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Strategies for a Low-Carbon Electricity Grid With Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs

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ABSTRACT

Strategies for a Low-Carbon Electricity Grid With Full Use of Wind, Solar, and Nuclear Capacity to Minimize Total Costs

Variable electricity demand has been historically met by burning fossil fuels. Operating fossil plants at part load is economically viable because the capital costs of fossil generating plants are low relative to fuel costs. In a low-carbon world, electricity is generated by capital-intensive, low-operating-cost nuclear, wind, and solar generators, where full power electricity output does not match demand on an hourly to seasonal basis. Operating capital-intensive facilities at part load is expensive. Five classes of technologies (Table A.1) were identified to enable full utilization of capital-intensive nuclear and renewable generating resources to match electricity production with demand that includes most technology options. The classification is based on the differences between heat and work (electricity). Each class of options can help avoid electricity price collapse that occurs in a deregulated market when electricity production capacity with low-operating-cost technologies exceeds demand, drives prices to very low levels and creates major barriers to the larger-scale use of low-carbon generating technologies. Each class of technology has different characteristics, can be treated as a "black box" relative to impacts to the grid, and provides a basis to develop strategies for a low-carbon grid. Fully utilizing expensive capital-intensive electricity generating resources minimizes total societal costs.

Table A.1. Classes of Systems to Match Electricity Production to Demand

Option	Method to Use Excess Low-Price Electricity	Notes
Electrics: Electricity Storage (Battery and equivalent)	Grid Electricity →Stored Work →*Electricity*	Includes functionally equivalent technologies such as demand management that do not change hardware and provide short-term storage
FIRES: Electricity to Heat Storage to Industry	Grid Electricity →Stored Heat →*Heat*	Electrically heat firebrick to high temperatures and blow air through hot firebrick to provide hot air to industrial furnaces and kilns to reduce natural gas use.
RATHS: Reactor Associated Thermal Heat Storage	Reactor Heat →Stored Heat →*Electricity*	Heat storage at reactors using technologies such as steam accumulators, nitrate salts, and hot rock to produce peak electricity. Option for solar thermal systems.

NUTOC: Nuclear Topping Cycle using FIRES Stored Heat for Topping Cycle Above Reactor Heat Input	Grid Electricity →Stored Heat in FIRES; Reactor Heat + FIRES Heat →*Peak Electricity*	Nuclear reactors with air-Brayton combined cycles similar in design to natural gas combined cycles that operate in two modes: (1) base-load on nuclear heat (2) and added peak electricity with auxiliary heat provided by FIRES, natural gas, biofuels, and other heat sources. Incremental heat-to-electricity efficiency: 66 to 70%.
Hybrid: Co-Produce Electricity and Second Product	Reactor Heat + Grid Electricity → *Electricity* + *Second Product*	Base-load reactors and thermal solar with variable electricity to grid and production of a second product. The largest potential future second product is hydrogen because of large existing and future demand

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Executive Summary

Strategies for a Low-Carbon Electricity Grid With Full Use of Nuclear, Wind and Solar Capacity to Minimize Total Costs

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The world requires economic variable electricity production to match demand by industrial, commercial, and residential customers. Historically, this has been provided by fossil fuels, where the capital costs of fossil generating plants are low relative to fuel costs, and fossil fuels are easy to store. Variable electricity production has historically been achieved by varying fuel input into fossil plants. The economic cost of operating fossil plants at part load is acceptably small because the largest cost is the cost of the fuel. In a low-carbon world with restrictions on carbon dioxide emissions, electricity would be generated by nuclear, wind and solar—technologies with high capital and low operating costs. The economic cost of operating these power plants at partial load to meet variable electricity demand is large. In addition, wind and solar are non-dispatchable, where output depends upon wind and solar conditions, not electricity demand. New technologies are required to match electricity production with demand to enable full utilization of capital-intensive nuclear, wind, and solar plants to minimize the cost of electricity.

This paper examines how the electricity markets change as one transitions from electricity markets based on fossil-fuel electricity generation to electricity markets based on capital-intensive nuclear, wind, and solar electricity generation. Five classes of options have been identified to address the mismatch between electricity production and demand based on their thermodynamic characteristics in terms of storing heat versus storing electricity (work). In some of these classes there are dozens of technical options, but from the perspective of the electricity grid all the options in a class can be considered as a black box with similar input and output characteristics. This classification strategy enables an understanding of the option space, helps define roles for nuclear and renewables, and enables development of a research and development pathway to a low-carbon electricity grid.

The primary constraint is economics. About 10% of the world's economy is associated with energy production. Increasing energy costs reduce the global standard of living. The global impact of higher energy costs implies that economics will be the dominant factor in energy choices. For this reason, the analysis approach starts with economics and electricity prices in deregulated markets.

Figure S.1 shows an electricity price curve for fossil generation sources (existing; blue bars) and zero-carbon electricity grids in a deregulated market, where the horizontal axis has the wholesale price of electricity ($/MWh) and the vertical axis shows how many hours per year electricity could be bought at a particular price. This specific example (blue bars) uses wholesale electricity price data from the Texas market in 2012. The price curve for an electrical grid primarily based on generating electricity from fossil fuels is approximately a bell shaped curve. At times of low demand the power plants with the lowest operating costs are producing electricity and thus the market price of electricity is low. At times of high electricity demand, old inefficient units or units that burn more expensive fossil fuels are brought on line at high cost and set the wholesale price of electricity—resulting in high electricity prices at those times. There is an apparent minimum price of electricity. This is set by the cost of fossil fuels used to produce electricity. Sales of electricity below this price occur at times of very low demand when hydroelectric, nuclear or wind plants set the price of electricity.

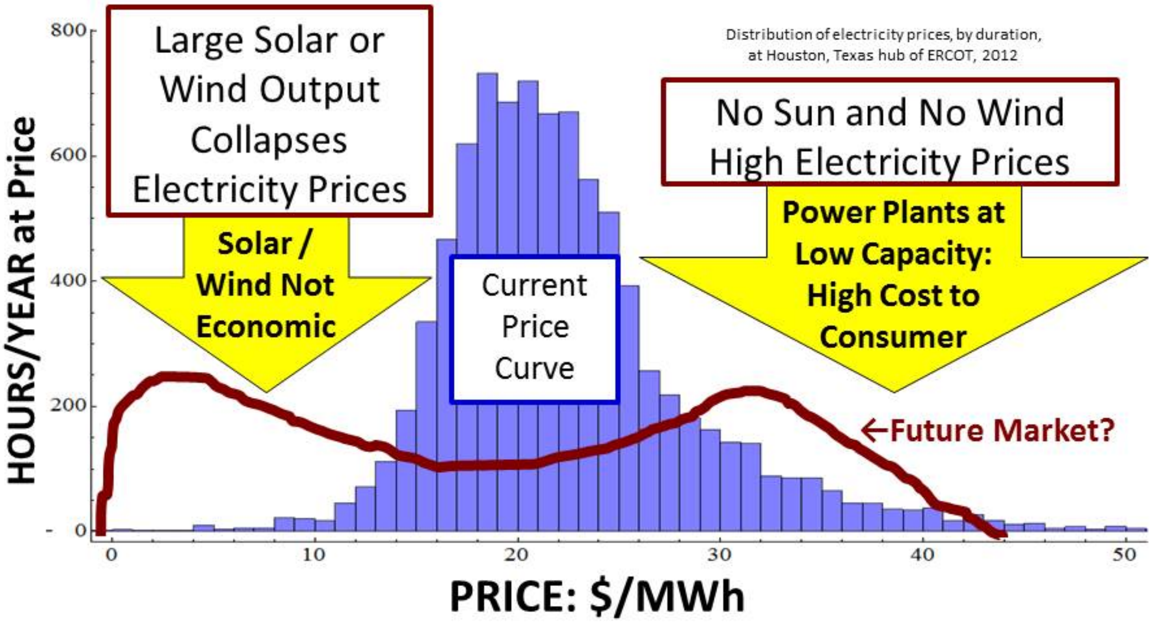

Fig. S.1. Electricity Price Curve for Fossil and Low-Carbon Electricity Grids

The red curve is a notational curve that shows what happens if one adds large quantities of renewables or nuclear and removes electricity generation by fossil fuel sources with no other changes. For example, if significant solar is added, the price of electricity will drop to zero in the middle of the day when there is high solar input and some solar output is curtailed due to the lack of markets. The incremental cost of solar production is near zero and solar producers will bid down hourly electricity prices to continue sales. The same happens for large wind input on windy days. To use an analogy, it's like selling tomatoes in August when everyone's tomatoes turn red at the same time—there is glut on the market that results in price collapse. Electricity price collapse limits the large-scale use of these resources—even if there are large decreases in the costs of these technologies because all such plants provide output to the grid at the same time independent of electricity demand.

When the wind stops or the sun does not shine, other power generators must be used to provide electricity. If these plants are used only half the time when the sun is down or the wind is not blowing, replacement plants will not be built unless the price of electricity doubles when they sell electricity to the grid to cover their costs. The long-term electricity price curve becomes bimodal—a fundamentally different price curve for electricity. This price collapse without storage technologies becomes economically significant when solar contributes ~10% of all electricity produced in a solar-fossil system, wind contributes ~20% of all electricity produced in a wind-fossil system or nuclear contributes ~70% in a nuclear fossil system. Revenue collapse discourages further investment in capacity of the very-low-carbon generating technologies in a free market. Subsidies can increase solar, wind, and nuclear capacities, but added capacity decreases revenue from the sale of electricity so subsidies have to increase as low-carbon technologies are added. Regulators can modify market rules so price collapse does not appear—but that does not change the costs to society—it just hides them as subsidies that increase the total cost of energy to society. The impact of price collapse is most severe on the energy technology causing price collapse, but it hurts the economics of all low-operating-cost high-capital cost technologies—solar, wind and nuclear. Price collapse primarily benefits low-capital-cost high-operating-cost electrical generating technologies (Natural gas) that provide electricity at times of low renewables or nuclear input on the right side of the price curve in Figure S.1. In the near-term price increases will be limited because natural gas is the backup fuel. Gas turbines have low capital cost and the price of natural gas has dropped because of fracking. However this solution also implies long-term carbon dioxide emissions from burning natural gas.

The Massachusetts Institute of Technology (MIT) *Future of Solar Energy* study provides a more detailed examination of the solar option that provides an example of the challenge of moving from an electricity grid dominated by fossil fuel generation to a low carbon grid. Figure S.2 shows market income for solar plants with increased use of solar. Electricity prices at times of high solar output collapse; thus, solar income collapses as solar production increases. This economically limits unsubsidized solar to a relatively small fraction of total electricity production even if there are large decreases in solar costs. Collapsing electricity prices at times of high solar input favor fossil plants to provide electricity at times of low solar input. Fossil plants have low capital costs but higher fuel costs; thus, price collapse locks in the use of fossil fuels to produce electricity at times of low solar or wind input. Electricity price collapse at times of high solar input hurts the economics of solar, wind and nuclear. Figure S.2 also shows the impact if a hypothetical zero-cost electricity storage technology is introduced to store electricity at times of excess electricity from photovoltaic (PV) and sold into the market at times of low production of solar electricity. *The economic viability of large-scale solar, wind, and nuclear partly depend upon developing low-cost technologies to prevent electricity price collapse if any of these technologies is used at a large scale.*

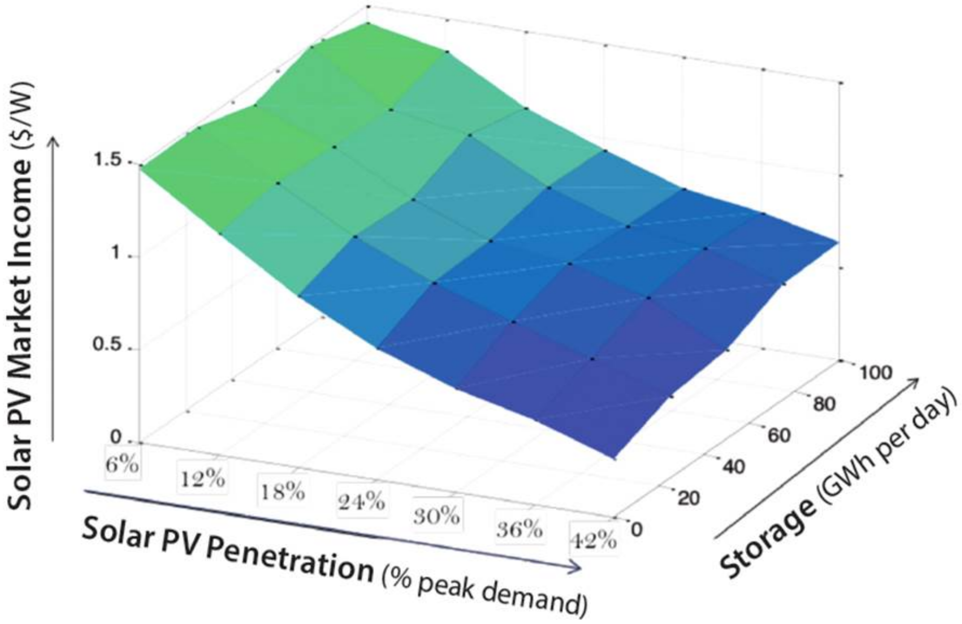

Fig. S.2. Solar PV Market Income versus Solar PV Penetration and Storage.

Technical options to enable full utilization of generating assets in a nuclear renewable grid have been categorized. This taxonomy is based on the thermodynamic differences between electricity (work) and heat. Each class of options has a common set of characteristics and can be treated as a "black box" in terms of its impact on electricity markets and the grid—and is different in its characteristics from the other sets of options and its impact on electricity markets. This approach results in five categories of technologies that can help economically match electricity demand with production and ensure full use of solar, wind, and nuclear generating assets. This excludes transmission that has traditionally been used to move electricity between time zones to reduce generation capacity and enable use of the lowest-price generating technologies. Figure S.3 shows the five options in terms of what they do to the electricity price curve.

- *Electrics: Electricity Storage (Battery or functionally equivalent system)*. Electricity (work) at times of low prices is stored in batteries or equivalent devices (pumped hydroelectric, demand management, etc.) to provide electricity at times of high prices. This reduces the quantities of low-priced electricity and the quantities of high-priced electricity (Fig. S.3). These technologies store electricity for hours, but not weeks or seasons. The U.S. Department of Energy goal for battery storage is $150/kWh(e). The major technical limitation of electricity storage is that storage capacity is limited with the risk that external conditions (multiday heat wave, cloudy weather, low wind, etc.) will deplete storage; thus, this option has limited capability to replace the need for dispatchable electrical capacity. The major economic challenge is the high capital cost of many of these storage devices; their levelized cost becomes large if they are not used for many cycles per year (typically a cycle per day).

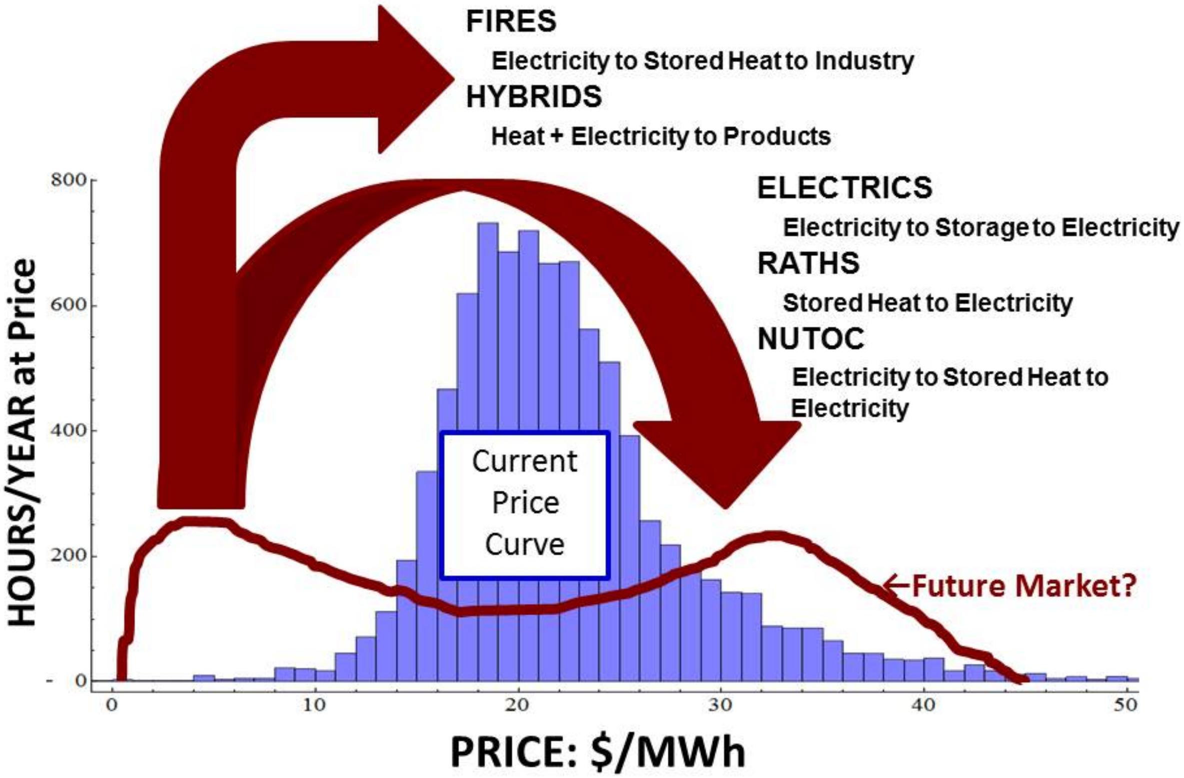

Fig. S.3. Effect of Different Classes of "Storage Technologies" on Price Curve—Reducing Quantities of Very-Low-Price Electricity.

