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Nuclear Energy Drop-In Replacements for Gas Turbines, Natural Gas and Fossil Liquid Fuels

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Abstract—We describe a roadmap, based on a series of workshops and studies, to use base-load nuclear reactors to replace fossil fuels in a low-carbon world that integrates nuclear, wind, solar, hydro-electricity and biomass energy sources. Nuclear reactors with large-scale heat storage enable variable electricity to the grid with nuclear plants that both buy and sell electricity. The low-cost heat storage and assured generating capacity enables efficient use of large-scale wind and solar. Nuclear hydrogen production facilities at the scale of global oil refineries produce hydrogen to replace natural gas as a heat source. Nuclear heat and hydrogen convert plant biomass into drop-in biofuels to replace gasoline, diesel, jet fuel and hydrocarbon feed stocks for the chemical industry. The external heat and hydrogen greatly increases the quantities of biofuels that can be produced per unit of feedstock. The system can produce variable quantities of biofuels and sequestered carbon dioxide that enables negative carbon dioxide emissions and increases revenue if there is a market for removing carbon dioxide from the atmosphere.

Keywords— Gas turbine, heat storage, biofuels, hydrogen, nuclear energy

I. Introduction

Fossil fuels are remarkable: (1) low cost, (2) easy to store and (3) easy to transport at low costs. They enabled billions of people to move from poverty to the middle class. None of the replacements for fossil fuels comes close to their remarkable capabilities. Each alternative to fossil fuels has its own significant limitations. We describe herein three coupled nuclear-energy-based systems that together integrate low-carbon energy sources to provide the equivalent energy services currently provided by fossil fuels. Table 1 shows these low-carbon energy options and their technical characteristics.

TABLE I. CHARACTERISTICS OF LOW-CARBON ENERGY SOURCES

Energy Source	**Output**	**Time Domain**	**Comments**
Nuclear (Including Fusion)	Heat	Steady State	Can Build Anywhere
Hydroelectricity	Electricity	Variable	Location Dependent
Biomass	Carbon Source Heat	Seasonal	Dual Characteristics; Carbon Feedstock and Energy Source
Wind	Electricity	Non-Dispatchable	Location Dependent
Solar PV	Electricity	Non-Dispatchable	Location Dependent

The essential requirement in a low-carbon world is to replace fossil fuels at minimum costs. Because fossil fuels are easy to store and transport costs are low, the world's energy system is relatively homogeneous. There are a few exceptions such as locations with large quantities of hydroelectricity. In a low-carbon world nuclear reactors can potentially be built almost anywhere; but, the other energy sources are local with costs per unit of energy output that vary widely by location. The replacement system will vary with location and must be designed with large variations in relative inputs of different energy sources. We describe three systems that use baseload nuclear reactors to replace three key fossil-fuel technologies and integrate the different low-carbon energy sources (Table 1) into an efficient low-cost low-carbon system.

- *Gas turbine for electricity production*. Gas turbines are the primary technology used to produce dispatchable electricity in the United States. They are the enabling technology for the large-scale use of wind and solar by providing dispatchable electricity on an hourly to seasonal basis to match production with electricity demand. The gas turbine is replaced with nuclear reactors with large-scale heat storage (to 100 GWh) to provide dispatchable electricity to the grid with the capability to buy excess low-price electricity from wind and solar facilities when available.

- *Natural gas*. The primary role of natural gas is providing heat. Natural gas can be cheaply stored in underground facilities thereby enabling variable delivery to customers via pipeline. The natural gas is replaced by hydrogen produced in nuclear hydrogen gigafactories enabled by the transport capacities of large-scale pipelines.

- *Liquid fossil fuels*. Liquid fossil fuels are the enabling technology for transportation and for purposes such as home heating with highly variable seasonal demand. The nuclear energy options are drop-in biofuels where nuclear heat and hydrogen inputs at the bio-refinery more than double the liquid fuel yield per ton of biomass feedstocks. The large-scale addition of heat and hydrogen enables biofuels at scale to replace liquid fossil fuels.

