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# Nuclear-Renewable Hybrid System Economic Basis for Electricity, Fuel, and Hydrogen

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*Concerns about climate change and altering the ocean chemistry are likely to limit the use of fossil fuels. That implies a transition to a low-carbon nuclear-renewable electricity grid. Historically variable electricity demand was met using fossil plants with low capital costs, high operating costs, and substantial greenhouse gas emissions. However, the most easily scalable very-low-emissions generating options, nuclear and non-dispatchable renewables (solar and wind), are capital-intensive technologies with low operating costs that should operate at full capacities to minimize costs. No combination of fully-utilized nuclear and renewables can meet the variable electricity demand. This implies large quantities of expensive excess generating capacity much of the time. In a free market this results in near-zero electricity prices at times of high nuclear renewables output and low electricity demand with electricity revenue collapse. Capital deployment efficiency—the economic benefit derived from energy systems capital investment at a societal level—strongly favors high utilization of these capital-intensive systems, especially if low-carbon nuclear renewables are to replace fossil fuels.*

*Hybrid energy systems are one option for better utilization of these systems that consumes excess energy at times of low prices to make some useful product.The economic basis for development of hybrid energy systems is described for a low-carbon nuclear renewable world where much of the time there are massivequantities of excess energy available from the electric sector.Examples include (1) high-temperature electrolysis to generate hydrogen for non-fossil liquid fuels, direct use as a transport fuel, metal reduction, etc. and (2) biorefineries.Nuclear energy with its concentrated constant heat output may become the enabling technology for economically-viable low-carbon electricity grids because hybrid nuclear systems may provide an economic way to produce dispatachable variable electricity with economic base-load operation of the reactor.*

## I. INTRODUCTION

A central challenge for electricity generation is matching production with demand because electricity can't be stored. Historically variable electricity demand has been met by low-capital-cost high-operating-cost fossil plants. Concerns about climate and ocean pH (acidity) change are likely to restrict the use of fossil fuels for electricity generation within decades. If this does not happen, by the end of the century fossil fuel depletion will begin to force mankind off fossil fuels.

The non-fossil electricity generating technologies (dispatchable nuclear and non-dispatchable wind and solar) have high capital costs and low operating costs. *Consequently, the question for the future electricity grid is how to economically produce variable electricity on demand with capital-intensive electric generating assets.* We describe the technical and economic characteristics of the grid followed by how hybrid energy systems can help create a system that can produce economic variable electricity.

## II. ELECTRICITY GENERATION IN A LOW-CARBON WORLD

### *II.A.Grid Technical Characteristics*

Electricity demand varies by the hour, week, and season as shown in Fig. 1 for New England. There are large peaks in the summer due to air conditioning. The 5-day workweek with the weekend is evident by the weekday peaks with lower demand on weekends. Imposed on these longer duration demand variations is the daily swing in electricity demand.

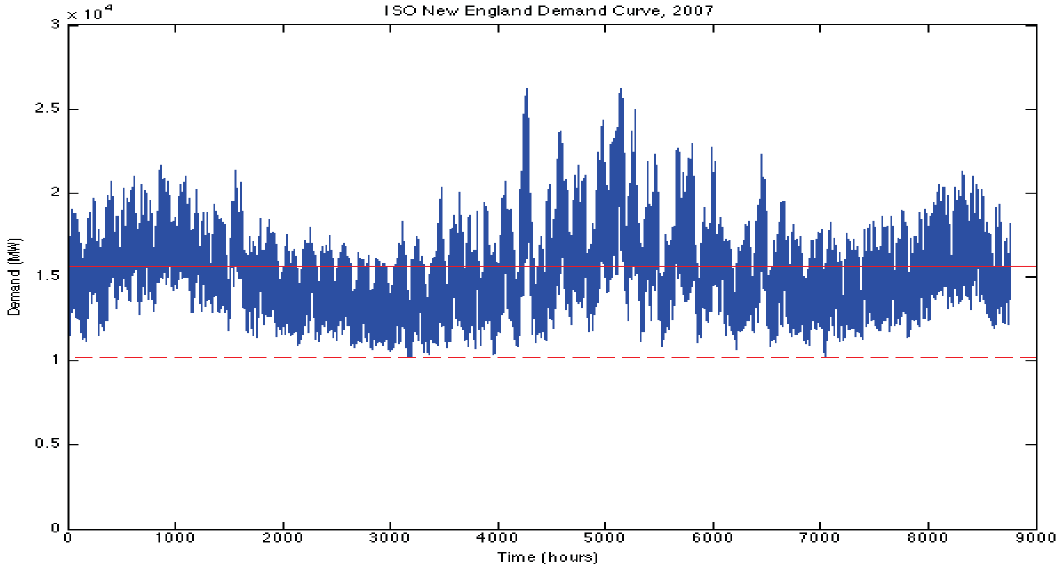


Fig. 1. 2007 Electricity Demand in New Englandwith Base-Load and Average Demand (Red Lines)

Electricity grids meet this demand with different types of generating systems. Base-load electricity demand (lower red line) is met with high-capital-cost low-operating-cost nuclear plants and large coal plants with medium capital costs and low-cost coal. Low-capital-cost higher-operating-cost fossil fuel plants meet the variable demand. Most of these use natural gas. In a few locations such as the Pacific Northwest, hydroelectricity meets base-load and peak demand; however, there is insufficient hydro in most of the world to provide economic variable electricity. In a low-carbon world, conventional fossil plants would disappear. There is the potential of fossil electricity-generating plants that capture and sequester carbon dioxide; however, these would be capital intensive plants where base-load operations would likely be required for economic operation.