- *FIRES. Firebrick Resistance-Heated Energy Storage—Electricity to heat storage to industry (Fig. S.4)*. FIRES is a new technology under development. Electricity is bought whenever the electricity is less than the price of natural gas (the traditional heat source in industry), converted to and stored as high-temperature heat, and partly replaces the use of natural gas in industrial furnaces and kilns. FIRES involves (1) heating firebrick using resistance electric heating, (2) storing high-temperature heat in firebrick, and (3) blowing air through the hot firebrick to provide hot air to industrial furnaces and kilns. The hot air is a substitute for the natural gas burner where natural gas is used when stored heat is not available. FIRES can be customized to specific needs with the resistance heating sized to match availability of low price electricity, the heat capacity (number of bricks) chosen to meet total quantity of heat to be stored and the heat output to the industrial furnace determined by (1) the air blower size to move hot air from FIRES to industrial furnaces or kilns and (2) operating temperature of the brick.

The cost of FIRES is low, a few dollars per kWh; thus, it has the economic capability to absorb low-price electricity as heat in very-large quantities for hours to several days. FIRES may set a minimum price of electricity in a deregulated market approximately equal to the cheapest available fossil fuel per unit of heat. This would effectively limit electricity price collapse from the large scale use of wind or solar—improving the economics of wind, solar, and nuclear. FIRES could be a means of enabling a decarbonized electric sector to partly decarbonize the industrial sector.

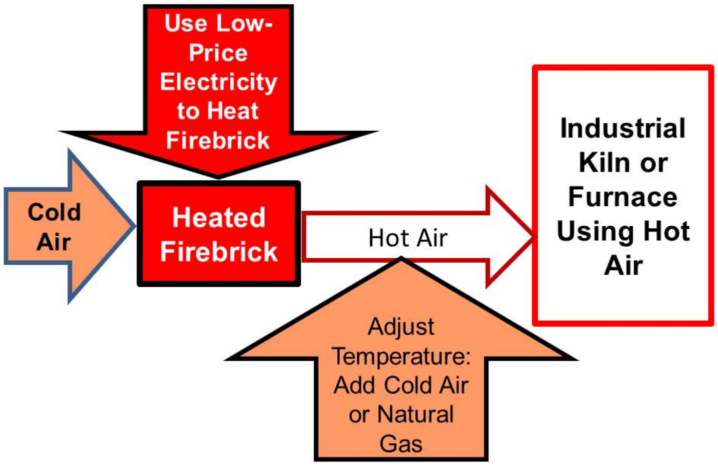

Fig. S.4. FIRES Conversion of Low-Priced Electricity to High-Temperature Heat for Industry.

- *RATHS: Reactor Assisted Thermal Heat Storage: Heat Storage at Reactor or Solar Thermal Site for Peak Electricity Production (Fig. S.3).* At times of low electricity prices, heat from nuclear reactors or solar thermal power systems is sent to heat storage rather than being used to generate electricity. The stored heat is used to generate electricity at times of higher prices. The same thermal storage technologies are applicable to nuclear and solar thermal systems with heat storage times ranging from minutes to seasons across several technological options. Two thermal storage technologies (hot nitrate salt storage and steam accumulators) are currently deployed at solar thermal power stations for hourly to daily heat storage in locations from Arizona to South Africa. Seasonal storage is possible using hot water to heat up rock a kilometer or more below ground that becomes a manmade rechargeable geothermal heat source for electricity production. High capacity storage may enable storage to reduce firm generating capacity requirements.

Heat storage in most cases will preferentially couple to nuclear plants rather than concentrated solar plants. The economics of thermal storage are driven by economics of scale, assurance of recharge, and the number of storage cycles per year. Doubling the number of storage cycles per year effectively cuts the capital cost per unit of heat storage in half. This implies that in an electricity grid with nuclear and solar thermal electric plants, the heat storage systems would be preferentially coupled to the nuclear plants because the nuclear plants operate continuously year round and thus can support more cycles of storage per year with lower storage costs. The second consideration is assurance of recharge. A nuclear plant with constant output can assure recharge of thermal storage systems each day and thus the storage system can displace some quantity of dispatchable generating capacity; however, a solar thermal system can't make such assurances since its output is tied to the weather—days of low cloud cover will deplete any storage device. Seasonal storage may provide an alternative to generating capacity that is only required certain parts of the year. Last, solar thermal systems require direct sunlight to focus light onto collectors. Solar thermal power is therefore limited in the United States to the southwest, as are utility solar storage systems coupled to solar thermal power plants. This is in contrast to nuclear plants that can be sited almost anywhere and solar photovoltaic power systems that can produce electricity under cloudy conditions. Thermal energy storage systems are an order of magnitude less expensive than electricity storage systems; the U.S. Department of Energy goal is \$15/kWh(th).

- *NUTOC: Nuclear Plant with Thermodynamic Topping Cycle Using Firebrick Resistance-Heated Energy Storage.* This is a family of nuclear power cycles that operate in two modes: base-load and peak electricity (Fig. S.5). Nuclear heat is used for base-load electricity production. Additional heat for peak electricity production can be provided by natural gas (near-term), FIRES, or ultimately hydrogen. Nuclear topping cycles are not new; however, high efficiency topping cycles now appear possible because of advances in natural-gas combined-cycle gas-turbine technology. The high-temperature reactor is coupled to a Nuclear Air-Brayton Combined Cycle (NACC). During base-load operation of a NACC, air is compressed, heat is added from the reactor, the hot compressed air goes through a turbine to produce electricity and the warm exiting air goes through a heat recovery steam generator to generate steam that is used to produce added electricity—the same basic power cycle as a natural gas combined-cycle plant. If coupled to a Fluoride-salt-cooled High-temperature Reactor (FHR), an advanced reactor currently under development, the heat to electricity efficiency is 42%. This is a good heat-to-electricity thermal efficiency for a nuclear, solar thermal, or coal power plant. (The original work was coupling NACC to the FHR because this is the technically easiest option; however, more recent work suggests NUTOP may be applied to other advanced reactors including potentially sodium fast reactors and high-temperature gas-cooled reactors)

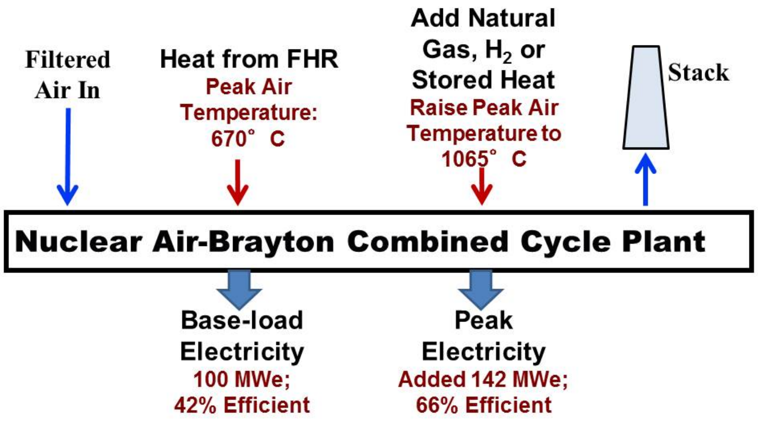

Fig. S.5. Nuclear Air-Brayton Combined Cycle (NACC)

In a gas turbine there is the option of adding heat after the nuclear heat to further raise compressed gas temperatures before entering a power turbine—a topping cycle. The incremental heat-to-electricity efficiency depends upon the design, ranging from 66 to 70%--the most efficient system on earth to convert heat to electricity. The added high-temperature heat can be provided by FIRES or by injection of another fuel, such as natural gas, into the hot compressed air. The peak gas temperatures exceed that possible in a nuclear reactor but are below peak temperatures in modern gas turbines (>1300°C).

In the operation of this system, (1) the reactor would operate at base-load, (2) electricity would be bought when prices are low and stored as high-temperature heat using FIRES—including the electricity generated by base-load reactor operations, and (3) the reactor and FIRES high-temperature heat is used to produce electricity at times of high prices. Added peak power production is more than base-load electricity production. If the reactor has a base-load output of 1000 MWe, the power plant might go from -2000 MWe (buying electricity and storing as high-temperature heat in FIRES) to +2000 MWe. The topping cycle round-trip efficiency of electricity to heat storage to electricity is 66 to 70%.

Normally it would be expected that the efficiency of a storage system that converts electricity to heat to electricity would be low. *That is not true here because the heat is added as a topping cycle above "low-temperature" 700°C nuclear heat*. The efficiency is similar to many other storage technologies (pumped hydroelectric) but uses low-cost heat storage. The round-trip efficiency is expected to improve with improvements in gas turbine technology. This is enabled by FIRES with its high-temperature capabilities. Because peak power can also be produced using natural gas or hydrogen, the assured electrical generating capacity of the plant equals its peak power capability. The baseline concept has NACC and FIRES coupled to an FHR with projected FHR commercialization dates of ~2030 in China. The option could not have existed 15 years ago because the gas turbine technology was not good enough.

- *Hybrid: Use heat from nuclear or thermal solar plant operated at full capacity to produce electricity and a second product with more electricity (and less second product) to the grid at times of high electricity prices. (S.3).* These options may also use heat from a nuclear reactor or solar thermal power station and added electricity from the electricity grid at times of low prices (excess capacity) to produce a variety of energy-intensive products. The maximum electricity output to the grid matches the output of the associated nuclear reactor or solar thermal power plant when no energy is diverted to producing a second product. Some hybrid systems can be designed such that at times of low prices, the hybrid system is a net buyer of electricity from the grid. Hybrid systems transfer heat from the electric sector to the industrial sector. The expectation is that many hybrid options will be more economic than many of the other options because they avoid the costs and inefficiencies of energy storage options.

  From a long-term perspective, hydrogen may be the primary non-electrical secondary product. About 1% of total energy consumption in the U.S. is for hydrogen production used in fertilizer production and converting crude oil into low-sulfur gasoline, jet fuel, and diesel. In a low-carbon world hydrogen may be used (1) to replace carbon in the reduction of iron ore to iron and other metal reduction processes, (2) to increase liquid biofuels yield per ton of biomass by up to a factor of two, and (3) directly as a fuel. If hydrogen is used for peak electricity production, there would be large incentives to burn the fuel in a nuclear topping cycle (NUTOC) because of the much higher efficiency in hydrogen-to-electricity conversion relative to other technologies.

The five categories are compared in Table S.1 based on five characteristics. The third column is the relative ability to prevent price collapse in a grid with large-scale solar or wind. The fourth column is the relative amount of electricity sent to the grid at times of higher prices. Some options do not have the ability to send added electricity to the grid. The fifth column is the ability of the system to replace dispatchable generating capacity and avoid the construction of added power plants—this applies to only some technologies within some classes. The sixth column is the practical energy storage duration—hourly to seasonal depending upon the system. These are approximate judgments and significant work will be required to provide good quantitative analyses. The technologies complement and reduce the need for large increases in the transmission grid that are often associated with addition of renewables—costs that can approach a third of the cost of electricity generated from natural gas if renewables produce 30% of all electricity. Structuring options by functional characteristics helps define the roles of wind, solar, and nuclear in a zero-carbon grid. It provides a way to develop R&D portfolios and defines unexplored areas of research.

Table S.1. Classes of Systems to Match Electricity Production to Demand and Impact on Electricity Price Curve

Option	Method to Use Excess Low-Price Electricity	Limit Price Collapse	Electricity To Grid (Relative)	Replace Gen. Capacity (MW)	Storage Times
Electrics: Electricity Storage (Battery and functionally equivalent)	Grid Electricity →Stored Work →Electricity	Limited	1	Limited (Future Grid)	Hour to Day
FIRES: Electricity to Heat Storage to Industry	Grid Electricity →Stored Heat →Heat to Industry	Very Good	0	No	Hour to Week
RATHS: Reactor Associated Heat Storage	Reactor Heat →Stored Heat →Electricity	Limited	1-2	Yes	Hour to Season
NUTOC: Nuclear Reactor Topping Cycle using FIRES Heat Storage (or natural gas, H_2, etc.)	Grid Electricity →Stored Heat in FIRES Reactor Heat + FIRES Heat →Peak Electricity	Good	1-2	Yes	Hour to Day, Seasonal with stored H_2
Hybrid: Co-Produce Electricity and Second Product	Reactor Heat + Grid Electricity → Electricity + Second Product	Good to Very Good	0	No	Hour to Season

Several conclusions are derived from this categorization strategy by the characteristics of different classes of technology.

- *FIRES can potentially limit electricity price collapse associated with the large scale wind and solar deployment and thus improve the economics of wind, solar, and nuclear by converting low-price electricity into high-temperature stored heat for industry*. Because FIRES is a low-cost technology it can set a minimum price for electricity near the cost per unit heat of the fossil fuels used in industrial furnaces and kilns. FIRES is the required coupling technology to enable buying large quantities of electricity from the grid at rates greater than needed as heat for industrial furnaces when the electricity prices are low. It is the changing characteristics of the electricity price curve that creates the incentives to deploy FIRES. If FIRES is successfully deployed, there are other implications for the electricity sector.

  - If solar or wind systems can reduce costs to match fossil fuels per unit of heat, there would be a massive market demand for these technologies to deliver heat to industry through FIRES.
  - FIRES enables a low-carbon electric sector to partly decarbonize the industrial sector and may ultimately provide a large fraction of heat to the industrial sector.
  - FIRES may limit the growth of energy storage systems such as batteries and long-distance transmission lines. The economics of batteries and long distance transmission lines are based on large differences in the price of electricity respectively in time and location. FIRES could reduce these variations in electricity prices by setting a minimum price on electricity.

- *Heat storage (RATHS) is cheaper than electricity storage, has the capability to meet weekly to seasonal electricity storage requirements, and can partly replace the need for electrical generating capacity.* Weekly and seasonal storage are not economically feasible with electricity storage technologies. This implies that nuclear energy coupled to heat storage is an enabling technology for large-scale use of wind and solar by reducing renewable-induced electricity price (revenue) collapse and providing electricity at times of low wind or solar conditions. Thermal storage is cheaper and with higher assurance of recharge when coupled with nuclear than solar thermal. Nuclear plants also have more siting options than solar thermal power plants, which require direct sunlight (southwest U.S.).

- *Hybrid systems have the potential to be the low-cost option*. Storage has associated costs and inefficiencies. Hybrid systems can potentially minimize storage requirements. Hybrid systems with hydrogen production deserve special attention because of the potential ability to transfer low-price energy to the industrial and transport sectors.

- *NUTOC can potentially meet zero-carbon variable electricity grid requirements with the capability to buy low price electricity and prevent price collapse from solar and wind systems.* This is the newest set of options enabled by advances in combined-cycle gas turbine technology in the last 15 years with potential deployment dates near 2030—the planning date for the Chinese FHR. NUTOC would logically burn the last cubic meter of natural gas and the first cubic meter of hydrogen in a low-carbon future for peak electricity production. Advancing gas turbine technology may enable coupling topping cycles to other types of advanced reactors.

