Last, the technical viability of an FHR with NACC is a consequence of advances in natural-gas-fired combined cycle plants and HTGR coated-particle fuel. Neither of these technologies was sufficiently advanced 15 years ago for this reactor concept to have been viable.

The case for the FHR with NACC and FIRES is not dependent upon the specific details of the FHR design except for the requirement of exit salt temperatures near 700°C or higher and a cold salt temperature above 550°C to enable efficient coupling to NACC. Given the massive ongoing R&D on gas turbines, the power systems will be further improved by the time an FHR can be deployed.

Because no FHR has been built, there are significant uncertainties. The next major step is building a test reactor to demonstrate viability. The earliest commercialization date is estimated to be ~2030 based on the history of development of other reactors.

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