About two thirds of the total electricity generated (kWh) is base load and one third is variable demand. This implies that base-load nuclear energy could meet two thirds of the total electricity demand. This fraction could be somewhat larger if refueling was scheduled to seasonal times of minimum electricity demand. However, generating all electricity using nuclear energy without other systems would imply excess capacity for much of the year.

There are large-scale efforts to deploy non-dispatchable solar and windthat produce electricity when the sun shines and the wind blows. Their output does not match electricity demand. Figure 2 shows the impact of adding non-dispatchable photovoltaic (PV) electricity generation to the California grid on a spring day[1]—the time of year with low electricity demand. The far left figure shows the total electricity demand and how it has been met with a mixture of different types of electricity sources. The other figures show the impact of adding different quantities of PV where the percent PV is the fraction of total California electricity demand over a period of a year met by PV. Most of this electricity is generated in the late spring and early summer because of more hours of sunlight per day and the higher location of the sun in the sky.In the spring at times of low electricity demand, surprisingly small amounts of PV result in the PV providing most of the electricity in the midday. For this to happen, other power generating systems must shut down as PV output increases and startup as PV output decreases in the evening.

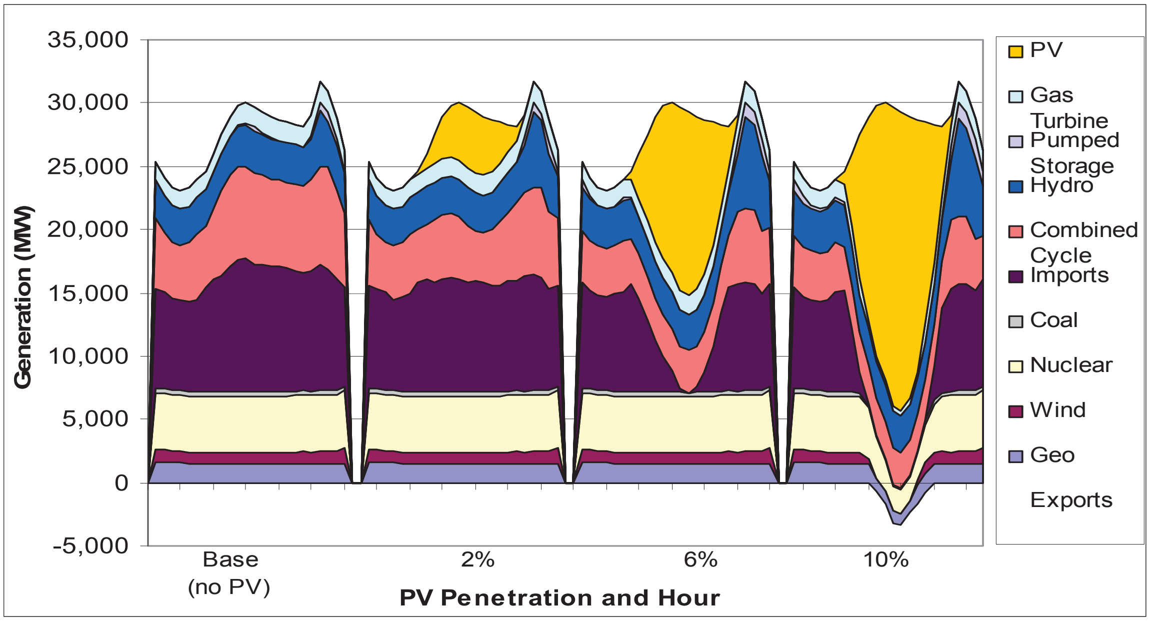


Fig. 2.California Daily Spring Electricity Demand and Production with Different Levels of Photovoltaic Electricity Generation