- The relative use of the five classes of technologies will vary with location because of the geographical variation in renewable resources and energy demand.

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1. INTRODUCTION

In this century, mankind will transition to a low-carbon energy future—either in the 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. Since the caveman first 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 to convert fuel to heat and light as needed.

In a low-carbon world, the energy sources are nuclear and renewables, primarily 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 that does not match the variable energy needs of mankind. To minimize costs to society new technologies are required that enable capital-intensive generating technologies to operate at full capacity while meeting the variable energy needs of a low-carbon world and improving economics.

Recent reports[1] have assessed national plans for a low-carbon world. There have been many studies of how to achieve a low-carbon world.[2] Most of these studies consider only the electricity sector, ignore seasonal variations in energy demand, and assume a small (or zero) contribution from nuclear energy. Only a few studies, such as the California low-carbon futures study,[3] have considered multiple energy scenarios. None of the studies systematically consider how to integrate nuclear and renewable systems to provide variable electricity on demand while fully utilizing nuclear, wind and solar assets.

This report examines a low-carbon electricity grid and how to integrate nuclear and renewables to assure reliable variable electricity at low costs. Chapter 2 describes how the electricity grid changes as one transitions from a grid based on fossil fuels to a grid based on nuclear, wind, and solar for electricity. Chapter 3 asks the question of how to provide variable electricity to the grid while operating nuclear, wind, and solar generating capacity at full capacity to minimize total costs to society. Chapters 4 through 8 discuss the five categories of technologies to match electricity generation with demand. The categories are defined by functional requirements to enable full use of nuclear, wind, and solar capacity to minimize total costs. Chapter 9 discusses impacts of these technologies on electricity transmission requirements.

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[1] J. Sachs and L. Tubiana (publishers), Sustainable Development Solutions Network and Institute for Sustainable Development and International Relations, *Pathways to Deep Decarbononization*, September 2014.

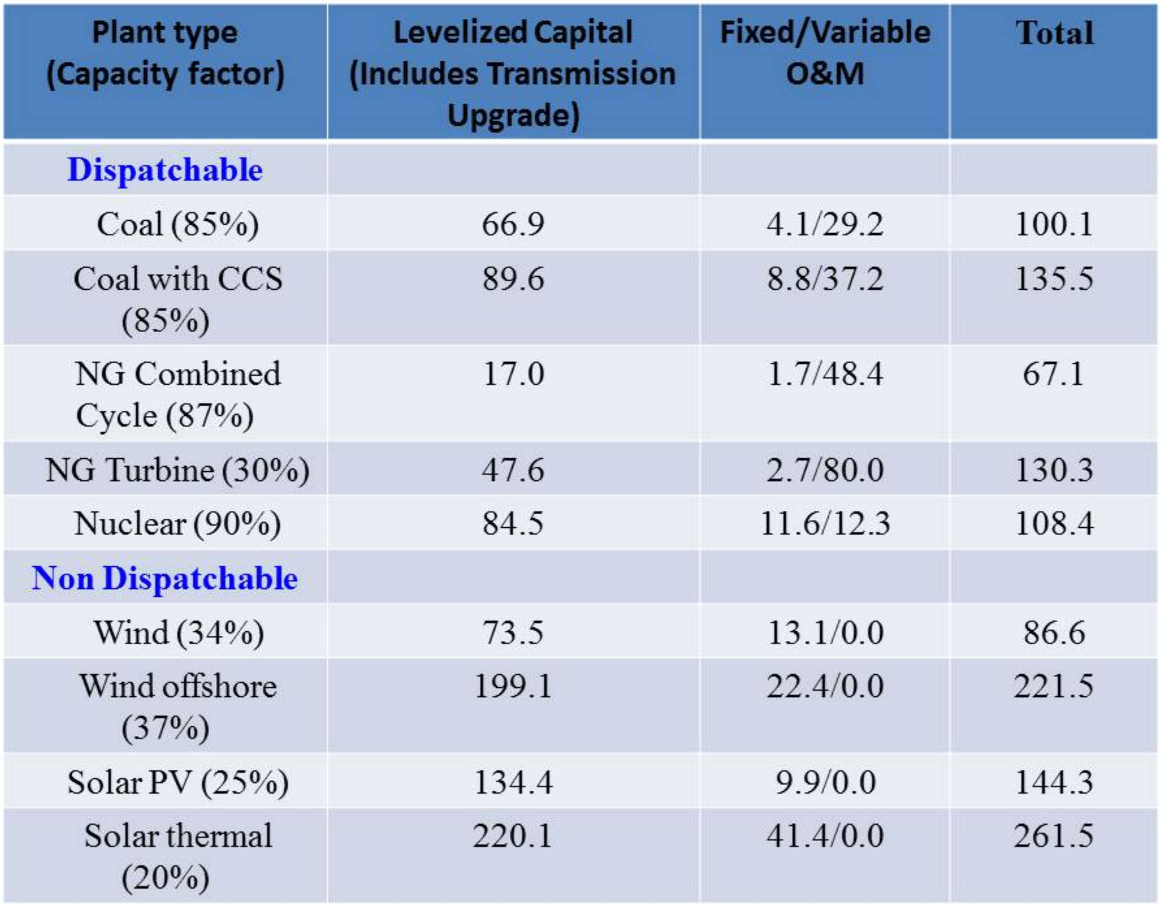
[2] P. Loftus et al., "A Critical Review of Global Decarbonization Scenarios: What do They Tell Us About Feasibility," *Advanced Review*, WIREs Clim Change 2014. Doi: 10.1002/wcc.324.

[3] California Council on Science and Technology, *California Energy Futures – The View to 2050: Summary Report*, April 2011.

Chapter 10 discusses the five technologies in terms of where they may be deployed and the associated research and development needs. Chapter 10 provides summary conclusions.

There are two assumptions. The first assumption is that renewables without subsidies will become significantly more competitive. Table 1.1 shows the current EIA-projected levelized costs of electricity from different sources. Today the only renewables that are economic on a large scale are hydroelectric and wind, with almost all of the competitive wind in the United States on the Great Plains. In the case of solar photovoltaic, there is an ongoing debate whether silicon cell technology costs will drop enough for PV to be a major non-subsidized energy source or whether a more advanced technology will be required.[4]

Table 1.1 Energy Information Agency 2018 Cost Estimates for Generation ($/MWh)[5]



Plant type (Capacity factor)	Levelized Capital (Includes Transmission Upgrade)	Fixed/Variable O&M	Total
Dispatchable			
Coal (85%)	66.9	4.1/29.2	100.1
Coal with CCS (85%)	89.6	8.8/37.2	135.5
NG Combined Cycle (87%)	17.0	1.7/48.4	67.1
NG Turbine (30%)	47.6	2.7/80.0	130.3
Nuclear (90%)	84.5	11.6/12.3	108.4
Non Dispatchable			
Wind (34%)	73.5	13.1/0.0	86.6
Wind offshore (37%)	199.1	22.4/0.0	221.5
Solar PV (25%)	134.4	9.9/0.0	144.3
Solar thermal (20%)	220.1	41.4/0.0	261.5

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[4] Massachusetts Institute of Technology, *Future of Solar Energy*, 2015

[5] Table 1.1 shows that nuclear, wind, and solar costs are dominated by capital costs whereas fossil generation costs have high fuel costs. Two renewables (off-shore wind and solar thermal) have very high costs. The challenge for offshore wind is resisting ocean storms that have historically translated into large quantities of steel and concrete.

The second caveat is about the intrinsic characteristics of renewables. There are large variations in solar and wind resources; as a result, the economics of wind and solar vary with location. Any significant use of wind or solar implies large variations in preferred energy choices with location and therefore, variations in the relative importance of any of the five classes of technologies discussed in this report. There is no one solution for efficiently coupling electricity production (nuclear, wind, and solar) with demand—it will depend upon location and markets.

Solar energy provides the clearest demonstration of this regional variation. Figure 1.1 shows the solar input for northern Chile (Atacama Desert - potentially the best solar site in the world), Southern California and Massachusetts. The Atacama Desert gets more sunshine overall. Equally important is that the seasonal variations in Atacama Desert solar intensity are a fraction of those seen in Massachusetts, which has little solar input in the winter months. The differences in seasonal energy storage costs between Massachusetts and the Atacama Desert to meet electricity demand may well exceed the differences in solar energy production costs; that is, storage, not the cost of solar, would be the primary factor in the viability of solar energy versus other energy sources at high latitudes such as Boston. The seasonal energy storage challenge exists for nuclear, wind and solar—it is the most severe for solar, but remains a challenge for other low-carbon options as well.

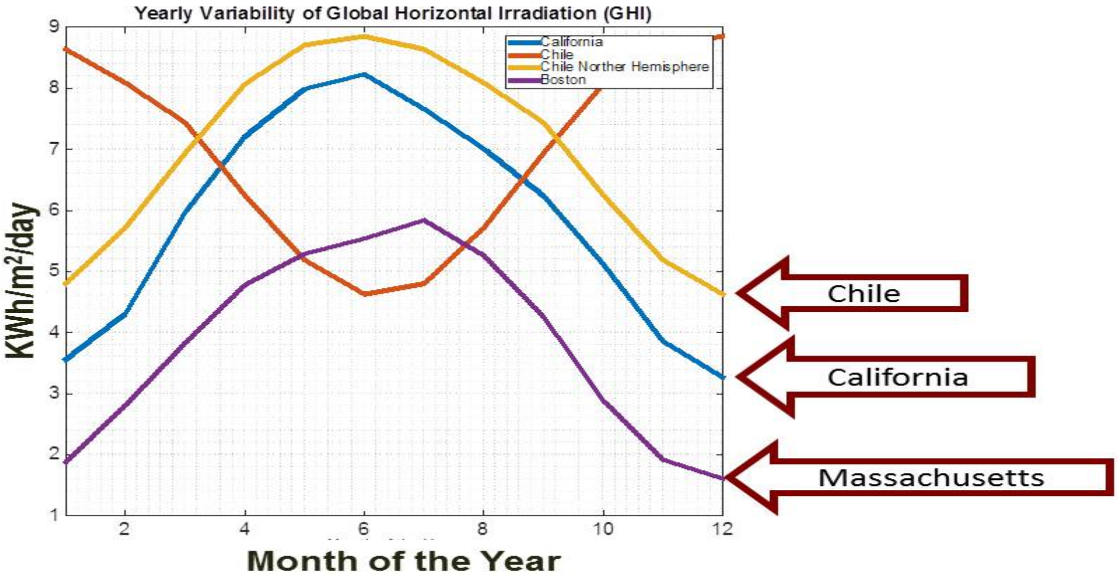

Fig. 1.1. Monthly Solar Input: Atacama Desert (Chile), Southern California and Massachusetts[6]

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[6] Chile is in the southern hemisphere and thus the seasons are offset by 6 months. For comparison, Chile data shown as if it was in the northern hemisphere.

It follows from the variations in solar and wind that these technologies will only be viable in certain parts of the world. This reality is in contrast to fossil fuels, where the energy costs are relatively uniform across the world because fossil fuels can be shipped very long distances by boat and rail at relatively low costs. If the costs of renewables drop dramatically, it would imply that energy intensive industries would be located in countries such as Chile. Unlike a fossil-based energy system that is relatively homogeneous, a low-carbon world will have some mix of nuclear, wind, and solar with large variations in the relative use of different technologies with location.

2. ELECTRICITY GENERATION AND DEMAND: IMPACT OF A LOW-CARBON FUTURE

To evaluate the impacts of transitioning from a fossil-fuel based electric grid to a low-carbon nuclear-renewable grid, the existing grid and potential future changes must be understood—including constraints.

2.1 Economic and Other Constraints

The primary constraint on energy options in a low-carbon world is economics. Historically, between 5 and 10% of the gross national product is energy—with peaks as high as 14%. Four out of five recessions since the 1970s can be explained by oil price shocks.[7] Doubling energy costs imply large decreases in the standard of living for the entire world. In contrast, U.S. defense spending is 4% of the gross national product. A political decision for a 50% increase in defense spending has a much smaller impact on societal standards of living than political decisions on energy options. No enduring political consensus to reduce risks of climate change is likely if it has major impacts on standards of living.

Given world poverty, there is an equally important moral imperative to avoid major increases in energy costs. The rate of energy use, which is the rate of work done, largely determines both national wealth and opportunities for human development. Ninety-three percent of the variation in per capita wealth production can be explained by per capita energy use, work being done. Figure 2.1 shows the United Nations Human Development Index (a composite measure of life expectancy, health, education, and standard of living) versus per capita primary power consumption. Our lives get better and better the more energy we consume—up to a point. That begins to level off at about four to five kilowatts per person. For a world of 8 billion people we will need 32 terrawatts—about twice today's energy consumption. The scale of the challenge requires that the cost of energy be minimized

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[7] C. A. S. Hall et al., ―EROI of Different Fuels and the Implications for Society,‖ *Energy Policy*, **64**, 141-152, 2014.

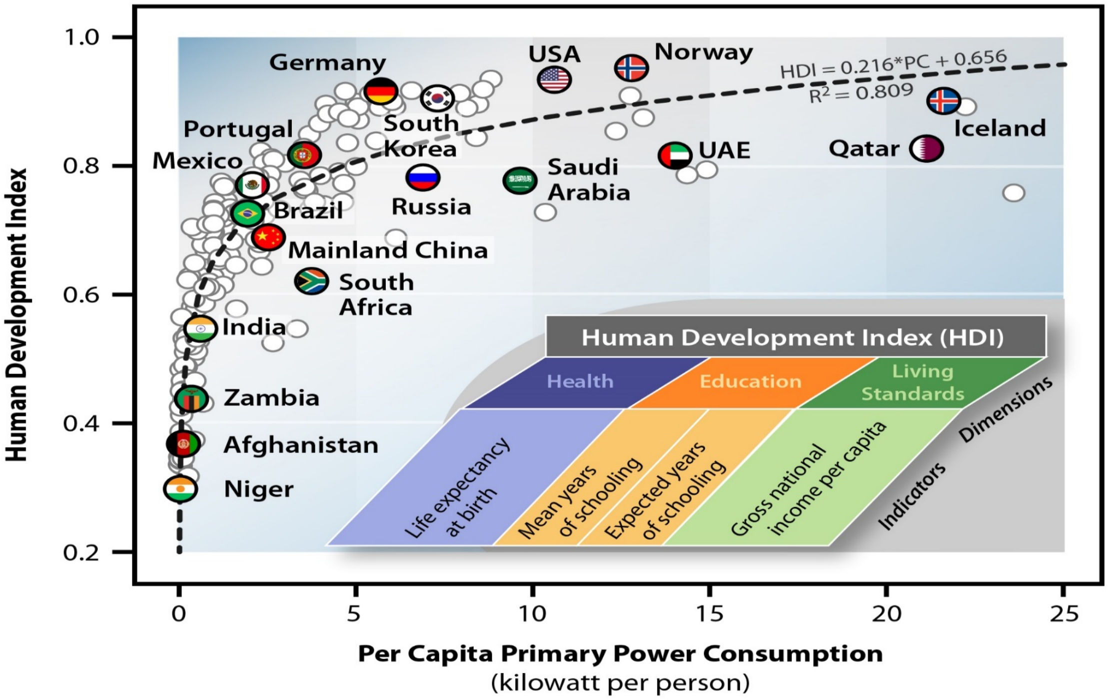

Fig. 2.1. United Nations Human Development Index by Country vs. Per Capita Power Consumption in 2010

2.2 Future Energy Demand

The starting point for defining an energy future is to understand the demand. Figure 2.2 shows existing energy flows in the United States. Today fossil fuels provide most of the primary energy. The electricity sector is the largest primary energy consumer followed by the transport and commercial sectors. A transition to a zero-carbon economy would change energy flows.

