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Base-Load Nuclear Systems for Variable Electricity and Hydrogen with Heat Storage

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Abstract— Fossil fuels are the primary energy source because of their (1) low cost, (2) ease of storage, (3) low-cost transport and (4) economic dispatchability. Because the capital cost of power plants, furnaces, and boilers is small relative to the cost of the fuel, it is economic to meet variable energy demand by operating fossil plants at part load. Nuclear, wind, solar and hydrogen production plants have high capital cost; thus, operating these facilities at half capacity can almost double energy costs. A low-carbon system is defined that enables high-capital-cost low-operating-cost technologies to operate at high capacity while providing variable heat, hydrogen and electricity to the customer. This minimizes total costs. In the U.S., over 80% of all energy used is in the form of heat; thus, heat production and storage is central to a low-carbon economy. Nuclear power is the primary low-carbon low-cost heat producing technology.

Keywords—Nuclear, heat storage, hydrogen, biofuels.

I. INTRODUCTION

The creation of the modern world and the high standard of living for billions of people was made possible by fossil fuels that enabled the industrial revolution. Fossil fuels are inexpensive, easy to store, inexpensive to transport and dispatchable. Concerns about climate change require reducing carbon dioxide emissions to the atmosphere. The question is how to replace fossil fuels. There are two major coupled constraints to a low-carbon economy: (1) what the customer needs and (2) how can one economically meet customer demands.

Most energy is consumed in the form of heat [1, 2]—what the burning of fossil fuels provide. The heat demand across all U.S. energy sectors far exceeds electricity use—83 percent versus 17 percent. The heat input into the industrial sector alone is about twice total U.S. electricity production. The other customer requirement is that energy must be delivered when needed. Fig. 1 shows the smoothed electricity demand in California over one year (where smoothing averages the higher-frequency daily and weekly variations). This demand is easily met with fossil systems (furnaces, boilers, power plants) that operate economically at part load. However it does not match output of wind, solar, or nuclear systems. Fig. 1 shows the smoothed production of wind and solar if total yearly electricity production matches total demand and smoothed production of nuclear if total yearly electricity production matches total demand. There is no combination of low-carbon production sources that matches electricity demand as required on an hour to hour basis.

The second constraint is economics. Historically energy has varied from 6 to 13% of the GNP [3]—primarily depending upon the price of oil and natural gas. Today it is near 6% because of the fracking revolution that drove down the prices of natural gas and oil. Major increases in the cost of energy imply major reductions in national and global standards of living.

Going to a low-carbon system changes the economics. The capital cost of fossil systems are low (electricity plants, boilers, furnaces) relative to the cost of fuel; thus, it is economic to operate energy conversion systems at part load to meet variable energy demand. In contrast the capital costs of nuclear, wind and solar are high while the operating costs are low. If these facilities are operated at half their potential output, energy costs almost double. This creates the economic requirement for low-cost storage to enable matching energy production with demand; that is, replace the function of fossil fuel storage (coal piles, oil tanks, underground systems for natural gas). Instead of the simple system of fossil fuel to fossil plant, we require an interconnected system of energy production facilities and storage facilities to meet energy requirements. We first describe some of the constraints of a low-carbon system, then the proposed low-carbon system and last three important subsystems (biofuels, hydrogen and heat storage).

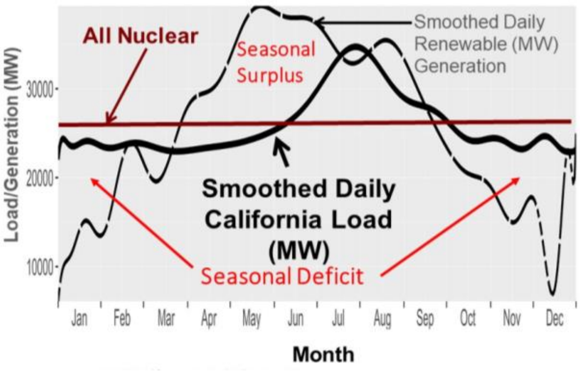

Fig. 1. Smoothed California electricity demand and renewable generation with total annual renewable generation equal to total annual electric demand. Courtesy of S. Brick, California Case Study, Clean Air Task Force.

II. HEAT AND WORK (ELECTRICITY)

Thermodynamics, the science of energy, divides energy into two categories: heat and work. Nuclear reactors, Concentrated Solar Power (CSP) plants, fossil-fuel plants, geothermal facilities and future fusion machines produce heat. Solar photovoltaic (PV), wind and hydro convert one form of work into another form of work. Wind converts momentum of air into mechanical energy that is converted to electricity. PV converts light photons into electricity. Hydroelectric facilities convert the energy of falling water into mechanical energy and then electricity.