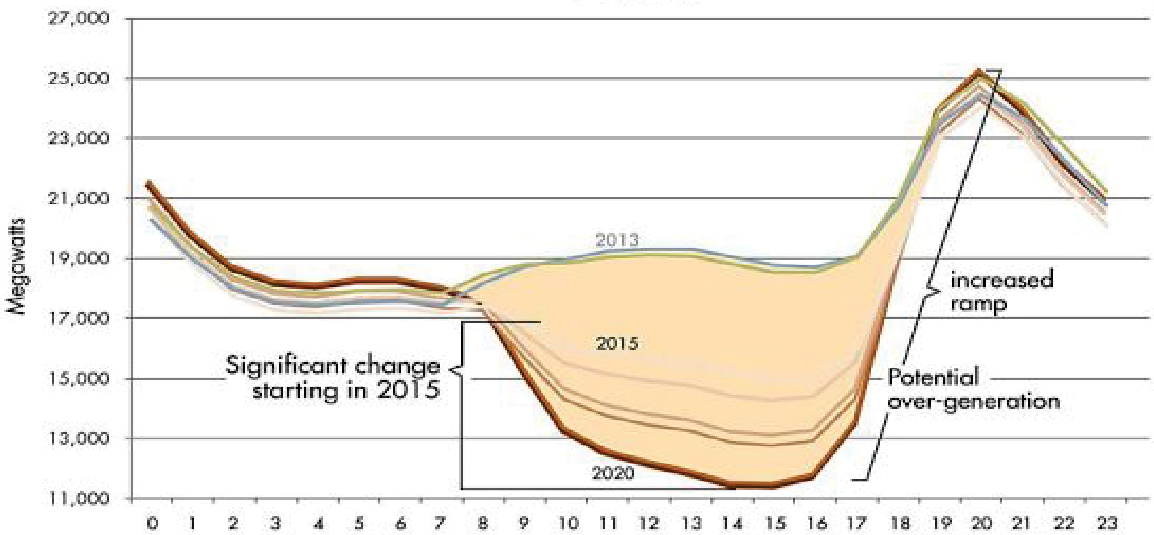


Fig. 3.Spring Impact of Adding Solar Between 2013 and 2020 on the Demand for Electricity from Other Sources of Electricity in California.

The Federal government and California have provided subsidies for construction of solar plants. The California electricity grid has published expected impacts [2] to the grid in the spring between now and 2020 (Fig. 3) as solar is added. Solar provides an increasing fraction of the load in midday but the peak demand is in the late afternoon and early evening. As the solar output rapidly decreases toward sunset, the demand rapidly rises, resulting in the California ISO electrical grid "duck-shaped" curve where the duck body (pink zone) is the solar electricity input. To meet the need for a rapid increase in non-renewable generating output in late afternoon while fully utilizing solar inputs, California is building rapid-start natural-gas-fired turbines—an expensive solution because of the high maintenance cost, the low efficiency of these power plants, and the very limited number of hours of operation per year.

*II.B.Grid Economics*

About half of the United States has partly deregulated markets that have a free market component and various regulatory mandates such as a required fraction of renewables. In a free market the price of electricity varies with time. Figure 4 shows the market price of electricity versus the number of hours per year electricity can be bought in California. There are negative prices for a significant number of hours per year when electricity generators pay the grid to take electricity. Nuclear and fossil plants can't instantly shutdown and restart. They pay the grid at times of negative prices to be able to sell electricity a few hours later at high prices. At times of negative prices, the grid dumps electricity to other grids across long transmission lines—an inefficient process.

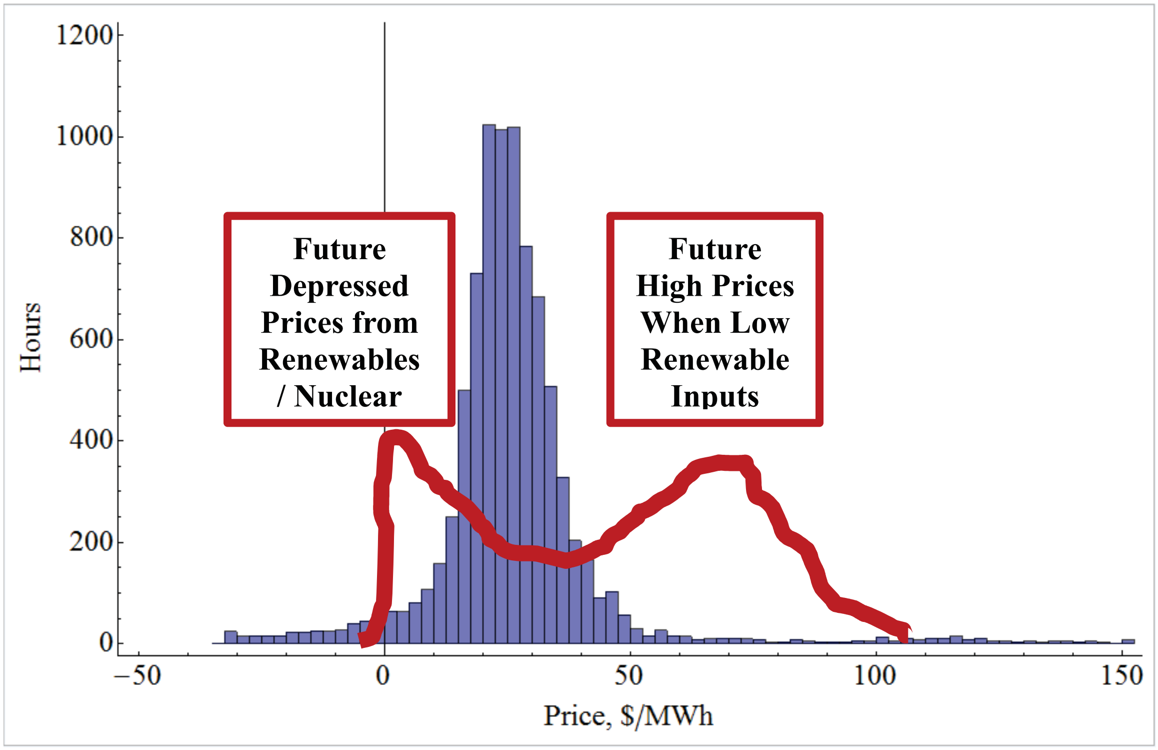


Fig 4.Distribution of Electrical Prices, by Duration, Averaged Over CAISO (California) Hubs (July 2011-June 2012) and Potential Impact of Low-Carbon Grid (Red Curve).