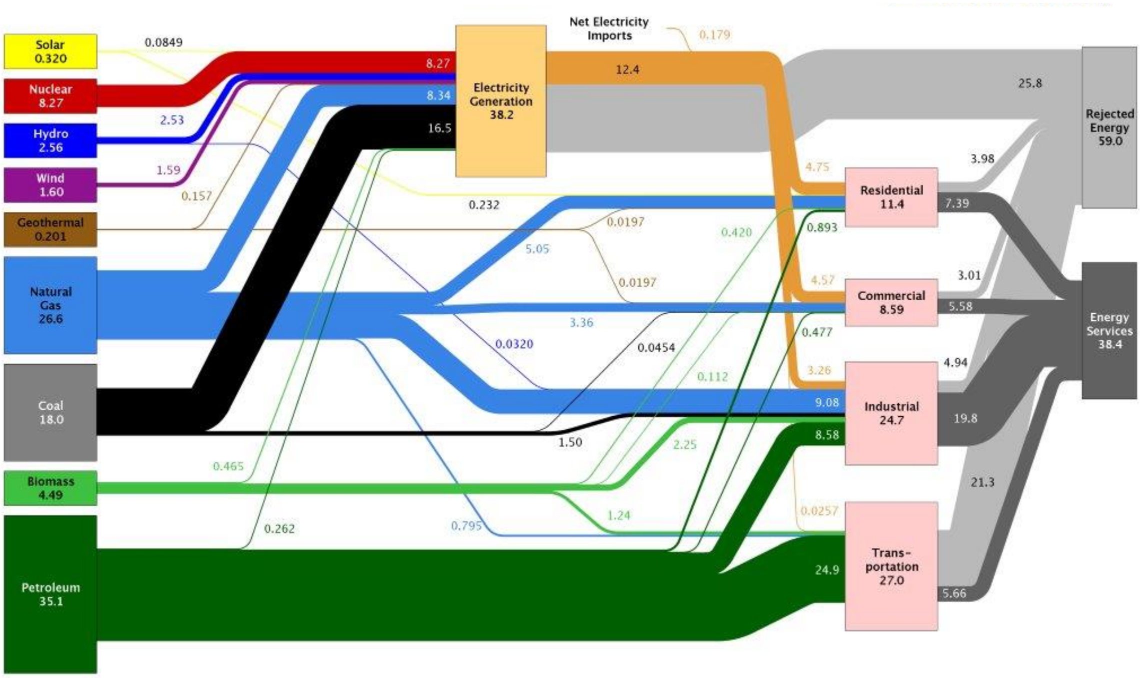

Fig. 2.2. Energy Flow Chart (Quads) for the United States[8]

The California low-carbon study[9] concluded that electricity production would likely double if the goal is to transition a low-carbon economy. This doubling would potentially occur due to (1) replacement of natural gas with electricity in the residential and commercial sectors and (2) partial electrification of the transport sector with hybrid and electric vehicles. Other studies have come to similar conclusions.[10] The other likely change would be a large increase in the production of hydrogen.[11, 12] Hydrogen is used today to produce ammonia fertilizer and in refineries to convert crude oil into liquid fuels. Its production uses about 1% of U.S. energy consumption. In a low-carbon economy, there are other potentially large markets for hydrogen.

- *Chemical reduction agent*. Carbon is used to convert metal ores such as iron oxide into metal. In a zero-carbon world hydrogen would replace carbon as the preferred chemical reducing agent. Currently about 4% of the world's iron is made using hydrogen from natural gas.

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[8] Lawrence Livermore National Laboratory, *Energy Flow Diagrams*, https://flowcharts.llnl.gov/

[9] California Council on Science and Technology, *California Energy Futures – The View to 2050: Summary Report*, April 2011.

[10] J. H. Williams, A. DeBenedictis, R. Ghanadan, A. Mahone, J. Moore,, W. R. Morrow III, , S. Price, M. S. Torn, "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: the Pivotal Role of Electricity," *Science*, **335** (6064), 53-59, 2012.

[11] C. W. Forsberg, "Future Hydrogen Markets for Large-Scale Hydrogen Production Systems," *Int. J. Hydrogen Energy*, **32**, 431, 2007.

[12] C. W. Forsberg, "Is Hydrogen the Future of Nuclear Energy?," *Nuclear Technology*, **166**, 3-10, April 2009

- *Hydrocarbon liquid fuels*. Replacement of fossil liquid fuels for transportation is the largest single challenge to a zero-carbon world.[13] While partial electrification of the transport system appears credible, there remains a need for gasoline, diesel, and jet fuel. These hydrocarbons can be produced from biofuels.[14] A major constraint is the availability of biomass. However, the yield of hydrocarbon fuel per kilogram of biomass is strongly dependent upon the input of hydrogen to the production process (Table 2.1). The use of more hydrogen can greatly increase liquid fuels production per ton of biomass feedstock.

Table 2.1. Options for Producing Hydrocarbon Fuels from Biomass[15]

Platform	Yield, Kg Octane per Kg Cellulose	Conversion Efficiency	Input Energy from Hydrogen
Thermochemical	0.310	86%	0%
Sugar	0.352	92.9%	4.9%
Carboxylate (Kolbe Electrolysis)	0.422	89.7%	23.4%
Carboxylate (2° Alcohol)	0.469	88.2%	32.3%
Carboxylate (1° Alcohol)	0.528	86.8%	40.8%

- *Fossil fuel replacement*. Hydrogen may be used to replace fossil fuels as a fuel for several applications, such as peak electricity production or use in cars. However, the production of hydrogen from water is energy intensive, implying that hydrogen will be a premium fuel. Many of these applications require technology breakthroughs, such as hydrogen storage for transport vehicles.

2.3 Matching Electricity Production with Demand

Separate from the need for energy is the requirement to deliver that energy when needed—be it to heat homes in winter or to provide electricity to an industrial facility. With fossil fuels, particularly natural gas, variable energy output is achieved by variable input into power plants. This is economically viable because most of the cost of electricity is the cost of the natural gas (Table 1.1)—the economic penalty of operating a natural gas plant at part load is small. In contrast, nuclear, wind and solar plants have high capital costs and low operating costs. Operating these plants at partial load is very expensive. Energy storage or some other technology is required to match energy production with demand.

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[13] L. Fulton, L. Lynd, A. Korner, N. Green, L. Tonachel, "The Need for Biofuels as Part of a Low Carbon Energy Future," *Biofuels, Bioproducts, and Biorefining*, 2015.

[14] B. Dale and M. Holtzapple, "The Need for Biofuels," *Chemical Engineering Progress*, **111** (*3*), 36-40, March 2015.

[15] M. Holtzapple, S. Lonkar, and C. Granda, "Producing Biofuels via the Carboxylate Platform", *Chemical Engineering Progress*, **111** (*3*), 52-57, March 2015.

Within the electrical sector[16] the mismatch between electricity production and demand for the state of California was analyzed assuming all electricity was produced by wind, solar, or nuclear. This provides a perspective on the challenge of matching electricity production with demand using storage or an equivalent technology. Electricity demand varies with daily, weekly (workweek and weekend), and seasonal cycles. The electricity storage requirements for California were estimated under three idealized futures where all electricity was generated by (1) nuclear, (2) wind or (3) solar. California was selected for this study because, unlike most other states, it has significant wind and solar resources.

The electricity demand was the hourly California electricity demand for 8760 hours per year. In each of the three cases with different sources of electricity (1) the electricity source over one year generated the total kilowatt hours consumed over one year, (2) the electricity source operated at its full capacity to minimize electricity production costs, (3) electricity was stored when production exceeded demand to be provided to customers when demand exceeded production, and (4) there were no losses or inefficiencies in the electricity storage systems.

- *Nuclear*. All electricity is from nuclear plants with steady-state output for 8760 hr./y.

- *Solar*. All electricity is from solar thermal trough systems in the California desert using the National Renewable Energy Laboratory (NREL) model for performance and California solar data for 8760 hours. This system has limited internal thermal energy storage.

- *Wind*. All electricity is from wind systems using California wind data and the NREL model for wind farm performance. It is unclear if California has sufficient wind to meet its total needs.

The results are shown in Table 2.2, where storage requirements are defined as the fraction of total electricity that is produced that must go into storage when production exceeds demand to provide the electricity to meet demand when production is less than demand. The U.S. electrical annual electrical consumption is about 500 gigawatt-years. This provides a perspective on the scale of the challenge for storage or other technologies for alternative low-carbon electrical systems for the U.S.

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[16] C. W. Forsberg, "Hybrid Systems to Address Seasonal Mismatches Between Electricity Production and Demand in a Nuclear Renewable Electricity Grid," *Energy Policy,* **62***,* 333-341, November 2013.

Table 2.2. California Electricity Storage Requirements as the Fraction Total Electricity Produced

	Hourly	Daily	Weekly
Nuclear	0.07	0.04	0.04
Wind	0.45	0.36	0.25
Solar	0.50	0.21	0.17

The hourly storage requirement refers to storage requirements based on production and demand, with analysis performed hour-by-hour for the 8760 hours in a year. For example, in the case where all California electricity is generated by nuclear power plants, 7% of the electricity that is generated goes into storage. This occurs when electricity demand is less than nuclear electricity production. This 7% is then used to meet electricity demands when demand exceeds production from the nuclear power plants.

The daily storage requirements assume some other technology (rechargeable hybrid electric vehicles, smart grids, pumped hydroelectric, etc.) results in a constant electricity demand each day (total electricity consumed in one day divided by 24 hours). This measures the fraction of electricity produced that must be stored in storage systems that can economically store electricity for more than one day. For example, the daily storage requirement for wind is 36% of all wind production. There are days when the wind does not blow, thus a wind system to provide all of California's energy demand requires a storage system to store energy from windy days for days when the wind does not blow.

The weekly storage requirements assume other technologies result in a constant electricity demand for each week. It measures the fraction of electricity produced that must be stored in storage systems that can economically store electricity for more than one week. For example, the weekly storage requirement for solar is 17% of all solar production. California's energy consumption peaks in the summer; these peaks only partly match solar production. However, the seasonal variation in solar production is greater than the seasonal variation in electricity demand, so there is a seasonal storage requirement that this parameter measures.

While there are many technologies to address short-term energy storage[17] (rechargeable hybrid electric vehicles, smart grids, pumped hydroelectric, batteries, etc.), there are no commercial technologies to address weekly and seasonal energy storage needs—half the potential energy storage market. While energy storage (coal piles, oil tanks, etc.) is a trivial economic challenge for fossil fuels, it presents a major economic challenge for a zero-carbon world. Consider a storage device that costs $300/kWh of storage capacity and operates for 10

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[17] Electric Power Research Institute, *Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits*, 1020676, 2010

years. If the electricity storage device is used 300 days per year, the capital-cost part of the storage cost per kWh is \$0.10/kWh (\$300/[300x10 cycles])—about the retail price of electricity today. If the same device is used for seasonal storage it will only be cycled 10 times in its lifetime, with a capital cost of storage of \$30/kWh—a prohibitively high cost.

The cost constraints for seasonal storage imply that the storage material has to have low costs. Thus far we have identified only two energy storage mechanisms that meet this requirement: heat and hydrogen. In each case the round trip efficiencies are lower than for short-term energy storage systems, such as batteries and pumped hydroelectric. Hybrid energy systems are the other class of options where the system produces electricity and some other product when production exceeds demand.

Electricity storage requirements for nuclear systems were both small and similar across the U.S. due to two factors. First, nuclear power produces steady-state electricity and two-thirds of electricity demand is base-load (Fig. 2.3). Second, most of the variable demand for electricity is not far above base-load. If one built sufficient nuclear power to meet average electricity demand (50% above base-load), that added capacity would meet most of the variable load that is above base-load. The relatively good match between nuclear production and electricity demand gives nuclear a competitive economic advantage relative to wind and solar in a low-carbon world because of lower investments in energy storage systems required to meet variable electricity demand.

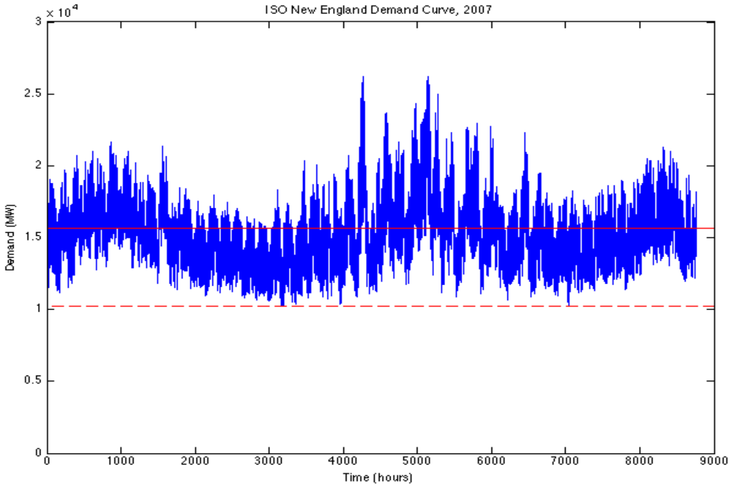

Fig. 2.3. New England Electrical Demand over One Year with Base-load and Average Demand

Storage requirements for solar and wind power systems are sensitive to latitude and climate. The southern California deserts are at latitude 34 N, the same as southern Spain, northern

Morocco, and southern Japan. California has good sky (low cloud) conditions, unlike southern Japan at the same latitude with high annual cloud cover.[18]

The other factor for solar storage requirements is latitude. Figure 2.4 shows monthly solar input for Massachusetts, Southern California and the Atacama Desert in Chile. The Atacama Desert may be the best solar site on earth—driest desert in the world, high elevation, and near the equator. The total solar input near the equator is higher since the earth's surface is perpendicular to the sun versus at an oblique angle. However, seasonal variations are equally important. The large seasonal variation in solar input in Massachusetts implies large seasonal storage requirements for a solar system versus much smaller seasonal storage in the Atacama Desert. The costs of those storage devices and the associated energy conversion inefficiencies implies that at higher latitudes the storage costs may exceed solar production costs—in addition to the higher costs of solar systems per unit of energy delivered at higher latitudes due to lower solar input.

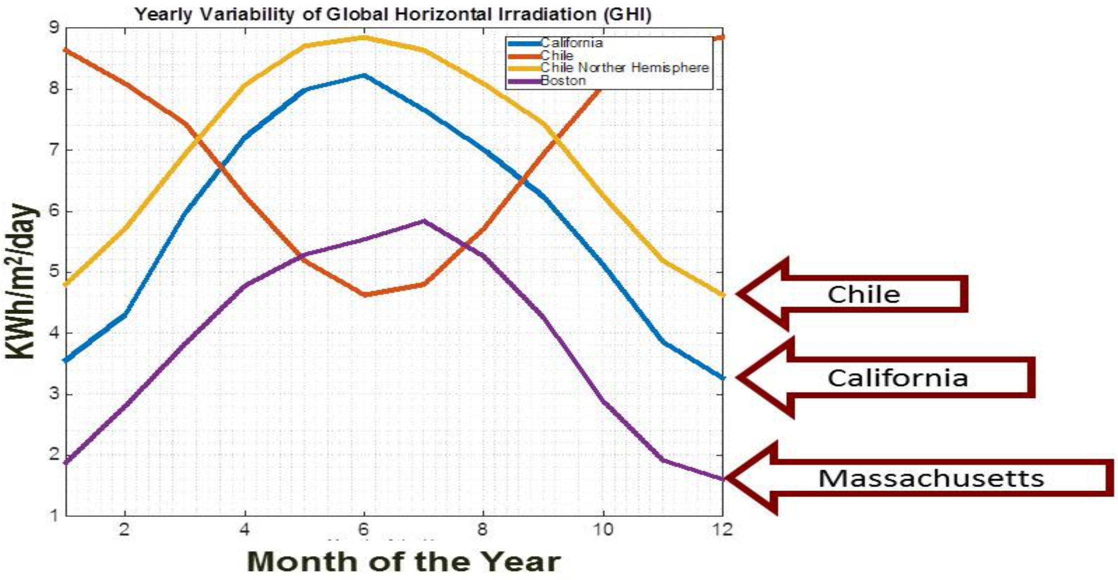

Fig. 2.4. Monthly Solar Input: Massachusetts, Southern California and Atacama Desert (Chile)

Last, the variable demand and the characteristics of the power generating system define many other characteristics of storage or any other system used to couple nuclear, wind, and solar with electricity demand. Any storage device is characterized by three parameters: charging rate (kW), capacity (kWh), and discharge rate (kW). If the generating system contains significant solar

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[18] S. G. Warren and C. J. Hahn, *Climate Atlas of Clouds over Land and Ocean*, University of Washington, http://www.atmos.washington.edu/CloudMap/index.html, 2012.

input, very high power discharge rates (kW) are required because solar peaks in the middle of the day, resulting in very short peak demand for increased electrical output by other electricity generating technologies just before and just after peak solar input. In contrast, wind patterns tend to result in several days of high wind conditions followed by several days of low wind conditions—as seen by the high weekly storage requirements for wind in Table 2.2. The charging rate (kW) for a storage system coupled to a wind system will be lower, but there is a greater need for a large amount of multiday storage capacity (kWh). The technology choices for storage coupled to wind and solar may be very different.