The Carnot cycle (thermodynamics) tells us it takes several units of heat to produce a unit of work; that is, electricity. As a consequence, nuclear energy and other thermal generators produce low-cost heat and more expensive electricity. Electricity can be converted into heat using resistance heaters with one unit of electricity producing one unit of heat. Wind and PV under the right circumstances produce cheap electricity but expensive heat. More efficient electricity-to-heat technologies such as electrically driven heat pumps have proven viable only near room temperature.

In the United States, the cost of electricity [3] is about six times the cost of heat (natural gas). Most electricity is produced from fossil fuels that produce heat. Because it takes several units of heat to produce a unit of electricity (Carnot cycle), electricity is several times more expensive than heat. The second factor that makes electricity more expensive than heat is the cost of delivery. The delivery system is about half the cost of electricity to the customer. The high delivery cost is partly because there is no cheap way to store electricity on an hourly to seasonal basis. To use an example, if a house is heated with heating oil, the delivery truck fills up the oil tank with variable oil to the furnace depending upon heating demand. If the same house is heated with electricity, the electric wires to the house must be sized for the peak electricity demand on the coldest night of the year. Most of the electricity grid and distribution system is operating at a small fraction of its capacity most of the time.

About 17% of energy demand is met by electricity; thus decarbonization of the economy by brute-force electrification implies increasing the electric sector by more than 500%. With advance technologies and improved efficiency, one might only triple the electricity demand. Electricity is six times more expensive than heat. That implies that a strategy to decarbonize the economy by electrification could increase the energy fraction of the GNP from 6% to somewhere between 20 to 30% of the GNP—implying a massive decrease in the standard of living. Economics, partly driven by the thermodynamics of heat and work, implies that heat generation and delivery is central to a low-carbon economy.

III. SYSTEM DESIGN

Fossil fuel characteristics (inexpensive, easy to store, cheap to transport and low-cost dispatchability) result in simple energy systems. Because of low transport costs, the cost of coal, oil or liquefied natural gas is about the same in New York City as Shanghai. We live in a world of flat energy costs with similar energy technologies used everywhere. No low-carbon energy source has all of these capabilities in a single package; thus, a system is required with multiple components to economically provide the same four functional capabilities. Figure 2 shows a system design to accomplish these tasks at minimum costs.

Primary energy sources are shown in double boxes: nuclear, PV/Wind, combustion heaters, and biomass. Nuclear reactors produce heat. From a systems perspective fossil fuels with carbon capture and sequestration (CCS), CSP, and future fusion systems serve the same function in this system. Nuclear can be built almost anywhere and provides dispatchable heat. Fossil fuels with CCS are limited to locations with good carbon-dioxide sequestration sites. CSP is limited to locations with good solar conditions with output dependent upon solar conditions. The output of PV and wind is dependent upon location with time varying wind and solar input. Biofuels are primarily associated with meeting transport fuel demand and discussed separately. Combustible fuels refer to stored fuels (hydrogen, biofuels, etc.). There are four storage technologies (Fig. 2) that replace the storability of fossil fuels: electricity (batteries and pumped hydro), heat, biofuels and hydrogen—including its derivative forms such as ammonia.

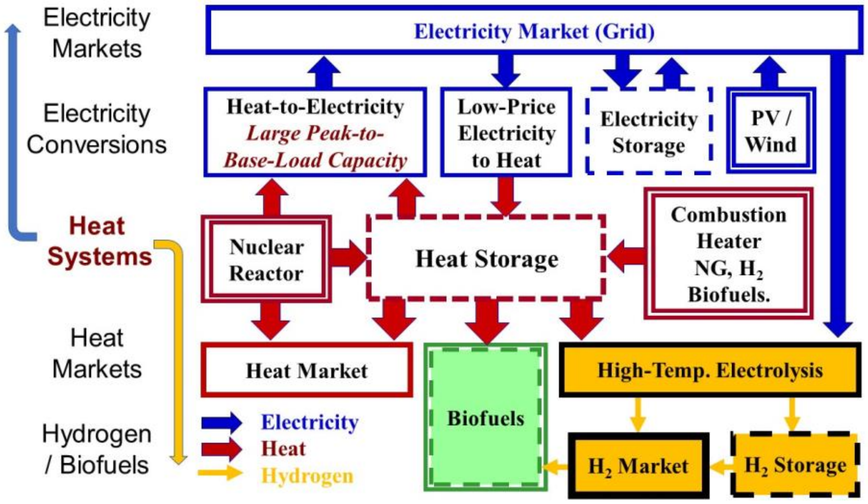

Fig. 2. Systems Energy Design

The system design allows high-capital-cost low-operating-cost nuclear, wind, solar and hydrogen production facilities to operate at near full capacity. The storage technologies (electricity, heat, hydrogen and biofuels) match production with variable heat and electricity demand. The costs of storing heat, hydrogen and biofuels are low and thus can address hourly to seasonal variations in energy demand.