II. VARIABLE ELECTRICITY—REPLACING GAS TURBINES

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

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 large variations in electricity prices in 2017 were a consequence of the large-scale addition of subsidized solar. Simultaneously there is increasing curtailment of wind and solar to the grid at times when excess production that exceeds electricity demand.

The high cost of storage makes it uneconomic to store excess electricity from wind and solar at the scale it is produced. Revenue collapse limits the scale of wind and solar deployment. Today gas turbines burning natural gas provide dispatchable electricity to assure meeting the variable demand for electricity. The question is what replaces the gas turbine in a low-carbon world?

Fig. 1. Wholesale Price of California Electricity over a Period of One Day

Multiple developers of advanced nuclear reactors are proposing to add heat storage to enable base-load reactors to provide variable electricity to the grid (Fig. 2). A recent workshop examined this option [1]. For higher-temperature reactors the heat storage material is a sodium potassium nitrate salt—the same solar salt used in Concentrated Solar Power (CSP) plants for heat storage. The reactor is not directly coupled to the power block. Instead the reactor receives cold salt, heats the salt and sends the salt 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. For lower-temperature light water reactor (LWRs), there are parallel technologies that use oil to transfer heat. Recent studies [2] have evaluated the value of storage for nuclear reactor systems in different parts of the United States

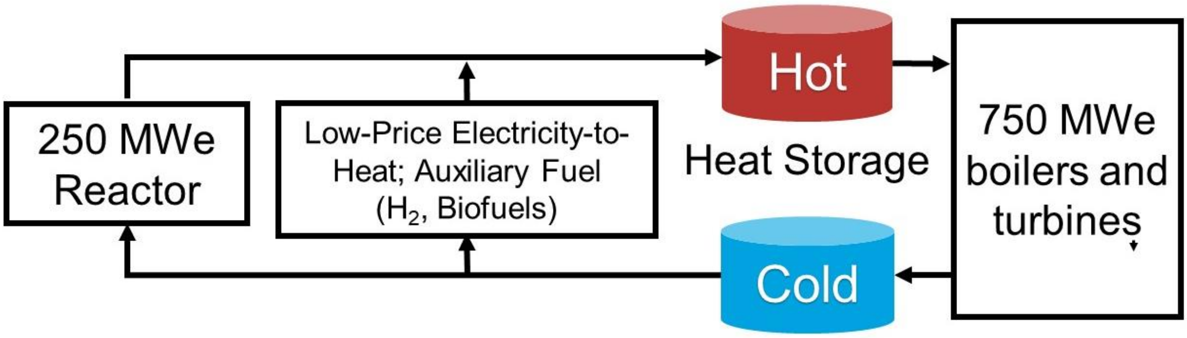

Fig. 2. Intermediate Salt Loop between the Reactor and Power Cycle

The reactor is sized to match average electricity demand. The power block with steam boilers and turbines is sized to match peak electricity demand. In Figure 2 the peak power output as an example is shown as three times the power output of the reactor. 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. The rate of power change is not controlled by the reactor. The power cycle can be designed to respond to changing electricity demand faster than a gas turbine can respond. The goal is to maximize revenue by selling electricity when the price is high.

The power block capacity may be several times larger than the nuclear block and is built to non-nuclear 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% while the reactor capacity factor is 90%.

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 can provide the additional necessary heat. Nuclear energy with heat storage becomes the enabling technology for the larger-scale use of wind and solar because of low-cost heat storage which (1) raises the minimum price of electricity at times of high wind or solar output (2) enables use of larger wind and solar inputs.

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 CSP 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 enable solar plants to produce electricity after the sun sets. The heat-storage capital costs are $20-30/kWh of heat—an order of magnitude less than battery or pumped hydro storage. Advanced heat storage systems are being developed that may lower costs to a few dollars per kWh of heat [3].