2.4 Market Implications of a Low-carbon Electricity Grid

Figure 2.5 shows an electricity price curve for a fossil-dominated (existing) electricity grid, where the horizontal axis shows the wholesale price of electricity ($/MWh) and the vertical axis shows how many hours per year electricity could be bought at a particular price. This specific example (blue bars) uses electricity price data from the Texas market in 2012. The price curve for an electrical grid primarily based on generating electricity from fossil fuels is a bell shaped curve. At times of low demand the power plants with the lowest operating costs produce electricity, resulting in a low market price for electricity. At times of high electricity demand, old inefficient units or units that burn more expensive fossil fuels are brought on line at high cost and set the wholesale price of electricity—resulting in high electricity prices at those times. There is an apparent minimum price of electricity that is set by the cost of fossil fuels. Sales of electricity below this price occur at times of very low demand when the operating cost of hydroelectric, nuclear or wind set the price of electricity.

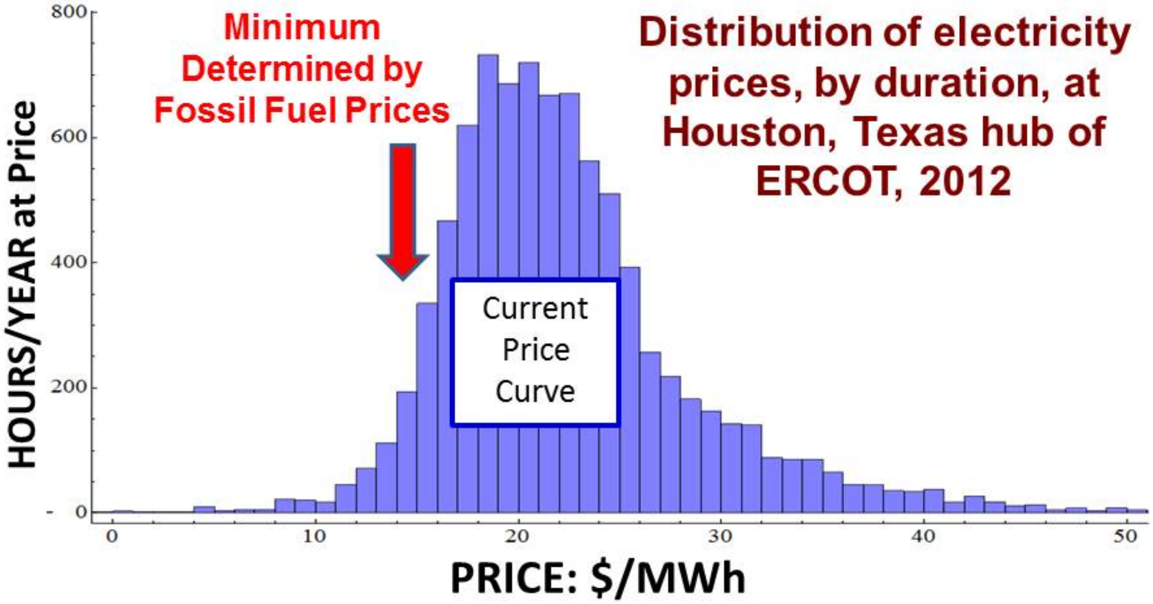

Fig. 2.5. Electricity Price Curve for Fossil-Dominated Texas Grid

The large scale addition of renewables changes the price curve. The recent MIT *Future of Solar Energy*[19] evaluated the price paid to solar power generators as solar capacity is added to the grid (Fig. 2.6). When the first solar power systems are added, they receive above average prices because most of the electricity is produced in the middle of the day at times of high electricity demand. As more solar is added, it begins to depress the electricity prices on sunny days with low electricity demand. Eventually the added solar approaches the midday demand for electricity and the price goes to near zero at this time as production exceeds demand—that is, electricity price collapse occurs. Collapsing prices discourage further investment in wind and solar generators—costs may go down but if the price goes down faster no one can afford to add wind or solar. The same effect occurs if nuclear plants are added when nuclear approaches 70% of total electricity generating capacity.

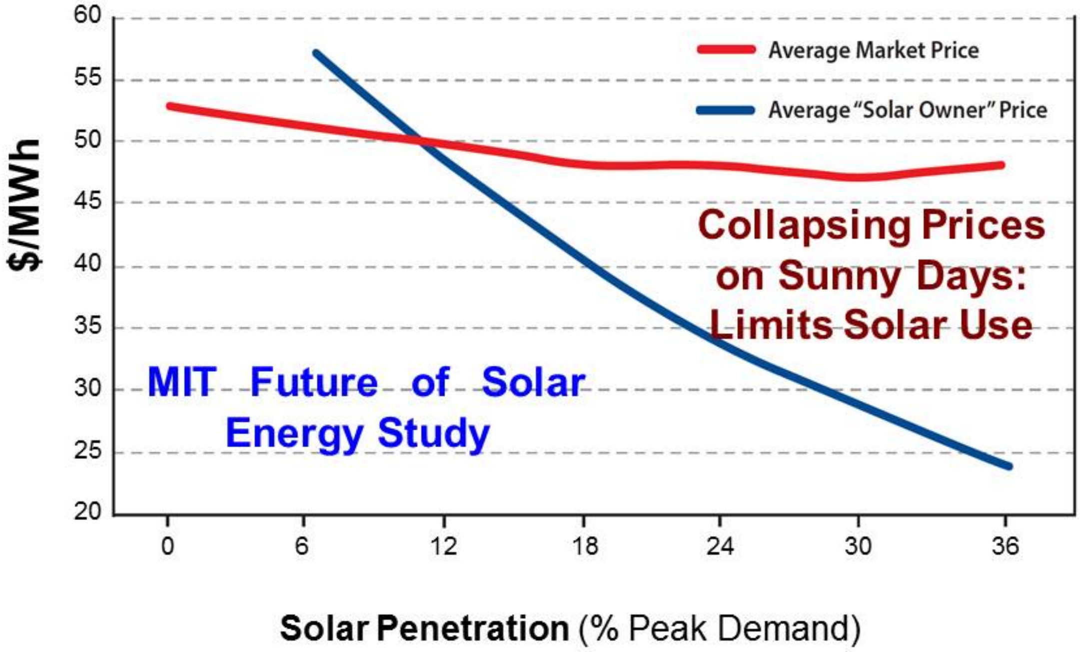

Fig. 2.6. MIT *Future of Solar* Price Curve for PV with Increased Solar Market Penetration

Figure 2.7 shows the market price of electricity versus the number of hours per year that electricity can be bought at different prices in California (blue bars). This grid is beginning to see the addition of significant wind and solar electricity generation. There are near-zero and negative prices for a significant number of hours per year when electricity production exceeds demand and electricity generators pay the grid to take electricity. This is a consequence of three effects.

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[19] *Future of Solar Energy*, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2015.

- *Added renewables*. The operating cost for wind and solar is very low. At times of low electricity demand and high solar output, these renewables drive down the price of electricity.
- *Renewables subsidies*. Production tax credits provide revenue for wind and solar plants to produce output independent of electricity prices. An owner of a wind or solar facility will sell electricity at negative prices (he pays the grid to accept the electricity) as long as the subsidies he receives are greater than the costs to sell electricity at negative prices. The taxpayer rather than the electric ratepayer is paying for the electricity.
- *Operational constraints*. Nuclear and fossil plants cannot instantly shut down and restart. These plants pay the grid at times of negative prices to remain on-line and thus be able to sell electricity a few hours later at high prices. This further depresses prices at times of high wind or solar input so the effects of price collapse show up earlier than might be expected.

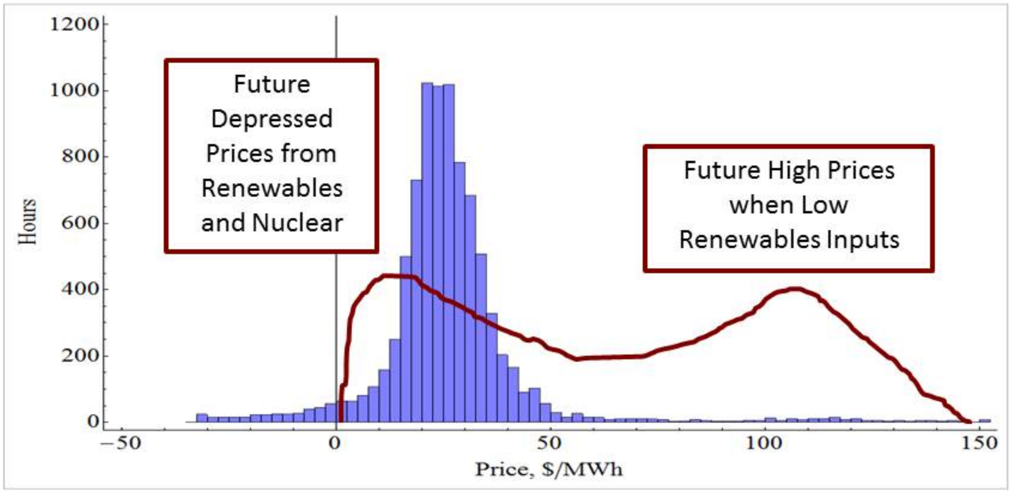
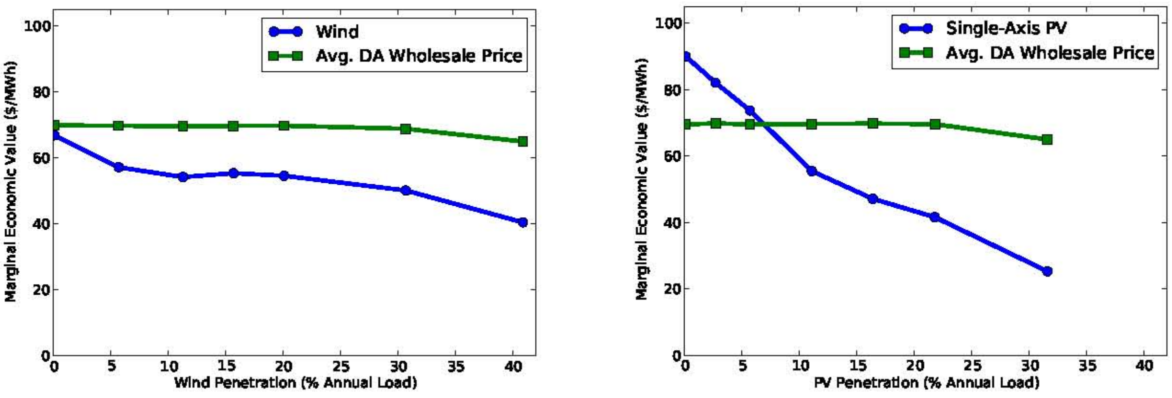


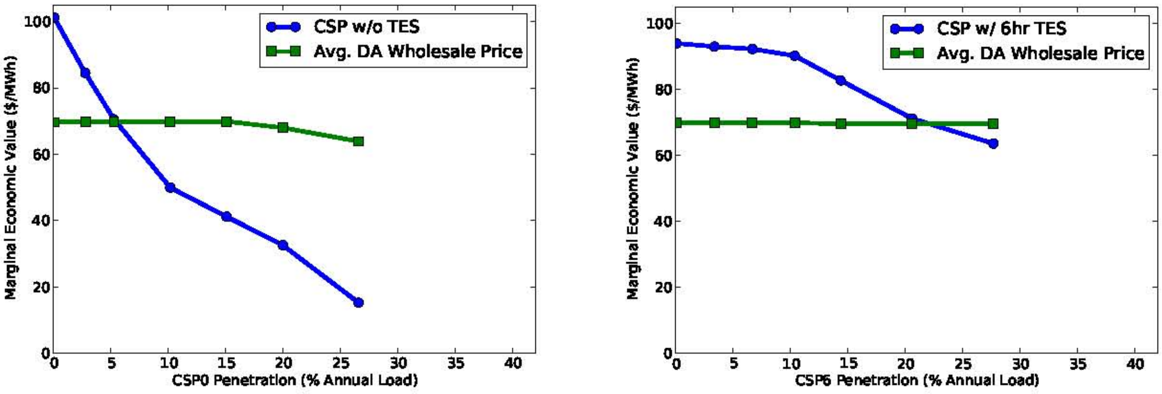
Fig. 2.7. Distribution of Electrical Prices (bar chart), by Duration, Averaged over CAISO (California) Hubs (July 2011-June 2012) and Notational Price Curve (Red Line) for Future Low-Carbon Grid.

The addition of significant non-dispatchable wind or solar changes the shape of the price curve. The first addition of solar electricity is sold at higher than average prices because the electricity is added at times of peak demand. However, as more solar is added, it drives down the price of electricity midday on sunny days. Each solar owner will sell electricity at whatever price exists above zero. This implies that when 10 to 15% of the total electricity demand is met by solar in California, the output from solar systems at midday for parts of the year will exceed electricity demand, the price of electricity will collapse to near or below zero, and the revenue to power plants at these times will collapse to near zero. Each incremental addition of solar at this point lowers the revenue for existing solar electricity producers.

Figure 2.8 provides a specific example from California that shows the expected decrease in revenue to owners of wind and solar plants as more renewables are added to the California grid.[20] The percentage of each renewable (percent penetration on the horizontal axis) is the percentage of the total annual electricity demand met by that renewable. Four types of renewables are considered: wind, photovoltaic, solar thermal and solar thermal with thermal energy storage (TES). In each case the revenue in $/MWh drops dramatically as there is increased use of that form of wind or solar electricity.



(a) Wind (b) PV



(c) CSP_0 (d) CSP_6

Fig. 2.8. Marginal Economic Value of Variable Generation and an Annual Flat-Block of Power with Increased Penetration of Variable Generation by 2030.

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[20] A. Mills and R. Wiser, *Changes in the Economic Value of Variable Generation at High Penetration levels: A Pilot Case Study of California*, LBNL-5445E, Ernest Orlando Lawrence Berkeley National Laboratory, June 2012.

The average day-ahead (DA) wholesale electricity price is also shown in each case. This is a remarkable story by itself. Take the example of PV (Case B). By the time PV is providing almost a third of the electricity in California, the price paid for electricity to PV owners has dropped by 70%--but it has had essentially *no impact on the price of electricity to the customer*. The savings from the lower prices paid to PV owners has been used to maintain large quantities of costly peaking capacity to be used at times of low solar input. Because the peaking systems are run fewer hours per year, new electricity peaking systems (primarily natural gas) are not built until the price of electricity when these systems are run is increased. One has created the double hump price curve shown in Figure. 2.7.

Table 2.3 shows the U.S. Energy Information Agency estimate of unsubsidized delivered costs of different sources of electricity. Today the cost of unsubsidized renewables exceeds the price for electricity by a significant margin in all cases except land-based wind. Without large subsidies, almost no renewables would be built today given the competition with natural gas. Equally important is the gap between wind and solar electricity costs and prices. Because of price collapse, the required subsidies to add a unit of wind or solar electricity increases as these technologies are deployed on a larger scale--unless the costs of these renewables drops faster than the revenue collapse with larger scale deployment. Other studies[21, 22, 23] show similar results.

Electricity price collapse is happing faster than the decreases in solar and wind costs with larger-scale deployment in most locations. If there is to be larger-scale deployment of wind and solar either (1) the cost of wind and solar must drop much more rapidly or (2) new technologies are required to stop electricity price collapse. However, price collapse does not just impact wind or solar. Price collapse associated with wind or solar hurts the relative economics of all capital-intensive low-operating-cost technologies: nuclear, wind and solar. Price collapse benefits natural gas.

While this is described in the context of markets, it also exists in regulated electricity grids. The fundamental problem is that it is costly to operate capital-intensive electricity generating technologies at part load. The effective capital cost of a nuclear, wind, or solar plant per unit of capacity is doubled if those plants operate at half capacity. To minimize costs to society, these technologies must be operated at full capacity.