The horizontal middle boxes (red) are heat technologies. The nuclear reactor or other heat generating technology operates at full capacity with heat going upward for electricity production, horizontally to heat storage (hourly to seasonal) and downward to provide heat to industry and other heat users. The nuclear reactor and heat storage can provide variable heat for conversion to electricity on demand. If heat storage is fully depleted, heat can be provided by a low-cost furnace or boiler fueled by low-carbon hydrogen or biofuels.

The electricity conversion boxes (blue) that couple to the electricity grid include systems for (1) conversion of heat-to-electricity, (2) conversion of electricity-to-heat, (3) electricity storage and (4) wind/solar electricity production. If there is excess low-price electricity from wind and solar, it can be converted to stored heat using electric resistance heaters. Electricity storage is defined by electricity input and output from the storage system—such as hydro pumped storage and batteries. Last are the electricity production technologies that convert one form of work into another form of work: wind that converts momentum of wind into electricity and PV that converts light into electricity.

There are multiple heat markets starting with the traditional industrial markets. There are also two future markets that could each consume more that 10% of all energy in a low-carbon market—hydrogen production and conversion of biomass into liquid fuels. These heat consumers produce potential transport fuels and fuels for the residential and commercial sectors as discussed below.

Nuclear cogeneration of electricity and heat to industry with heat storage directly links the industrial heat market to electricity markets. Coupling the industrial sector with the electricity sector via storage adds a new dimension to balancing electricity production with demand. Unlike traditional cogeneration where one must match production with demand on a second-by-second basis, the requirement is to match production with demand over a period of several days. Many industrial processes have the capability to vary their heat input over a period of hours or days but not over short periods of time to provide variable electricity to the grid. Storage enables industrial systems to optimize heat consumption in a way that maximizes electricity and product revenue, in parallel with decarbonization of the industry and electricity sectors.

IV. STORAGE

A low-carbon world requires replacement of the storage functions of fossil fuels. A typical nuclear plant has about 9 months “storage” in the nuclear fuel. In the U.S. the underground storage capacity for natural gas is somewhat less than 90 days with most of that capacity filled before the winter heating peak. Oil and coal storage varies between 45 and 60 days. In a low-carbon world one loses the energy storage associated with fossil fuels. There is no energy storage associated with solar and wind.

A. Biomass

Potentially the most important low-carbon energy storage system is associated with biofuels coupled to hybrid (gasoline + battery) vehicles and secondarily to building heating. Biofuels provide assured transportation enabling recharging of batteries when electricity prices are low. In contrast, all-electric vehicles are the nightmare scenario for the electricity grid because much of the recharging occurs at times of high power demand [4].

Globally biomass could meet a quarter of future energy demands [5]. It is a low-carbon energy source because plants remove carbon dioxide from the atmosphere to produce biomass. However, biomass is also a source of carbon; that is, biomass can be converted into high-quality liquid fuels—gasoline, diesel and jet fuel. With external sources of heat and hydrogen, the energy content of liquid biofuels can be almost double that of biomass [6]. In contrast, processes that convert biomass to ethanol lose at least a third of the energy value and a third of the carbon as carbon dioxide. If biomass is used as a carbon source and secondarily as an energy source, it has the potential to meet most or all of the future demand for liquid fuels. This is partly because of continued improvements [7] in engines and the use of electricity in transportation (electric cars and plug-in electric vehicles) are expected to decrease liquid fuels demand over the next several decades in the U.S. However, the requirement for massive liquid biofuels production is for massive heat and/or hydrogen input to biorefineries—where the heat and hydrogen input could exceed 10% of total U.S. and global energy demand.

Recent assessments [8] have evaluated the potential of biofuels to meet U.S. liquid fuel demand. The U.S. annual transportation energy consumption is 29 EJ. This amounts to 0.6 billion tons of petroleum per year. The estimated U.S. harvestable biomass is a billion tons [9] with an energy value of 21 EJ. The carbon content of the petroleum is about 0.5 billion tons per year while the carbon content of the biomass is about 0.4 billion tons per year. We have a low-carbon pathway for the entire transport sector that uses drop-in liquid biofuels to meet transport and other needs for liquid fuels.

B. Hydrogen

Hydrogen can be stored in the same geological structures used for natural gas. Storing a million cubic meters of hydrogen is cheap, easy and safe—storing a couple of kilograms for a hydrogen fueled vehicle is a major challenge. Storing a 90 day hydrogen supply is viable.