The free market price distribution has major implications for a low-carbon grid with nuclear and renewables. The addition of a small amount of solar (2 %) as shown in Figure 2 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. Each owner of a PV array will sell electricity at whatever price exists above zero. This implies that when somewhere between 10 to 20% of the total electricity demand is met by solar in California, the output from solar systems during midday for parts of the year will exceed demand, the price of electricity will collapse to near or below zero, and the revenue to solar power plants will collapse to near zero much of the time. Each incremental addition of solar will lower the revenue for existing solar electricity producers. This low-revenue trap in a free market limits the fraction of electricity produced from solar and wind.

This also implies that the price of electricity at times of low renewable input will rise. If other types of power plants operate half the time because they do not generate electricity at times of high renewable inputs, replacement plants will not be built unless there is a rise in the prices of electricity when renewable energy sources are not producing electricity. There may be no benefit to the customer.

*II.C.Transition to a Low-Carbon Grid*

The transition from fossil fuels to a low-carbon grid will depend upon specific rules. In the United States there are large subsidies for renewables including a \$0.022/kWe investment tax credit. This implies that an owner of a PV facility will be willing to sell electricity to the grid at negative prices as long as those prices are above -\$0.022/kWe. However, as renewables grow the cost of this credit will soon be unaffordable. This has resulted in countries such as Germany and Spain reducing subsidies with time.

Simultaneously, one expects major impacts on non-fossil generating assets as renewables are built and displace these power systems during times of high wind and solar inputs. Table 1 shows the expected short-term impact on electricity prices and the profitability of other types of power plants in the United States as one introduces non-dispatchable renewables[3]. The addition of renewables displaces the power generating systems with the highest operating costs and thus favoring the power generating systems with the lowest operating costs—nuclear and coal. Because natural gas tends to get squeezed out of the market, added renewables may increase carbon dioxide emissions (as in Germany and elsewhere) as coal is preferentially dispatched over natural gas. In the short-term this will lower prices but this is a transient effect.As these plants are retired, replacement plants will not be built until there are large increases in electric prices at times of low wind and solar outputs.

TABLE I. Short-term Impact of Added Renewables in the United States on Other Power Generation Systems[3]

| **Penetration level** | | **10%** | | **30%** | |
|---|---|---|---|---|---|
| Technology | | Wind | Solar | Wind | Solar |
| **Load Losses** | Gas Turbine (OCGT) | -54% | -40% | -87% | -51% |
| | Gas Turbine (CCGT) | -34% | -26% | -71% | -43 |
| | Coal | -27% | -28% | -62% | -44% |
| | **Nuclear** | **-4%** | **-5%** | **-20%** | **-23%** |
| **Profit Loss** | Gas Turbine (OCGT) | -54% | -40% | -87% | -51% |
| | Gas Turbine (CCGT) | -42% | -31% | -79% | -46% |
| | Coal | -35% | -30% | -69% | -46% |
| | **Nuclear** | **-24%** | **-23%** | **-55%** | **-39%** |
| Electricity Price Variations | | -14% | -13% | -33% | -23% |

As existing power stations are retired, replacement power stations will be required to provide electricity at times of low wind or solar input. For these new power stations, the economic preferred option [4]will be open-cycle gas turbines (OCGT). These plants have low capital cost but are relatively inefficient and have higher greenhouse gas emissions relative to combined cycle gas turbines (CCGT). CCGTs have a heat recovery steam generator that converts hot Brayton-cycle exhaust gas into steam.  OCGTs have the capability to rapidly change power levels—a required capability with large-scale use of renewables.

The simultaneous peaking wind and solar (Fig. 2) generators that can exceed demand leads to low capacity factors and, in turn, low capital utilization unless major investments are made in grid level storage and hybrid energy systems. This implies low revenues in free electricity markets, even for the renewable generators that current policies are intended to favor. This trend causes major challenges for other types of power generation and higher long-term electricity costs. The greatest challenges are for mid and high latitudes with large seasonal variations in energy demand and renewables outputs. That includes the United States, Europe, Japan, and much of China. This would not necessarily apply to (1) countries near the equator or (2) those few countries (Sweden and Switzerland) with sufficient hydroelectricity that they can operate with significant non-dispatchable renewable inputs because of the flexibility of hydro systems with large seasonal storage of water. The preferred steady-state output of nuclear results in similar challenges but only when a much higher fraction of total generation is supplied by nuclear systems.