Equally important, heat storage is more efficient than battery or pumped hydro storage for many nuclear heat storage systems. The U.S. Energy Information Administration [4] reported that the average round trip electricity-to-electricity efficiency of utility battery systems is 82% and for hydro pumped storage is 79%. The low round-trip efficiency is because of the multiple conversion steps in the storage process—such as in a battery from alternating current to direct current to chemical energy and back. In a 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 energy conversion steps with associated inefficiencies. There are some small heat losses from the reactor through storage to the power block but those are less than 1%. The efficiency penalty of adding storage is small relative to batteries and pumped hydro storage.

The efficiency of buying electricity, converting it to stored heat and converting the heat back to electricity is much lower. Converting electricity to heat is near 100% efficient but converting heat to electricity for these salt systems is between 40 and 50%. However, the incremental capital cost of the electric resistance heaters is very low—everything else in this thermal battery (storage tanks, power conversion block, connection to the transmission grid, etc.) already exists. The system has two storage systems that use most of the same equipment: (1) the highly-efficient reactor heat to heat storage to power block and (2) the less efficient but very-low-incremental-cost electricity to heat storage to power block system.

In a low-carbon world nuclear energy with heat storage replaces the gas turbine and thus becomes the enabling technology for large-scale wind and solar. The U.S. Energy Information Agency [4-5] has estimated the levelized cost of electricity for solar ($31.30/MWh), on-shore wind ($31.45/MWh) and offshore wind ($115.04/MWh) in good locations. However wind and solar can provide electricity less than half the time because the sun sets and there are days with no wind; thus, most electricity in such systems is provided by gas turbines. The cost and performance limits of existing electricity storage systems are large. The levelized cost of storage batteries [4-5] is $121.86/MWh—far higher than the cost of making electricity. Furthermore, batteries are only good for two to six hours and thus unable to provide electricity for multi-days of cloudy weather or a week of low wind conditions. Batteries can reduce the number of hours per year the gas turbines operate but do not eliminate the need for gas turbine generating capacity. Batteries are primarily used for grid services, delay building of transmission lines and to address short duration electricity peaks. Large-scale wind and solar imposes large system costs [6-8] onto the grid in terms of resource adequacy (assured generating capacity), energy adequacy and reliability. The economic viability of large-scale wind and solar is tightly coupled to finding an economic replacement for the gas turbine. Nuclear reactors with large-scale heat storage and assured peaking capacity may be the required enabling technology for a low-carbon system that use large scale wind and solar resources.

III. HYDROGEN PRODUCTION—REPLACING NATURAL GAS

The second market is hydrogen production as a replacement for natural gas for non-electricity markets. This market includes about 4000 industrial users in the U.S. with heat demands above one megawatt [9]. The question is how to economically produce hydrogen. In this context, hydrogen is very different from electricity. First, hydrogen is inexpensive to store using the same underground facilities used for natural gas storage. We store up to 20% of a year's supply of natural gas to meet peak winter demand. There is no need to match hydrogen production on a second-to-second or even month-to-month basis with demand since storage provides assured supply.

Second, a single hydrogen pipeline can ship tens of gigawatts versus electricity transmission lines that are limited to one or two gigawatts. However, transcontinental shipment of hydrogen is more expensive than natural gas because the volumetric energy density of hydrogen is several times smaller than natural gas. That fact 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 [10-12] where nuclear plants can provide electricity and steam—an intrinsic advantage of nuclear energy to produce hydrogen versus electrolysis of liquid water using electricity generating technologies such as wind and solar photovoltaic. However, hydrogen plants from the power supplies to electrolysis cells are capital intensive. The hydrogen plant capacity factor must be high as shown in Fig. 3 to produce cheap hydrogen [13]. The higher efficiency of HTE and the requirement for high capacity factors provides 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% versus wind near 41% and solar near 30%.