The U.S. hydrogen market could reach 18 percent of energy consumption by 2050 [10]. In the United States today, about 10 million tons of hydrogen are used each year—primarily for fertilizer production and oil refining. In a low-carbon economy, hydrogen would be the chemical reducing agent to replace carbon in the production of steel and other metals. It may also be used as a transport fuel and to provide high-temperature heat for industrial applications.

There are two classes of low-carbon hydrogen production options: reforming and water splitting. Steam methane reforming (SMR) of fossil fuels is the predominate method of hydrogen production today. It can be a low-carbon hydrogen production method if coupled with CCS and would be the low-cost low-carbon hydrogen production method where there are low-cost fossil fuels and good sequestration sites—such as Texas. Water splitting includes low-temperature electrolysis of water using electricity, high-temperature electrolysis (HTE) of steam, or thermochemical hydrogen production from water with heat input. These processes are less technically mature than SMR. The HTE process is not fully commercial but has potentially major economic advantages because part of the energy input is in the form of steam that costs less than electricity, no expensive catalyst is required, and the process is more efficient in converting water to hydrogen and oxygen. Hydrogen production facilities are capital intensive with large economies of scale. They may need to operate more than 80 percent of the time [11] to be economically viable.

In the proposed system (Fig. 2), at times of low electricity prices, electricity from the grid can be used for HTE while lower-value heat from the nuclear plant is directed to storage and the HTE unit. At times of high electricity prices, heat from the reactor and heat storage produce peak electricity with no hydrogen production. The nuclear plant may produce hydrogen 80% of the time to minimize hydrogen production costs (Fig. 3) and peak electricity 20% of the time. This enables the nuclear plant to operate at full capacity and as a peaking unit to meet daily to seasonal high electricity demands (Fig. 1).

C. Heat

Electricity storage is expensive while heat storage is cheap. The U.S. Department of Energy goal for electricity storage is $150/kWhe with the electronics more than doubling that. The U.S. Department of Energy goal for heat storage is $15/kWh of heat. Some advanced heat storage systems may reduce those storage costs to below $4/kWh of heat. Recent workshops [12-14] have explored the various heat storage options. The large difference in cost reflects the choice of materials. Heat storage systems use rock, salt, concrete and other very low-cost materials whereas batteries use expensive materials and hydro-pumped storage requires the right geography. This cost difference reflects the fundamental differences between heat and work.

In a separate category of storage is nuclear geothermal heat storage. With this option heat in the form of hot water is injected underground to heat rock and create a geothermal heat source [15]. Heat is recovered using geothermal power plant technology. This technology enables seasonal heat storage at a scale of gigawatt-years of heat. However, its viability depends upon the local geology.

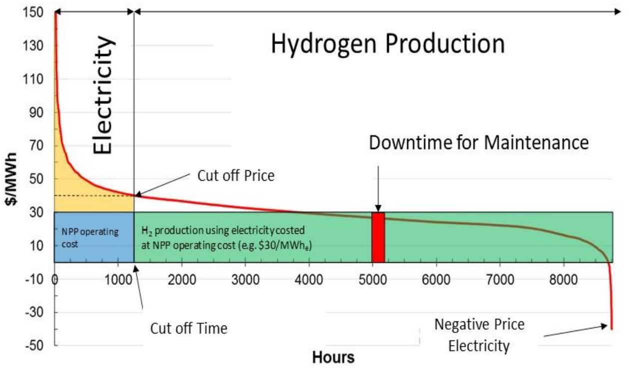

Fig. 3. Hydrogen electricity production strategy

V. CONCLUSIONS

Fossil fuels provide an economic source of energy. The capital costs of systems that convert fossil fuels to electricity and heat (furnaces, boilers, etc.) are low relative to the cost of fossil fuels; thus, it is economic to provide variable heat and electricity to the customer. The cost of storing and transporting fossil fuels is small. In a low-carbon world the requirement is for a coupled energy system with multiple subsystems that can provide the four characteristics of fossil fuels. The proposed system to accomplish this has two major features. High-capital-cost low-operating-cost energy technologies (nuclear, wind, PV, hydrogen) operate at near full capacity to minimize energy production costs. Lower-cost energy storage technologies enable matching energy production with variable demand for work (electricity) and heat.

Common to both systems is the difference between work (electricity) and heat that makes electricity an expensive commodity and implies that the central challenge to decarbonize the world is heat production. There are differences between the two systems. Fossil fuels created a global flat-world of energy costs because the storability and transportability of fossil fuels results in the price of coal, oil and liquefied natural gas to be about the same in New York harbor as Shanghai. There are large geographical differences in the costs and availability of some (1) energy sources (wind and solar PV) and (2) storage systems (sequestration sites for carbon dioxide, geothermal heat storage and geological hydrogen storage). The shift to a low-carbon system implies significant variations in energy costs with location and movement of industry to locations with nuclear heat or fossil fuels with CCS.

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