These challenges of a low-carbon nuclear-renewable grid require rethinking the electricity grid. Economics demands full utilization of capital-intensive low-operating cost nuclear and non-dispatchablerenewables. Nuclear power costs are driven by the capital costs of the power plant, while fuel and operating costs are low[5]. The capital costs of wind and solar are driven by the capital costs of the power systems and the grid with other costs sometimes exceeding the cost of the solar and wind systems[3, 6, 7]. In 2008 the average U.S. capacity factor [8] for wind was 25.6% while the average capacity for solar photovoltaic was18.4%. The low capacity factors imply larger grid investments per unit of energy delivered to the consumer. In addition there are longer transport distances for some wind and solar resources.

Without changes in the power generating systems, an electricity system primarily consisting of high-capital-cost low-operating-cost generating facilities implies in a free market(1) large periods of the year with very-low price electricity (times of low demand and high nuclear-renewables input) and excess generating capacity and (2) large periods of the year with very high-price electricity. These conditions will make it economically expensive to eliminate the burning of fossil fuels for electricity production.

## III. OPTIONS FOR EFFICIENT USE OF CAPITAL-INTENSIVE GENERATING RESOURCES

### *III.A.Changing the Electricity Grid*

Expanding the grid can partly address the low-carbon grid mismatch between production and demand. Larger east-west grids can spread peak demand out over more hours, reduce some of the variability of the wind, and transfer solar energy over long distances. However, the U.S. population and electricity demand is concentrated on the coasts that have a north-south orientation while peak electricity demand and solar energy output move east to west each day. This geographical orientation limits benefits of a larger grid to address the mismatch between capital intensive generating technologies and demand.

### *III.B. Changing Nuclear Electricity Generation Characteristics*

In the context of nuclear energy, work is underway (9, 10) to develop a Fluoride-salt-cooled High-temperature Reactor (FHR) coupled with a Nuclear Air-Brayton Combined Cycle (NACC) with variable power output to address the challenges of a low-carbon electricity grid. The reactor uses the same graphite-matrix coated-particle fuel as is used in gas-cooled reactors with a high-temperature liquid salt coolant.

NACC would be similar to a natural-gas-fired power plant. Air is compressed, heated with nuclear heat, and goes through a gas turbine producing electricity with the hot gas exhausted to a steam boiler. The hot exhaust air produces steam that drives a steam turbine producing added electricity. NACC has some special characteristics.Auxiliary natural gas (NG) can be added after nuclear heating to further increase the temperature of the compressed air to double plant output—with the long-term option of replacing NG with hydrogen or biofuels. The peaking capability is built on top of a base-load capability. Relative to a traditional stand-alone NG plant that implies: (1) no natural gas consumption when operated in base-load mode with only nuclear heat, (2) very fast ability to add power to the grid and (3) more efficient conversion of NG, hydrogen or biofuels to electricity relative to traditional gas turbines.

This type of nuclear power station can partly address the challenge of a low carbon grid with its variable output on demand. The economics are substantially better than a traditional base-load nuclear plant with about a 50% increase in revenue after subtracting the cost of natural gas. This is based on analysis of the California and Texas grids using 2012 hourly electricity price inputs. The peak power can initially be produced using natural gas but the system can also burn low-carbon biofuels and hydrogen. This reactor and power system is early in the development cycle with potential deployment in the 2030 timeframe.

### *III.C.Energy Storage*

The challenge to efficiently use capital-intensive generating capacity can be addressed by energy storage. There are many technologies (batteries, pumped hydro storage) for hourly electricity storage. However, there are large weekly (workdays/weekend) and seasonal variations in energy demand. There are also large variations in seasonal renewables output with maximum solar output in late June and maximum wind output in the spring. The storage requirements are massive if the seasonal factors are considered [11].

Unlike hourly storage over a period of 24 hours, daily and seasonal energy storage present a much larger economic challenge. Consider astorage device that costs $300/kWh of storagecapacity and operates for 10 years. If theelectricity storage device is used 300 days per year, thecapital-costcomponent of the storage costper kWh is $0.10/kWh ($300/[300x10 cycles])—about theaverage price of electricity today. Ifthe energy storage device is used 50 times per year(once a week), the capitalcost part of the storage cost per kWh is$0.60.kWh. If the same device is used for seasonalstorage it will only be cycled10 times in its lifetime, with a capital cost of storage of $30/kWh—a prohibitively high cost.

Thus far we have identified onlytwo potentially viable seasonal energy storagemediathat are potentially economic: heat and hydrogen.In each case theround tripefficienciesare lower than for short-term energy storagesystems such as batteries andpumped hydro.The seasonal heat storage technology option [12, 13]involves heating rock a kilometer underground with steam when low-cost energy is available from nuclear or very-large solar-thermal plants and using geothermal power technology to recover the heat from the rock and convert it to electricity at times of high energy demand. The other seasonal energy storage option is hydrogen as will be discussed later. Hydrogen is stored underground like natural gas with low storage costs. However, the round trip efficiency from electricity to hydrogen and back to electricity is less than for thermal heat storage. The efficiency penalty comes from having two conversion steps: electricity to hydrogen and hydrogen to electricity.