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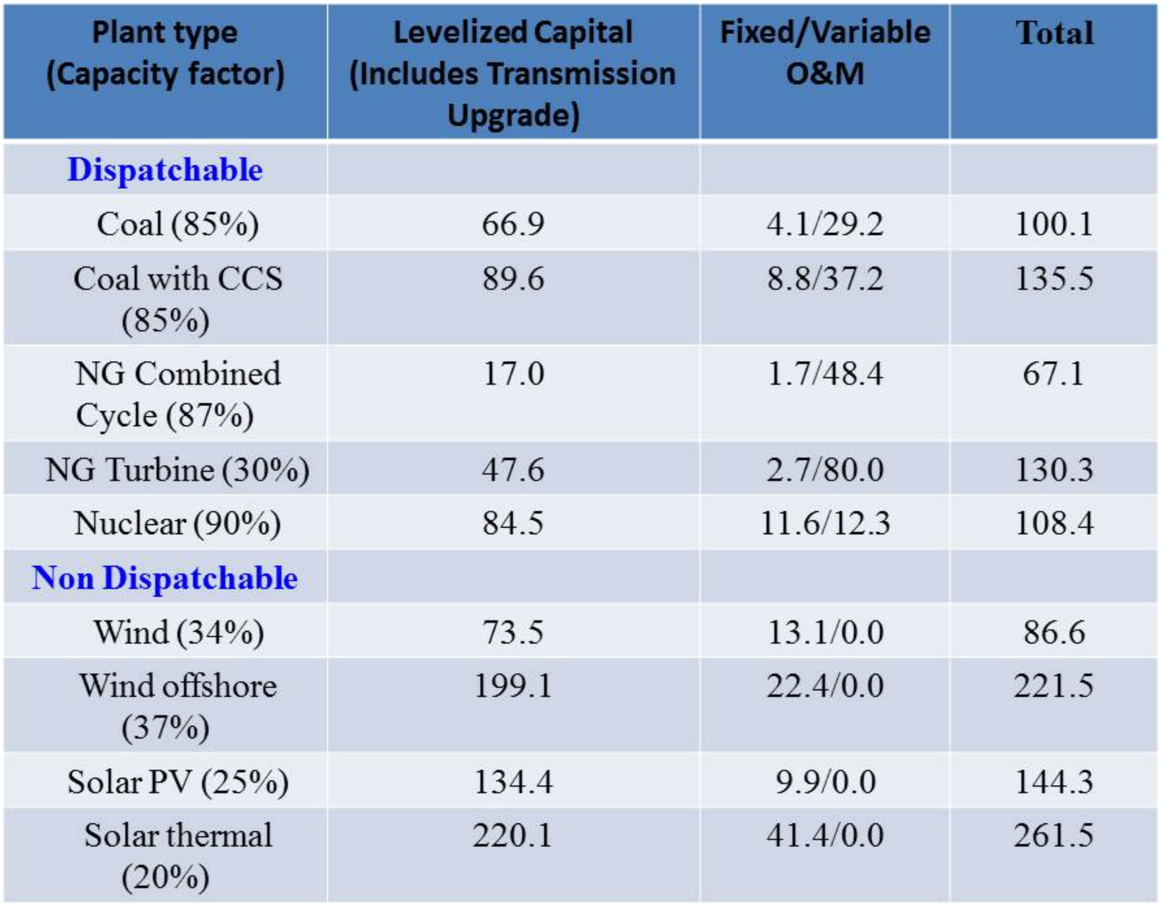
[21] Massachusetts Institute of Technology, *Future of Solar Energy*, 2015.

[22] L. Hirth, "The Market Value of Variable Renewables, the Effect of Solar Wind Power Variability on Their Relative Prices," *Energy Economics*, **38**, 218-236, 2013.

[23] L. Hirth, "The Optimal Share of Variable Renewables: How the Variability of Wind and Solar Power Affects their Welfare-Optimal Development," *The Energy Journal*, **36** (1), 2015.

Table 2.3. Energy Information Agency 2018 Cost Estimates for Generation ($/MWh)



Plant type (Capacity factor)	Levelized Capital (Includes Transmission Upgrade)	Fixed/Variable O&M	Total
Dispatchable			
Coal (85%)	66.9	4.1/29.2	100.1
Coal with CCS (85%)	89.6	8.8/37.2	135.5
NG Combined Cycle (87%)	17.0	1.7/48.4	67.1
NG Turbine (30%)	47.6	2.7/80.0	130.3
Nuclear (90%)	84.5	11.6/12.3	108.4
Non Dispatchable			
Wind (34%)	73.5	13.1/0.0	86.6
Wind offshore (37%)	199.1	22.4/0.0	221.5
Solar PV (25%)	134.4	9.9/0.0	144.3
Solar thermal (20%)	220.1	41.4/0.0	261.5

The same effect occurs as one adds wind capacity, but wind input is more random. As wind penetrates the market it drives the price of electricity down on days with high wind conditions and low electricity demand. Recent studies have estimated this effect in the European market.[24, 25] If wind grows from providing 0% to 30% of all electricity, the average yearly price for wind electricity 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 could provide the total electricity demand, but the price of electricity would be near zero; hence, 28% of all wind energy would be sold in the market for prices near zero. The results are presented as Euros to avoid adding the uncertainties of currency exchange

The 'value factor' is defined as the average price at which a generation technology sells its electricity divided by the load-weighted market electricity price. At low penetration, wind and solar generally exhibit value factors of greater than unity as they tend to produce at hours of high

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[24] L. Hirth, "The Market Value of Variable Renewables, the Effect of Solar Wind Power Variability on Their Relative Prices," *Energy Economics*, **38**, 218-236, 2013.

[25] L. Hirth, "The Optimal Share of Variable Renewables: How the Variability of Wind and Solar Power Affects their Welfare-Optimal Development," *The Energy Journal*, **36** (1), 2015.

demand. The value factor drops sharply as renewables penetration increases. A review[26] of estimates of the value factor of solar across a wide range of electricity markets found that it is significantly greater than unity and can be as high as 1.3 for the first unit of solar installed on a grid. However, multiple reviewed studies found that the value factor drops sharply – ranging between 0.9 and 0.4 – as solar reaches 10% to 30% market share. The same effect will occur with nuclear but only when nuclear provides ~70% of the total electricity demand. This is because nuclear plants run at base-load, which is approximately 70% of electricity demand.

These market effects lead to several conclusions.

- In a competitive market non-dispatchable electricity generation causes price collapse at times of peak production. This occurs first with solar because it peaks in the mid-day in June. Price collapse reflects the low value of electricity at these times. This effect occurs when solar approaches 10% of all electricity produced, wind approaches 20% of all electricity produced, and nuclear approaches 70% of all electricity produced.
- Improving the economics of the technology will have limited impact on the scale of deployment of that technology once the technology is deployed on a large enough scale if price collapse determines revenue.
- Price collapse most hurts the specific technology being deployed but also hurts the relative economics of all low-operating-cost high-capital-cost generating technologies (nuclear, wind, and solar) compared to high-operating-cost low-capital-cost generating technologies (fossil fuels).
- Price collapse strongly favors deployment of fossil electricity generation to provide electricity at times of low nuclear, wind, and solar output. Fossil plants have low capital costs and high operating costs relative to nuclear, wind, and solar. They are the preferred generating technology for partial-load operation.

These effects have been seen in countries such as Germany[27] that have provided large subsidies to renewables. The consequences have been reductions in wholesale electricity prices at times of high wind and solar output, increased prices to consumers where the electricity bills include surcharges to pay for those subsidies, and no drop in greenhouse gas emissions. There was no change in greenhouse gas emissions because in Germany soft coal became the economically preferred backup source of electricity for the added renewables—an unintended consequence. Figure 2.9 shows household electricity rates by country in 2012, with high electricity costs appearing in Germany (wind and solar) and Denmark (wind). Since then there have been additional large increases in German electricity prices as renewables have grown to a

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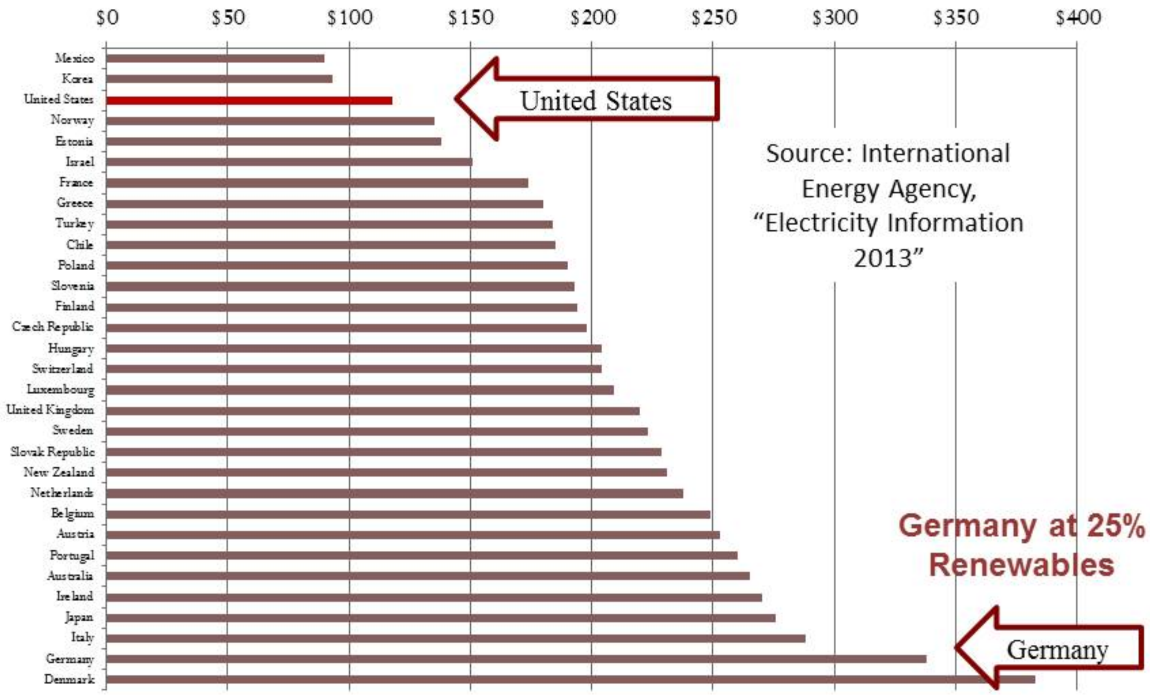
[26] L. Hirth, "The Optimal Share of Variable Renewables: How the Variability of Wind and Solar Power Affects their Welfare-Optimal Development," *The Energy Journal*, **36** (1), 2015.

[27] H. Poser et al., *Development and Integration of Renewable Energy: Lessons Learned from Germany,* Finadvice, FAA Financial Advisory AG, Switzerland, July 2014.

quarter of the electricity production. The low electricity rates in the U.S. are a consequence of low natural gas prices. The cost of renewables in the U.S. is not fully seen in household electricity rates because of a political decision to subsidize renewables at the federal level with a production tax credit; that is, taxpayer subsidies rather than electricity ratepayer subsidies. This will change with time because many states have renewable portfolio standards (required amounts of renewables) where those costs will be ultimately paid by the electricity ratepayer.



United States

Source: International Energy Agency, "Electricity Information 2013"

Germany at 25% Renewables

Germany

Fig. 2.9. Electricity Prices of Households in Dollars per MWh (2012)

Market analysis shows fundamental differences in behavior between electricity systems with significant low-capital-cost high-operating-cost electric generating systems (fossil fuels) versus electricity generating systems dominated by high-capital-cost, low-operating-cost generating systems (nuclear, wind, and solar). The technical problem is the mismatch between electricity generation and electricity production. The implication is that if one is to create a low-carbon electricity grid, one must develop technologies that enable capital-intensive generating systems to operate at full capacity while avoiding price collapse to enable large-scale deployment. Subsidies can force a technology into the market even if there is price collapse, but the cost to society increases—via the price of electricity and the costs of the subsidies. Price collapse must be avoided to minimize total electricity costs to society (price plus subsidies).

2.5 Grid Level System Costs

Different types of electrical generators have different associated grid costs. Table 2.4 shows these estimated costs for the United States for adding different types of electricity generation. As a basis of comparison, the EIA estimate for the generating cost of electricity in 2018 is $67.10 /MWh. If 30% of the electricity is generated by wind or solar, the added grid costs for these renewables can approach a third of the cost of generating electricity from natural gas. Transmission is a major contributor to the total cost of electricity. The technologies described in the report can significantly reduce these costs. Chapter 9 discusses in further detail the coupling of the technologies in this report and impacts on the transmission grid cost structure.

Table 2.4. Grid-Level System Costs in the United States ($/MWh)[28]

Technology	Nuclear		Coal		Gas		Onshore Wind		Offshore Wind		Solar	
Penetration Level	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%
Backup Costs	0.00	0.00	0.04	0.04	0.00	0.00	5.61	6.14	2.10	6.85	0.00	10.45
Balancing Costs	0.16	0.10	0.00	0.00	0.00	0.00	2.00	5.00	2.00	5.00	2.00	5.00
Grid Connection	1.56	1.56	1.03	1.03	0.51	0.51	6.50	6.50	15.24	15.24	10.05	10..5
Grid Reinforcement & Extension	0.00	0.00	0.00	0.00	0.00	0.00	2.20	2.20	1.18	1.18	2.77	2.77
Total	1.72	1.67	1.07	1.07	0.51	0.51	16.30	19.84	20.51	28.26	14.82	28.27

These costs assume the existing grid system; thus, backup costs for times of no solar or wind implies the use of natural gas. Balancing costs refers to the ability to maintain system performance on a minute-to-minute basis in the presence of uncertainty in supply and demand. Grid connection costs are high for offshore wind and solar but for different reasons. Offshore wind connection costs reflect the costs of undersea power cables. Higher solar connection costs are a consequence of several factors: (1) solar capacity factors are ~20% versus 90% for nuclear—implying more than four times as much grid is required to move one kWh of electricity and (2) grid costs are strongly dependent on whether the solar is distributed or utility scale. As analyzed in the MIT *Future of Solar Energy* study, large-scale distributed solar has higher grid connection costs because with distributed solar, peak solar production determines distribution grid sizing and distribution grids are an expensive way to move electricity relative to high-voltage grids (See Chapter 9).

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[28] Nuclear Energy Agency, *Nuclear Energy and Renewables: System Effects in a Low-Carbon Electrical Systems*, Paris, France, 2012.

In addition, there are other impacts[29] including grid stability from the addition of large-scale non-dispatchable wind and solar. These impacts are much less severe with solar thermal technologies where storage is coupled to the system to provide some degree of dispatchability.

2.6 Other Analysis Methodologies

This report uses a market analysis methodology because it is the basis for most decision making in the United States and the need to minimize costs to maximize standards of living. There are alternative methodologies that can be used. Energy systems[30] can be analyzed based on energy return on investment (EROI), which is the energy out of an energy system (coal, oil, natural gas, nuclear, wind, etc.) divided by the energy inputs. Such analysis provides similar results to a market analysis but with some exceptions. In particular, it does not distinguish between the unique value of liquid fuels for transport versus other energy sources. What EROI emphasizes is the importance of operating capital-intensive energy systems (wind, solar, nuclear) at maximum capacity since the EROI decreases with capacity factor.

There are also technical viability analyses of a variety of systems, including integrated nuclear-renewable systems with heat storage[31], that is the first step toward EROI and economic analysis. These determine the technical ability to meet variable electricity demand while fully utilizing capital-intensive assets but must be coupled with market analysis.

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[29] E. Ela et al. *Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation*, NREL/TP-5D00-61765, National Renewable Energy Laboratory, September 2014.

[30] C. A. S. Hall et al., “EROI of Different Fuels and the Implications for Society,” *Energy Policy*, **64**, 141-152, 2014.

[31] C. W. Forsberg and E. Schneider, “Increasing Base-load Light-Water Reactor Revenue with Heat Storage and Variable Electricity Output,” *Transactions of the American Nuclear Society Annual meeting*, 2014.