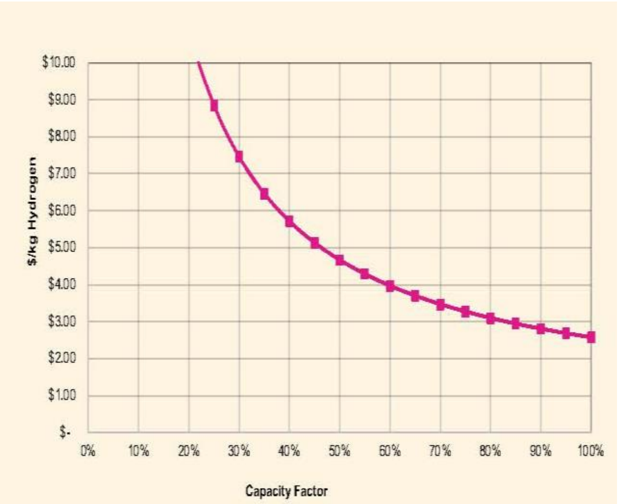

Figure 3. Illustrative Cost of Hydrogen Vs Capacity Factor (Courtesy of LucidCatalyst)

The hydrogen cost versus capacity curve enables peak electricity production during the 5 to 10% of the year with the highest electricity prices. This is because the cost versus capacity curve is relatively flat between 80 and 90% capacity. The economic penalty incurred by lower hydrogen plant capacity factors is relatively small if electricity is diverted to the grid for a limited number of hours per year. This feature can help meet the occasional peak summer or winter electricity loads.

Because of the large capacity of pipelines, we have the option to build very large nuclear hydrogen production complexes on the same energy scale as oil refineries. This possibility creates a new nuclear plant production model (See Fig. 4.). First build a modular nuclear reactor fabrication plant that produces reactors to be sited next to the factory with the hydrogen plant. Second with shipyard cranes that can lift several thousand tons, move reactors from factory to nuclear plant site by crane. Third, if the reactor needs refurbishing, transport it back into the factory. Overall this approach changes nuclear energy into a factory operation where the site hydrogen production capacity grows over 10 years and thereafter the factory produces replacement reactors. Factory fabrication [14] can dramatically lower the cost of nuclear power plants—in addition to improved economics of operation of multiple reactors at a single site and economics of scale for the hydrogen production plant.

Figure 4. Hydrogen Gigafactory with Factory in Back, Reactor Field in the Middle and Hydrogen Plant in the Front (Courtesy of LucidCatalyst)

IV. NUCLEAR DROP-IN BIOFUELS—REPLACING LIQUID FOSSIL FUELS

Recent studies [15] have examined the potential of a nuclear bio-refinery system to produce sufficient gasoline, diesel, jet fuel and other hydrocarbons for chemical plant feedstocks to replace all liquid fossil fuels and hydrocarbon chemical feedstocks. Lignocellulosic biomass has long been used as an energy source but it is also a source of renewable carbon that can be converted into hydrocarbon fuels. Because plants capture carbon dioxide from the air, the burning of biomass does not increase atmospheric carbon dioxide levels. About 100 billion tons of biomass, roughly containing 50% carbon on a mass basis, are created by photosynthesis each year [16]

Many studies of the energy potential of biomass indicate biofuels could supply about a quarter of global energy demand in a low-carbon world. However, if biomass is considered first as carbon source for hydrocarbon production and secondarily as an energy source, the potential of biofuels is much larger. Biomass has a typical composition near $CH_{1.44}O_{0.66}$. If one wants to convert biomass into a hydrocarbon fuel with a composition near CH_2, the oxygen must be removed and replaced with hydrogen. If a bio-refinery uses the biomass as a feedstock and also as an energy source to operate the bio-refinery, the oxygen is essentially removed as carbon dioxide. This approach also consumes some of the carbon in the feedstock. Alternatively, one can add hydrogen so that the oxygen leaves the bio-refinery as water. Equally important, all of the carbon is converted into a hydrocarbon fuel. If external heat and hydrogen from a nuclear plant are provided in the bio-refinery, rather than using biomass as feedstock and energy source for the bio-refinery, the energy content of the biomass-derived hydrocarbon fuels can be more than twice the energy content of the original biomass.