## IV. HYBRID ENERGY SYSTEMS

### *IV.A.General Description*

Hybrid energy systems use excess energy (heat and electricity) from the power sector at times of low demand and low prices to produce other storable products—not electricity. Hybrid energy economic viability depends upon the savings from access to low-cost energy exceeding the costs of variable energy input.
The successful development of hybrid systems places a floor on the price of electricity. It may be a required enabling technology for an economically viable low-carbon grid with electricity produced from high-capital-cost low-operating cost nuclear renewable systems. It is a transition from a grid where fossil electricity plants provided variable electricity on demand to a grid where hybrid industrial systems provide variable demand for the output from capital-intensive low-operating-cost power plants.

For a nuclear renewable electrical system, thepotentialquantities of low-cost energy from the electrical sector are large—hundreds ofgigawatt years of electricity or more for the United States. The required scale defines those hybrid systems that can make a difference. Figure 5 shows the energy flows in the United States [14]andsuggests candidate hybrid systems.

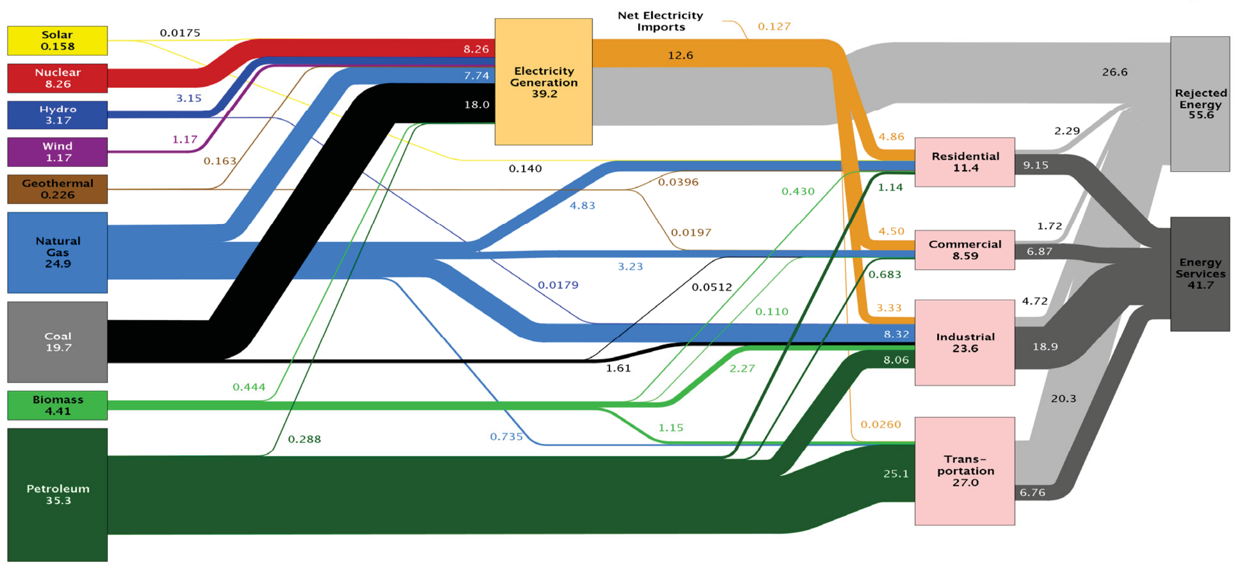


Fig. 5. 2012 Energy Flows in the United States

The electricity sector is the largest and is expected to grow relative to other energy sectors. The second largest sector is the transport sector—the sector large enough to absorb low-cost energy from the electrical sector using hybrid systems. The next largest sector is the industrial sector.These sectors have concentrated demands for heat and electricity. The electrical grid enables dispersed renewables and nuclear to provide the electricity. The concentrated heat demand requires nuclear as the preferred energy source or requires such facilities be built in areas with high solar potential to enable very-large-scale solar thermal systems.

### *IV.B.Hybrid Systems for a Zero-Carbon World*

In terms of future market size and total energy consumed, the largest future hybrid systems will likely produce hydrogen[15, 16]. Today hydrogen production consumes about 2% of the total global energy consumption but could ultimately consume a quarter or more of global energy consumption. The primary uses are production of fertilizer (ammonia) and liquid fuels. Hydrogen is used to remove sulfur from crude oil and convert heavy oil to gasoline and diesel. Much larger quantities of hydrogen would be required to convert biomass into high value gasoline, jet fuel, and diesel.Production of higher-energy content fuels could potentially double the energy value of biofuels per ton of biomass feedstock versus production of fuel ethanol. Equally important, hydrogen can replace coke (coal) as the chemical reducing agent in the production of most metals. Today about 4% of global iron is produced using hydrogen rather than coke. Hydrogen can replace natural gas for peak power production and coupled to NACC systems as described earlier.

There are more futuristic hydrogen applications. Research is underway to use hydrogen directly or in alternative chemical forms such as ammonia ($NH_3$) as a transportation fuel to replace liquid fuels. The U.S. Navy [17-21]and others [22-25]are examining production of liquid fuels (gasoline, diesel, methanol) using carbon dioxide extracted from air or the ocean and hydrogen extracted from water. The navy interest is to produce jet fuels at sea with nuclear energy to avoid the vulnerabilities of shipping fuel to the fleet in wartime. Because the carbon dioxide is extracted from the air, there is no net addition of carbon dioxide to the atmosphere when such fuels are burned. This provides an unlimited source of liquid hydrocarbon fuels at costs estimated at 2 to 3 times that of electricity[24-25]. The primary energy input into these processesis hydrogen from electrolysiswhich converts carbon dioxide into carbon monoxide. Added hydrogen is combined with the carbon monoxide to produce syngas that in turn is converted into liquid fuels. The conversion of syngas to liquid fuels is the standard process used worldwide to produce liquid fuels from natural gas and coal.