3. OPTIONS TO ENABLE FULL UTILIZATION OF NUCLEAR, WIND AND SOLAR GENERATING CAPACITY

Changing the characteristics of electricity generation from a fossil-based system to a nuclear-renewable system changes the price curve for electricity. That will dramatically increase electricity costs (price of electricity plus subsidies) to society, unless efficient methods are found to fully utilize nuclear, wind and solar generation to meet variable demand.

3.1 Technology Options

Five classes of technologies to enable full utilization of nuclear, wind, and solar power systems have been identified and are briefly described in this chapter. Figure 3.1 shows the potential impact of each class on the electricity price curve. Detailed descriptions of the five classes of technologies are in the subsequent chapters (Chapters 4-8). Each class of options contains many different technologies but from the perspective of the grid can be considered as a "black box" that has a set of similar characteristics in terms of impacts on the electricity grid.

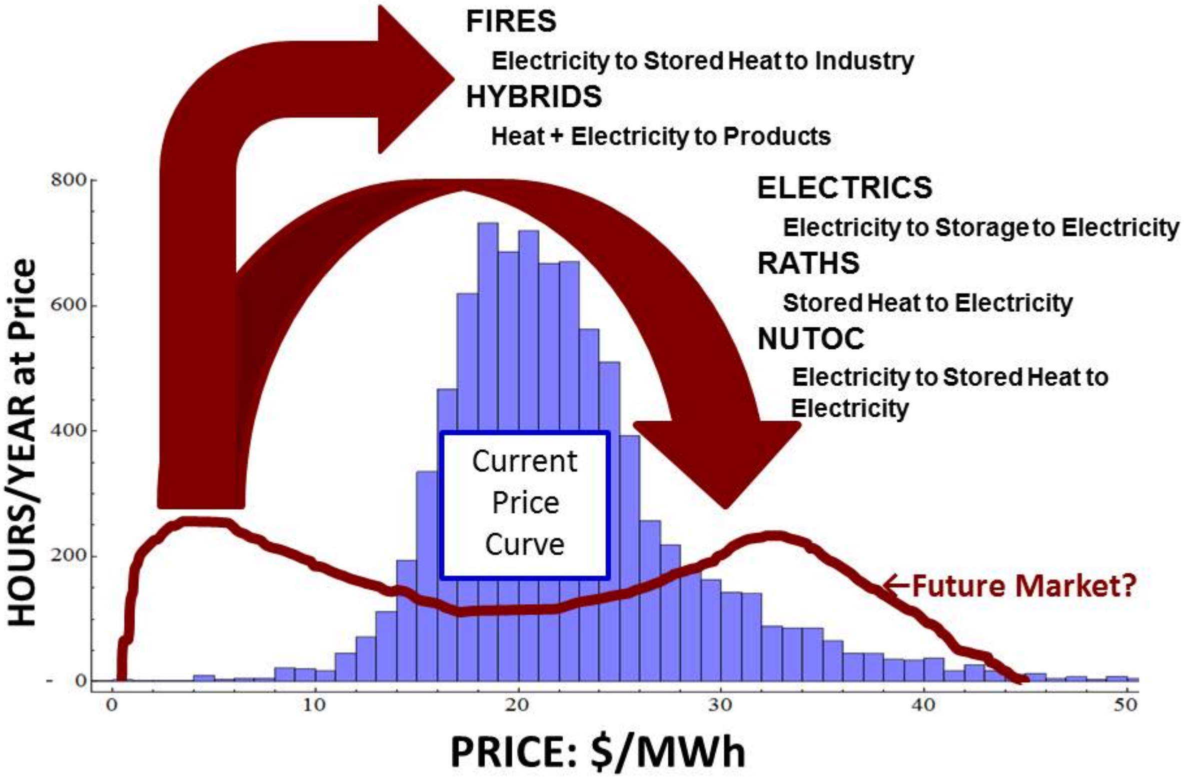

Fig. 3.1. Effect of Different Classes of "Storage Technologies" on Price Curve

Table 3.1 summarizes the options with brief descriptions of the options below the table and detailed descriptions in the following chapters.

Table 3.1. Classes of Systems to Match Electricity Production to Demand and Impacts on Electricity Price Curve

Option to Match Generation with Production	Method to Use Excess Low-Price Electricity	Impact on Low-Price Electricity	Impact on High-Price Electricity	Characteristics
Electrics: Electricity storage (Battery and functionally equivalent)	Grid Electricity →Store Work →Electricity	Buy electricity when low prices and raise minimum prices	Sell electricity to grid when high prices thus reducing peak prices	Practical storage devices store for hours; they do not address weekly or seasonal mismatch. Many technologies: batteries, pumped storage, smart grid, etc. Rate of input usually about equal to rate of output
FIRES: Firebrick Resistance-heated Energy Storage; Electricity to Heat Storage to Industry	Grid Electricity →Store Heat →Heat	Eliminates electricity prices below fossil fuel prices	Limited	Converts low-price electricity into high-temperature heat in firebrick to provide high-temperature heat to industrial furnaces and kilns. Air is blown through hot bricks to provide hot air for furnaces and kilns. Potentially a very low-cost option
RATHS: Reactor Associated Thermal Heat Storage. Technologies applicable to solar thermal but constraints	Reactor Heat →Store Heat →Electricity	Reduce production of electricity when low prices with heat to storage	Provide peak electricity to reduce peak prices	Multiple technologies to store heat from nuclear reactor or solar thermal plants for hours to seasons. Several technologies deployed at solar thermal power stations. Deployment at nuclear plants less expensive than solar thermal because more storage cycles per year are possible. Low-cost technology
NUTOC: Nuclear Topping Cycle, Electricity to High-Temperature Heat Storage to Provide Heat for Thermodynamic Topping Cycle	Low Price Electricity →Store Heat Reactor Heat + Stored Heat →Electricity	Buy electricity from grid when low prices	Provide variable electricity to grid with peak output multiple of base-load nuclear plant output	Base-load reactor where station buys and sells electricity to grid. Multiple technology options. Example is the Nuclear Air-Brayton Combined Cycle (NACC) with FIRES coupled to high-temperature reactor. Electricity-to-heat-to-electricity efficiency up to 70%. Most cases can also provide peak electricity using auxiliary natural gas
Hybrid: Co-Produce Electricity and Second Product	If Low Price Electricity, Reactor Heat + Electricity → Electricity + Product	Reduced electricity to grid, use heat and electricity for second product	Provide variable electricity up to the capacity of nuclear or solar thermal plant output	Produce secondary product that requires heat and electricity when electricity costs are low. Many possible products. Likely long-term product is hydrogen for industry. Potential for low cost by avoiding storage cost

- *Electrics: Electricity Storage (Battery or functionally equivalent system)*. Electricity (work) at times of low prices is stored in batteries or equivalent devices (pumped hydroelectric, smart grid, etc.) to provide electricity at times of high prices. This reduces the quantities of low-priced electricity and the quantities of high-priced electricity (Fig. 3.1).

- *FIRES. Firebrick Resistance-Heated Energy Storage—Electricity to heat storage to industry (Fig. 3.2)*. Electricity is bought whenever the electricity is less than the price of natural gas (the traditional heat source in industry), converted to and stored as high-temperature heat, and partly replaces the use of natural gas in industrial furnaces and kilns. FIRES involves (1) heating firebrick using resistance electric heating, (2) storing high-temperature heat in firebrick, and (3) blowing air through the hot firebrick to provide hot air to industrial furnaces and kilns. The hot air is a substitute for the natural gas burner where natural gas is used when stored heat is not available.

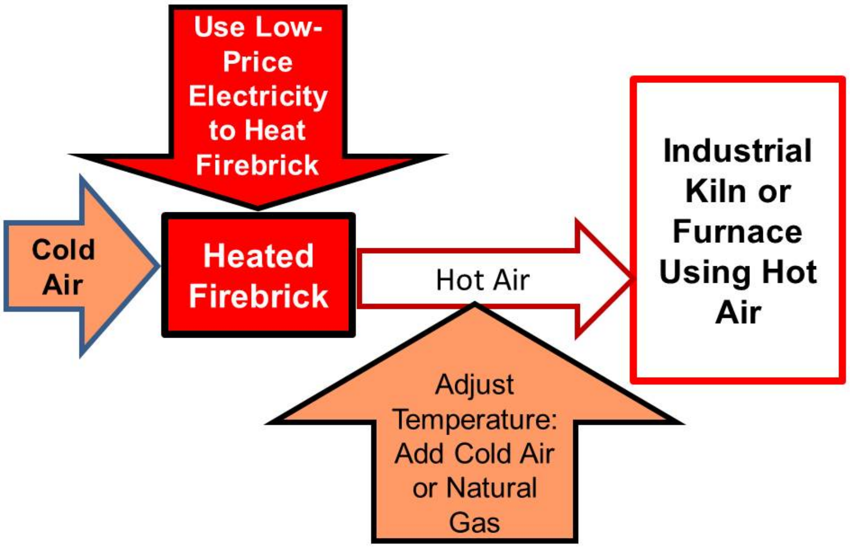

Fig. 3.2. FIRES Conversion of Low-Priced Electricity to High-Temperature Heat for Industry

- *RATHS: Reactor Assisted Thermal Heat Storage: Heat Storage at Reactor or Solar Thermal Site for Peak Electricity Production (Fig. 3.1).* At times of low electricity prices, heat from nuclear reactors or solar thermal power systems is sent to heat storage rather than being used to generate electricity. The stored heat is used to generate electricity at times of higher prices.

- *NUTOC: Nuclear Plant with Thermodynamic Topping Cycle Using Firebrick Resistance-Heated Energy Storage.* This family of nuclear power cycles that operate in two modes:

base-load and peak electricity (Fig. 3.3) where the high-temperature heat for peak electricity production is from FIRES. It is a new option under development made possible by advances in natural-gas combined cycle gas turbines coupled to high-temperature reactors. The high-temperature reactor is coupled to a Nuclear Air-Brayton Combined Cycle (NACC) where in base-load operation air is compressed, heat is added from the reactor, the hot compressed air goes through a turbine producing electricity and the warm exiting air goes through a heat recovery steam generator with steam that is used to produce added electricity—the same basic power cycle as a natural gas plant. If coupled to a Fluoride-salt-cooled High-temperature Reactor (FHR), an advanced reactor under development, the heat-to-electricity efficiency is 42%. This is a good heat-to-electricity thermal efficiency for a nuclear, solar thermal, or coal power plant.

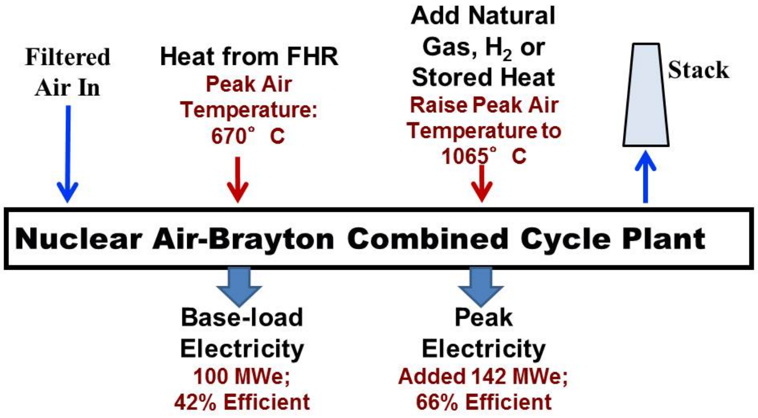

Fig. 3.3. Nuclear Air-Brayton Combined Cycle (NACC)

In a gas turbine there is the option of adding additional heat after the nuclear heat to further raise compressed gas temperatures before entering a power turbine—a topping cycle. Depending on the design, the incremental heat-to-electricity efficiency is estimated to be between 66 and 70%--the most efficient system on earth to convert heat to peak electricity. The added high-temperature heat can be provided by FIRES or injecting another fuel such as natural gas into the hot compressed air. The peak gas temperatures exceed that possible in a nuclear reactor (~700°C delivered) but are below peak temperatures in modern gas turbines (>1300°C).

In the operation of this system (1) the reactor would operate at base-load, (2) electricity is bought when prices are low and stored as high-temperature heat using FIRES—including the electricity generated by base-load reactor operations, and (3) FIRES high-temperature heat is used to produce peak electricity at times of high prices. Peak power production is more than base-load electricity production. If the reactor has a base-load output of a 1000 MWe, the site may go from -2000 MWe (buying electricity from grid and converting to high temperature heat stored in FIRES) to +2000 MWe. The topping cycle round-trip efficiency of electricity to heat storage to electricity is 66 to 70%--making the system a potential competitive with batteries and other electricity storage devices.

- *Hybrid: Use heat from nuclear or thermal solar plant at full capacity to produce electricity and a second product with more electricity (and less second product) to the grid at times of high electricity prices (Fig. 3.1).* These options may use heat from a nuclear reactor or solar thermal power station and added electricity from the electricity grid at times of low prices (excess capacity) to produce a variety of energy-intensive products. The maximum electricity output to the grid matches the output of the associated nuclear reactor or solar thermal power plant when no energy is diverted to producing a second product. Hybrid systems can be designed such that at times of low prices, the hybrid system is a net buyer of electricity from the grid. Hybrid systems transfer heat from the electric sector to the industrial sector. The expectation is that many hybrid options will be more economic than many of the other options because they avoid the costs and inefficiencies of energy storage options.

The other consideration is the transmission grid—the other capital intensive component of the electricity grid. The above options are partly in competition with added transmission capability. Transmission grids serve multiple purposes. They connect electricity generators to consumers. Grids are used to lower peak electricity demand and reduce required generating capacity by (1) averaging loads of different customers and (2) moving electricity across time zones where peak demands occur at different times. Transmission grids enable bringing lower-cost electricity to areas with higher electricity costs. Because transmission / distribution costs are typically a third or more of residential electricity costs, there are significant economic limits to large-scale expansion of the electricity grid to enable a low-carbon electricity grid. The options discussed earlier in this section can reduce these transmission and distribution costs. This is further discussed in Chapter 9.

3.2 Preferred Options

There is no single set of preferred options to fully utilize solar, wind, and nuclear generating assets to minimize total costs because different parts of the country have different renewable resources (wind and solar) and different demands for electricity. The different options can be evaluated on different criteria. Table 3.2 defines those criteria. Chapter 10 applies these criteria to the five sets of options.

Table 3.2. Criteria to Compare Different Classes of Options to Match Electricity Production to Demand

Criteria	Description
Stop Price Collapse	Capability of the technology to prevent electricity price collapse if large-scale use of wind or solar (or nuclear—but does not happen until ~70% nuclear)
Electricity to Grid	Capability to send electricity to the grid to reduce hours of high-price electricity
Generating Capacity	If long periods of low wind or low solar, need dispatchable electric generating capabilities. Can the technology substitute for building dispatchable generating capacity?
Where Energy Goes	Does the excess energy from the grid at times of low prices ultimately go back to the grid (like batteries) or to industry? An option that converts low-price electricity into a form useful for industry is only viable if there is sufficient industrial capacity to absorb that energy.
Economics	This includes capital and operating costs. Externalities can be included directly such as carbon taxes or as constraints on the technologies.

4. CHANGING THE ELECTRICITY PRICE CURVE WITH ELECTRICIY STORAGE

Storage devices (Fig. 4.1) buy electricity at times of low electricity prices and thus raise electricity prices at those times. Electricity is sold from storage at times of high prices thus reducing electricity prices at those times. Electricity storage reduces the number of hours of high-price and low-price electricity (price collapse). Electricity storage can reduce the need for new generating capacity but in the future this capability may be limited.