Initial studies indicate there are sufficient biomass feedstocks to replace liquid fossil fuels without major impacts on food or fiber prices. The use of external heat and hydrogen at the bio-refinery has two impacts on biomass feedstock availability. First, much larger quantities of liquid fuels are produced per unit of biomass input [17] because all carbon is converted into hydrocarbon fuels. Nuclear energy provides a significant fraction of the energy value of the biofuel. Second, there are biomass feedstocks that are poor energy sources but excellent carbon sources for a bio-refinery with external heat and hydrogen inputs. Historically surveys of biomass availability have been conducted to determine the energy content of available biomass, not the carbon content.

Another relevant factor is the remarkable productivity of American agriculture. For example, corn yields have gone from 20 to 180 bushels per acre in the past century [18]. We have never asked what the full capability of agriculture would be if there was a large market for biomass feedstocks. For example, studies have identified multiple routes to increase biomass production such as double cropping [19] that would increase biomass feedstocks by hundreds of millions of tons per year. Extensive double-cropping is not practiced today because of the lack of a market for such large quantities of biomass.

Overall system economics require very large bio-refineries (equivalent to 250,000 barrel/day oil refineries). The base-line process for conversion of biomass into hydrocarbon fuels is the Fischer-Tropsch process—the same process used to convert coal and natural gas to liquid fuels. There are very large economics of scale associated with these processes. The Sasol coal-to-liquids plant in South Africa produces 150,000 barrels per day of liquid fuels. The newer Shell natural gas-to-liquids plant in Qatar produces 260,000 barrels per day of liquid fuels. There are several other processes to convert biomass into hydrocarbon fuels [20]—all with large economics of scale. These processes produce a hydrocarbon feedstock that is the replacement for crude oil. The downstream refinery processes [21] yield gasoline, diesel and jet fuel. Typical world-class crude-oil refineries process 500.000 barrels of crude oil per day. The refinery component of the bio-refinery must be large to provide the required infrastructure and technical capabilities to produce the entire product slate.

The daily biomass feedstock requirements for a large bio-refinery are much larger than can be economically shipped directly from farms and forests. Harvested biomass has a low density and is uneconomic to ship long distances. Large bio-refineries require: (1) conversion of locally-produced biomass in intermediate processing facilities called "depots" into energy-dense storable intermediates that can be economically shipped from these depots to the large bio-refineries and (2) low carbon, concentrated energy inputs at the bio-refinery that are only available from nuclear power (or fossil fuels with carbon capture and sequestration) [22]. Large oil refineries have heat inputs measured in gigawatts. Large bio-refineries will have even larger heat inputs—partly due to the water content of the biomass feedstocks. A simplified system schematic is shown in Fig. 5. There are many variants (barge rather than unit rail, alternative product slates, etc.)