There are two candidate hybrid hydrogen production technologies[16, 26]—room temperature electrolysis and high-temperature electrolysis(HTE) where heat and electricity are used to produce hydrogen and oxygen. Room temperature electrolysis has been a commercial technology for over a century. HTE is a new technology being developed that is based on high-temperature fuel cells operated as electrolyzers. The heat input reduces the amount of electricity required per unit of hydrogen produced. The high temperature eliminates the use of expensive noble metals—an unavoidable cost with low-temperature electrolysis. With either process the primary cost is the cost of electricity thus the goal is to optimize liters of hydrogen produced per dollar of electricity. That implies operating at lower efficiencies with higher voltages when low cost electricity is available to minimize overall production costs.

Because hydrogen can be stored cheaply in large volumes, like natural gas, there is no requirement for steady-state production to meet industrial demand. Large-volume storage of hydrogen and syngas has been a commercial process since the 1930s. Hydrogen can be made when excess low-price electricity from the grid is available. Most of the production may occur over a few months in the spring and fall when there is excess electricity generating capacity. Recent studies have examined hybrid options such as nuclear wind hydrogen systems [27] for pipeline hydrogen to be delivered to refinery and other markets.

A second and more complex hybrid application is biofuels production. The limit on biofuels production [28] is biomass feedstock availability. Existing biofuels use the biomass as a feedstock for fuels production and an energy source for the biorefinery. For example in fermentation processes the yeast converts part of the sugar to ethanol while consuming part of the sugar energy content to stay alive and multiply. Analysis shows that the liquid fuels yields can be more than doubled per ton of biomass by changing to processes that require added heat and hydrogen. In the U.S.[29], the available U.S. biomass energy content is equivalent to burning 10 million barrels of diesel fuel per day. If converted into traditional biofuels, the energy content of those fuels is equivalent to 5 million barrels of diesel fuel per day—about half the initial energy value of the biomass. If there areexternal sources of hydrogen and heat, that same biomass can be converted into the equivalent of 12 million barrels of diesel fuel per day—about equal to U.S. liquid transport fuels consumption. The potential of biofuels to meet U.S. liquid fuel demand is dependent upon availability of low-cost external energy sources.

The limited availability of biomass for chemicals and liquid fuels in a low-carbon world suggest that ultimately biomass will be too valuable as a feedstock to be a boiler fuel. That eliminates it as an option to provide energy at times of low wind and solar output.

A third class involves fuel from algae [30]. In theory, algae could meet the world's liquid fuel demand. Some of these systems would not efficiently couple to hybrid systems but other variants would favor deployment of hybrid systems. For example, one of the more futuristic examples is the use of light-emitting diodes (LED) to produce liquid fuels. Special algae that produce hydrocarbon fuels are grown in tanks. Growing algae in tanks has the benefit that fertilizer and other inputs are fully recycled with light being the major net energy input. The lights are turned on when the price of electricity is low and turned off when the price of electricity is high. The economic viability depends upon the development of low-cost efficient LEDs that produce light at the frequencies required by the algae. The storable products are liquid fuels. Like other liquid fuels production methods, heat is required for refining.

These are competing examples for production of fuels. We do not know at this time which processes will become the most economical in a low-carbon nuclear-renewable energy system. However, all processes that produce fuels require massive inputs of energy and in most cases massive quantities of heat—the output of a nuclear reactor.

### *IV.C.Hybrid Systems for a Low-Carbon World*

The above examples are for hybrid systems for a zero-carbon electricity grid. There are however many hybrid systemsthat include the use of fossil fuels that reduce greenhouse gas releases relative to current technologies and are potentially competitive in the near term. Most of these systems [31-33] use nuclear plants that operate at constant output. At times of high electricity prices, electricity is sold to the grid. At times of low electricity prices, steam or high-temperature heat is sold to industrial customers who turn down their steam boilers and thus reduce fossil fuel consumption. Nuclear plant revenue is increased by the ability to sell energy into two markets based on price. It eliminates the sale of electricity by nuclear plants when electricity prices are low or negative.

Such hybrid systems can serve as transition technologies to a low-carbon world or as longer-term options depending upon allowable long-term release rates for carbon dioxide to the atmosphere. The earth has some capability to absorb carbon dioxide. In such a constrained world, the fossil hybrid systems that would be used would be those that provided the maximum benefits per unit of carbon dioxide released.

There is one near-term hybrid system that deserves special consideration because of its potential impact: the nuclear renewable shale-oil system. This system may (1) enable very-large-scale economic use of renewables in the U.S. western electricity grid, (2) produce gasoline and diesel with a lower carbon footprint than any other method to produce these fuels from fossil fuel sources, and (3) eliminate U.S. dependence on foreign oil. The largest shale oil (kerogen-derived hydrocarbons) reserves in the world are concentrated in a few small locations in Colorado, Utah, and Wyoming [34]. New technologies allow the slow in-situ heating of oil shale (solid kerogen) to convert it into a light crude oil, gases, and solid char. Because of the low thermal conductivity and large thermal mass of oil shale, the heat input can vary with time without significantly impacting oil production. Slower heating has almost no impact on the capital cost—it just implies that underground heating pipes must be installed earlier and operate over a longer lifetime. The heat input is between a quarter and a third of the energy value of the resultant oil and gas.

Shell and Exxon are examining underground electric heating of the shale oil. Others have examined underground closed steam loops (slant drilling) with the steam heated by burning fossil fuels. An alternative is to use heat from nuclear reactors [35, 36]. The near-term option is to use light water reactor (LWR) technology [36]. The complete conversion of oil shale requires heating the rock to ~370°C. LWR peak steam temperatures are near 300°C but after accounting for temperature drops needed to transfer heat into the rock, delivered heat temperatures will be between 210 and 250°C. To fully heat the oil shale, a two-step process would be used. LWR steam in closed loops would heat the rock to between 210 and 250°C. Electric resistance heaters will then be used to heat and circulate the steam in a closed loop to raise the temperatures to the final required temperatures. The use of steam heat for initial heating rather than electricity is more efficient because it takes two to three units of heat to generate a unit of electricity. The currently proposed Shell and Exxon processes plan to use only electric heating of shale oil.

The LWR would operate at full capacity. At times of high electricity prices, the steam from the reactor would be used to produce electricity for the grid. At times of low electricity prices the steam would be used to preheat oil shale between 210 and 250°C. At the same time, other underground blocks of previously steam-heated oil shale would be further heated using electric heat and circulating steam as the heat transfer fluid. This electricity would be purchased from the electric grid. The production of a million barrels of oil per day (5% of U.S. oil demand) would require about 20 GWt of heat. From grid perspective, it is a super battery that produces oil. This has major impacts.

- *Intermittent renewable backup*. The system enables nuclear to provide low-cost variable electricity backup to non-dispatchable renewables (wind and solar). Nuclear and renewables are complementary in this system
- *Floor on the price of electricity*. It would place a floor on the price of electricityand thus increase revenue for solar and wind facilities at times of maximum production.
- *Low-carbon system*. The system eliminates most of the greenhouse gas releases from the production of a light crude oil—it can potentially be the liquid fossil fuel with the lowest greenhouse impact and the last fossil fuel that should be burnt on earth. It also eliminates greenhouse gas emissions from fossil-fuel combustion turbines used to backup renewables on the electricity grid, since these systems would no longer be necessary in the region of the nuclear shale oil facility.
- *Reduced secondary environmental impacts*. A quarter of the natural gas produced in North Dakota is flared rather than collected and sold. This gas is a

byproduct of oil production that is flared because it is uneconomic to collect gases from dispersed oil wells. In contrast, American oil shale is the most concentrated fossil resource on earth with over a million barrels of recoverable oil per acre. This allows economically efficient recovery of secondary gases with major reductions in environmental impacts (releases of methane, particulates, sulfur compounds, etc.) per unit of oil and gas produced relative to traditional oil production.

- *Economics.* This system enables nuclear and renewable power generation systems to operate at full capacity to minimize production costs. It can reduce electricity costs to the customer because expensive nuclear and renewable assets operate at full capacity rather than at part load. The use of steam heating of oil shale, even for only part of the total heating of each well, would reduce the biggest single cost of oil shale recovery—energy.

The option has limited global applicability. The most concentrated resources are in Colorado, Wyoming, and Utah in a very small geographical area. The other concentrated resource is around the Baltic Sea (northern Europe). The U.S. oil shale resource base is larger than the oil resources of the Mideast. It is an option that potentially eliminates the use of fossil fuels for electricity production from the western electricity grid.

## V. CONCLUSIONS

A low-carbon nuclear renewable electricity grid has different characteristics than an electricity grid with large quantities of dispatchablefossil-fuel electricity. Non-dispatchable renewables and nuclear have high capital costs and low operating costs. In such an electrical grid that can meet peak electricity demand in a deregulated market, revenue collapse occurs with very low electricity prices when production capacity exceeds demand. The electricity price is close to the operating costs. This first impacts the growth of non-dispatchable solar, then wind and later nuclear. Efficient capital deployment and transitioning to low-carbon electricity generation requires maximum use of these assets. That, in turn, requires technologies that can use the low-cost electricity and raise the minimum electricity prices while moderating the peak electricity prices.

This changing environment creates large economic incentives for hybrid energy systems designed to consume variable amounts of low-priced electricity and heat from nuclear reactors. It enables base-load nuclear energy to provide variable dispatchable electricity to the grid—what a low-carbon grid requires. It is an alternative to energy storage that bypasses the challenge of daily to seasonal energy storage by producing useful storable products. It is complementary to an FHR with NACC that is good at meeting peak electrical demands and moderating price spikes when large mismatches between production capacity and demand. It enables greater utilization of capital assets in the electric power sector to meet other energy needs.

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