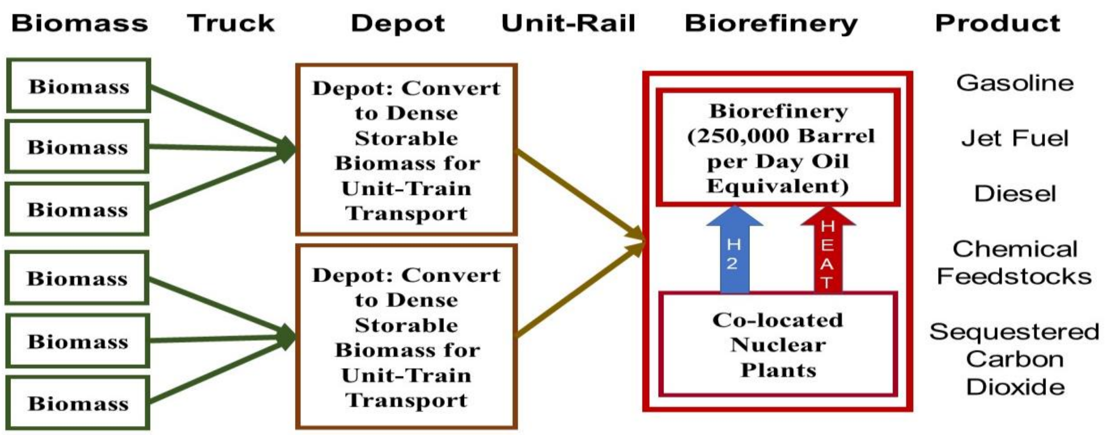

Fig. 5. Nuclear Biofuels System Design

Large-scale bio-refineries using processes such as Fischer Tropsch can produce variable quantities of hydrocarbon fuel and pure carbon dioxide for sequestration, depending upon the markets. Carbon capture and sequestration from a conventional fossil power plant is expensive because of the cost of removing dilute carbon dioxide from the stack gas—sequestration in appropriate locations is relatively inexpensive [23]. In contrast, the process chemistry of a bio-refinery provides cheap ways to produce a relatively pure carbon dioxide stream. If there is a carbon tax that provides payment for removing carbon dioxide from the air, this system allows for producing carbon dioxide as a product for sequestration—that is, negative carbon dioxide emissions.

The practical implication is that the bio-refinery can vary production of gasoline, diesel, jet fuel, hydrocarbon chemical plant feedstocks and sequestered carbon dioxide based on (1) current prices for liquid fuels that vary seasonally and (2) cost and availability of biomass feedstocks. This variable product slate with time has the potential to substantially improve economics by (1) full utilization of the bio-refinery at all times and (2) maximizing revenue. Carbon dioxide sequestration, with large-scale negative carbon emissions, becomes the swing product that enables high nuclear bio-refinery capacity factors and assured liquid fuels production if biomass feedstock availability is reduced in some years. This approach has potentially massive implications on the practicality of negative greenhouse gas emissions because of its potential for low cost and large-scale deployment relative to other options.

V. CONCLUSIONS

The challenge in the transition away from fossil fuels is developing an affordable system to replace fossil fuels. It is a systems challenge—not one that will be solved by a single technology. The different energy generating technologies are not interchangeable—each has different strengths and weaknesses and produce different products (electricity, heat and biomass). The important technical characteristic of nuclear energy is that it is a heat source that provides a constant output. The important economic characteristic is that it has high capital cost and low operating cost; thus, there are large incentives to operate nuclear plants near maximum base-load capacity. The choice of the reactors type is a second-level consideration.

Three large-scale nuclear systems integrated with wind, solar and biomass can replace fossil fuels. The first nuclear system couples nuclear reactors to large-scale heat storage to provide variable electricity and heat while providing the energy storage function for the electricity grid. Low-cost heat storage is the integrating technology between nuclear and the electricity-generating non-dispatchable wind and solar energy sources that enables larger-scale use of wind and solar where economic. Nuclear energy is used for hydrogen generation where base-load heat and electricity input enables high hydrogen plant capacity factors that minimizes the cost of hydrogen. The hydrogen production system can provide peak electricity for several hundred hours per year without significant impacts on hydrogen production. Nuclear energy inputs in the form of heat and hydrogen enable liquid biofuels to replace fossil liquid fuels by enabling full use of biomass as a carbon feedstock rather than an energy source. This maximizes the value of biomass. The nuclear bio-refinery also enables removal of carbon dioxide from the atmosphere for sequestration. The variable coproduction of gasoline, diesel, jet fuel, chemical plant feedstocks and sequestered carbon dioxide to match markets can significantly improve system economics

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