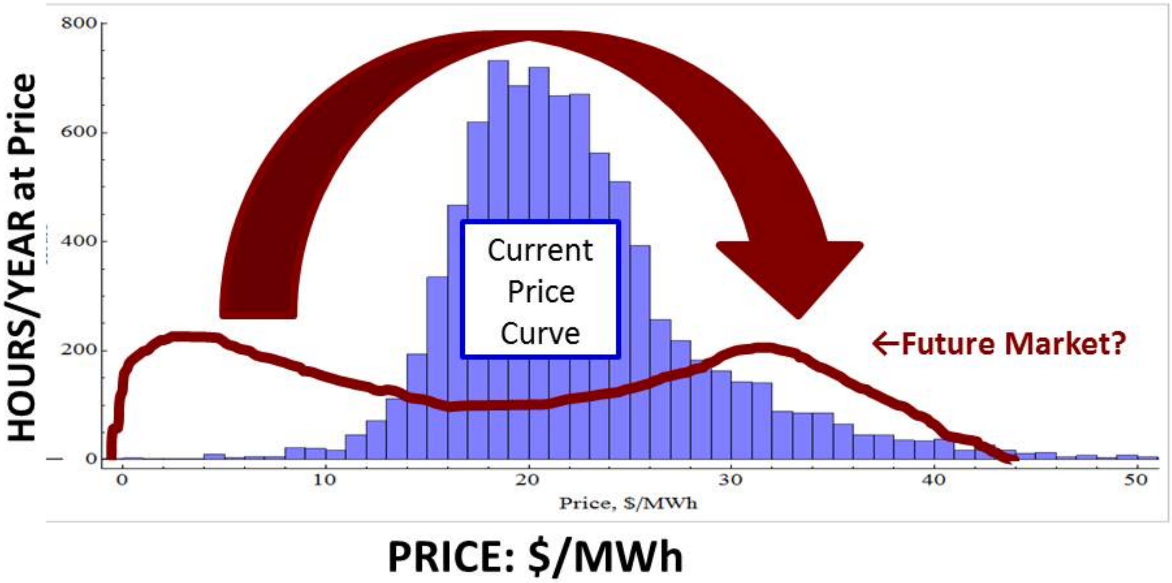

Fig. 4.1. Electricity Storage Systems Buy Low-Price Electricity, Store in Some Form, and Sell Electricity when Prices are High—Reduces Hours of Low-Priced and High-Priced Electricity

The traditional technology used to address the mismatch between production and demand is pumped hydroelectric. In terms of capacity it remains the primary form of electricity storage. More recently many other technologies are being developed including electric batteries. All of these devices are functionally equivalent to batteries; that is, the same function could be performed by a battery. Most of these technologies have the characteristic that the rate of charging is roughly proportional to the rate of discharge. The U.S. Department of Energy goal for battery storage is $150/kWh(e). The largest technical limitation of these technologies is that storage capacity is limited with the risk that external conditions (multiday heat wave, etc.) will deplete storage.

There are extensive reviews of electricity storage options that include technical and economic characteristics.[32, 33] While the primary purpose of most of these technologies is load shifting,

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[32] U.S. Department of energy, *Grid Energy Storage*, December 2013.

some of these technologies provide a variety of other services including improving power quality. Figure 4.1 classifies these technologies based on system power ratings versus discharge time at rated power. Note that all of the existing sets of options have discharge times measured in seconds to hours; that is, they can address hourly storage times but are not designed to address weekly to seasonal storage times.

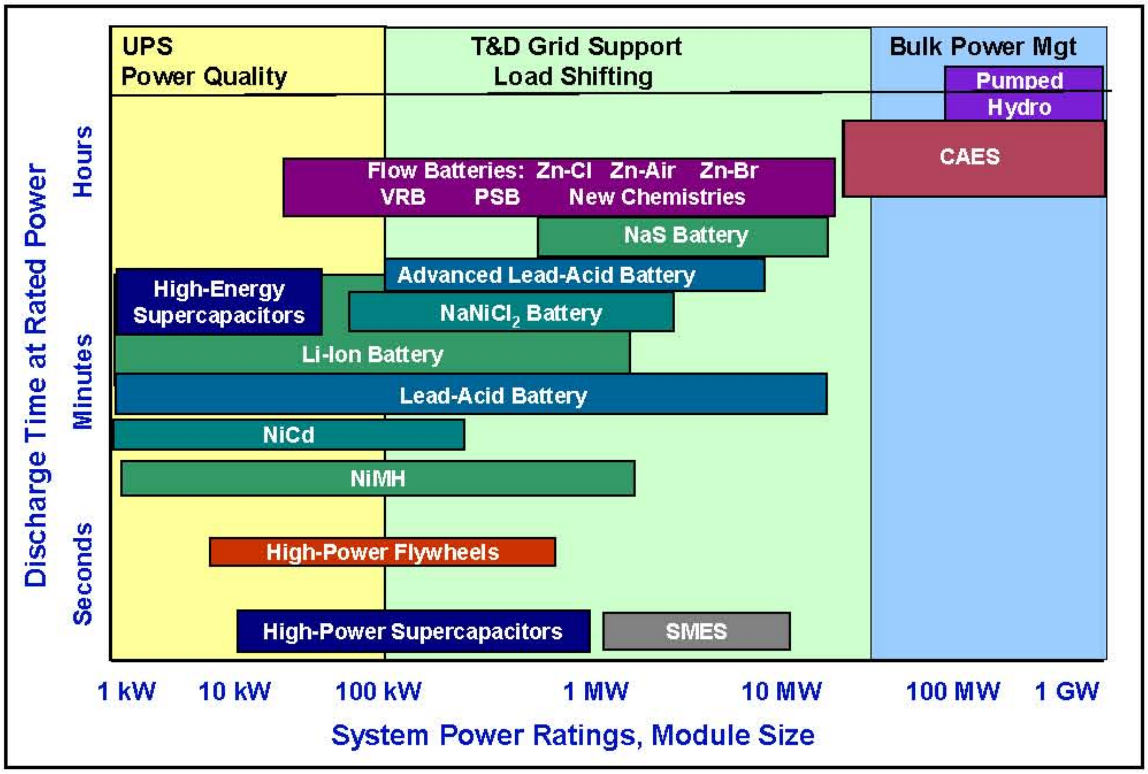

Fig. 4.2. Characteristics of Electric Storage Technologies[34]

Many smart grid systems[35] are functionally equivalent to batteries when they are used for demand management. For example, a hot-water heater that only heats water at times of lower prices during the day is functionally equivalent to a regular hot water heater and a battery that buys electricity at low prices for the hot water heater. Many smart grid systems are competing with batteries and other storage technologies for many grid functions.

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[33] D. Bhatnagaret et. al, *Market and Policy Barriers to Energy Storage Deployment*, SAND13-7606, September 2013

[34] A. A. Akhil et. al., *DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA*, SAND2013-5131, Sandia National Laboratories, July 2013. UPS is uninterrupted power supplies—assuring continuous power primarily to electronics where even small voltage dip causes major problems. Most of these systems are batteries. CAES is compressed air Energy Storage. SMES is superconducting magnetic energy storage.

[35] C. Gellings et. al, Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid, Report 1022519, March 2011.

The benefits of electricity storage include reducing electricity generating capacity in addition to avoiding the use of generating plants that burn expensive fuels. However, the benefit of reducing generating capacity may be reduced in the future as more of that generating capacity is from non-dispatchable renewables. Historically, the primary electricity storage technology has been pumped storage where water was pumped uphill in the middle of the night (time of lowest electricity demand) and flowed down the hill to generate electricity at times of peak demand. Because peak electricity consumption never happens in the middle of the night, pumped storage capacity directly replaced the need for some generating capacity. However, that is not fully true if storage is used with grids with large amounts of solar or wind. In the case of solar the peak charging time may be in the middle of the day with peak electricity demand slightly later in the day as the sun begins to set—typically near 6:00 or 7:00 pm in locations such as California. However, if there are several cloudy days with low solar input, backup generation capacity may be needed because the storage systems those cases may be depleted by the lack of solar input. One can no longer have assurance that 100 MWe of storage output replaces 100 MWe of generating capacity.

5. CHANGING THE ELECTRICITY PRICE CURVE BY CONVERTING LOW-PRICE ELECTRICITY INTO HIGH-TEMPERATURE STORED HEAT FOR INDUSTRY

Low-priced electricity can be minimized with Firebrick Resistance-heated Energy Storage (FIRES) systems—a technology being developed in response to changes in the electricity price curve. With FIRES electricity would be bought whenever the electricity price is less than the price of natural gas, the electricity would be converted to high-temperature stored heat, and that heat would then be used to supply heat to industrial furnaces and kilns. The heat replaces burning of natural gas or other fuels. Figure 5.1 shows the impact on the electricity price curve.

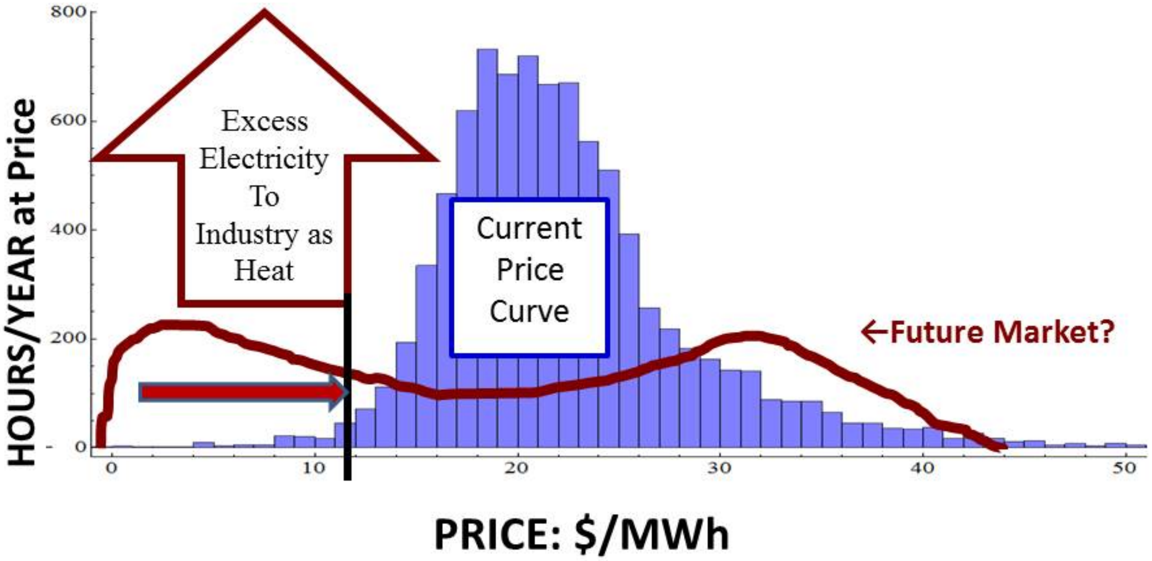

Fig. 5.1. FIRES Buys Electricity when Below the Price of Natural Gas and Sets a Minimum Price of Electricity Near that of Natural Gas—The Primary Industrial Heat Source in the U.S.

FIRES could enable larger-scale use of low-operating-cost high-capital-cost nuclear, wind, and solar systems by preventing complete price collapse in the case of large amounts of installed capacity of nuclear, wind and solar. The minimum price of electricity is below the minimum price of electricity set in an electricity market where fossil fuels determine the price curve. If natural gas is burnt to produce electricity with a heat-to-electric efficiency of 60%, the minimum price of electricity set by FIRES would be about 60% of the price of electricity set by burning natural gas to produce electricity. This minimum price is always below the market price of electricity set by fossil fuel electric generators.

FIRES[36] consists of a firebrick storage medium with relatively high heat capacity and density. Low-cost firebrick can operate up to temperatures of ~1800°C. The firebrick can be resistance heated by three mechanisms.

- Conventional heating rods found in many high-temperature electrically-heated furnaces from lower-temperature calrod heaters to SiC heaters.
- Conductive firebrick that operates as both the resistance heater and the storage medium where electricity directly flows through the firebrick.
- Induction heating of firebrick with coils of wire.

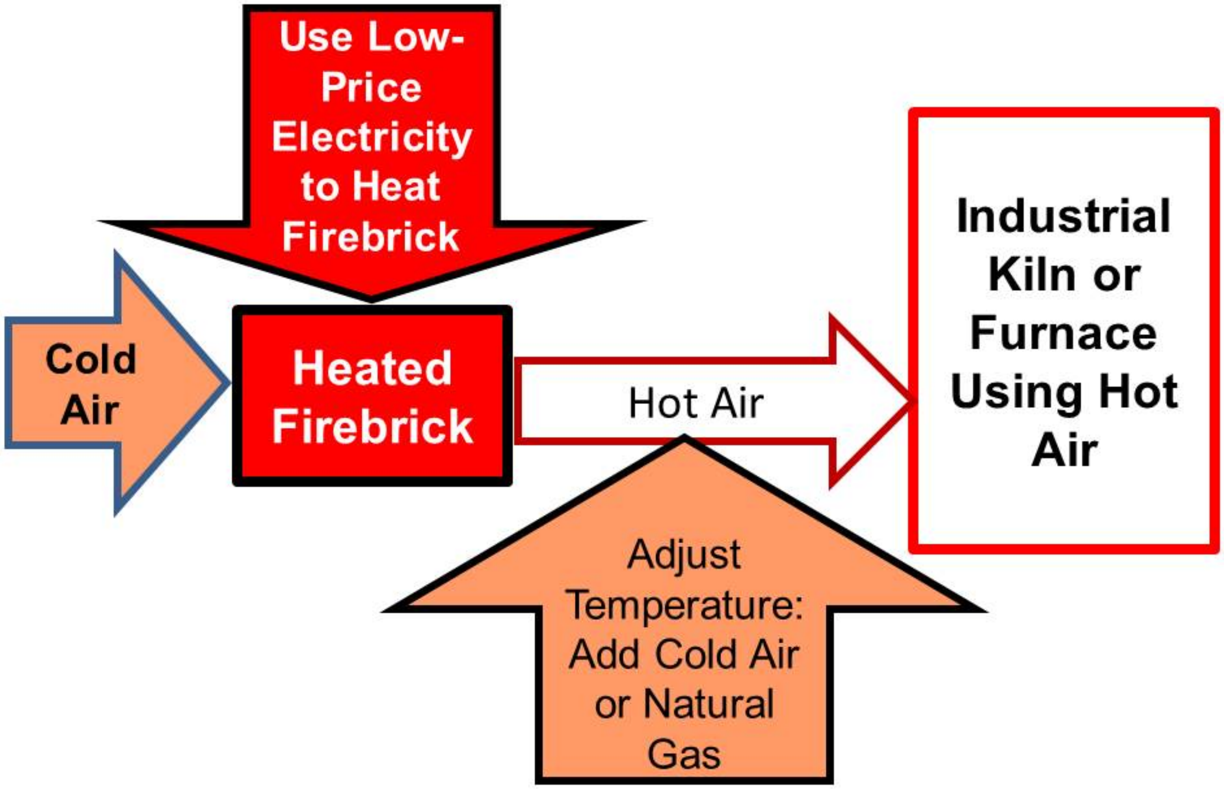

Fig. 5.2. Proposed Operation of FIRES

In most industrial applications FIRES (Fig. 5.2) would be coupled to natural-gas-fired industrial furnaces or kilns to provide hot air that replaces the burning of natural gas. The furnaces may be producing glass, cement, steel, or providing heat to chemical facilities including refineries. In this design, cold air is blown through FIRES by laying the firebrick in a pattern that includes air channels. If the exit air is above the temperature limits for the furnace, the hot air is

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[36] D. C. Stack and C. Forsberg, "Improving Nuclear System Economics using Firebrick Resistance-Heated Energy Storage (FIRES)," *Transactions of the American Nuclear Society*, San Antonio, Texas, June 2015.

mixed with cold air to match furnace requirements. If the FIRES temperature is below the temperature needed for the furnace, natural gas heating is used to raise temperatures to the required furnace temperature. From the perspective of the furnace, FIRES is a substitute for a natural gas flame. Electric heating of the firebrick may be done at the same time FIRES is providing heat to industrial processes—that is, it is being charged and discharged at the same time. With this feature one only has to buy one set of electrical heaters to take advantage of low electricity prices.

The firebrick storage medium is surrounded by insulating firebrick and insulating padding that allows for the thermal expansion of the firebrick over a ~1000°C temperature range. If one allows a 1000°C from cold to hot in temperature, the heat storage capacity is ~0.5 MWh/m^3. The firebrick, insulation systems, and most other storage components are similar to high-temperature firebrick industrial recuperators used in the 1920s open hearth steel production process that cycled between room temperature to over 1600°C. The ceramic firebrick was used because of the low cost and durability, while also having large sensible heat storage capabilities. Firebrick with electric heating has been used at low temperatures for home heating in Europe—non-industrial scale. At times of low electricity prices, the firebrick is heated. The hot firebrick then provides hot air when needed for room heating. For industrial applications, each FIRES system would be designed for the specific application and local market conditions (Fig. 5.3). This is different than other storage devices and offers major economic benefits because it would be designed to match local grid and industrial requirements.

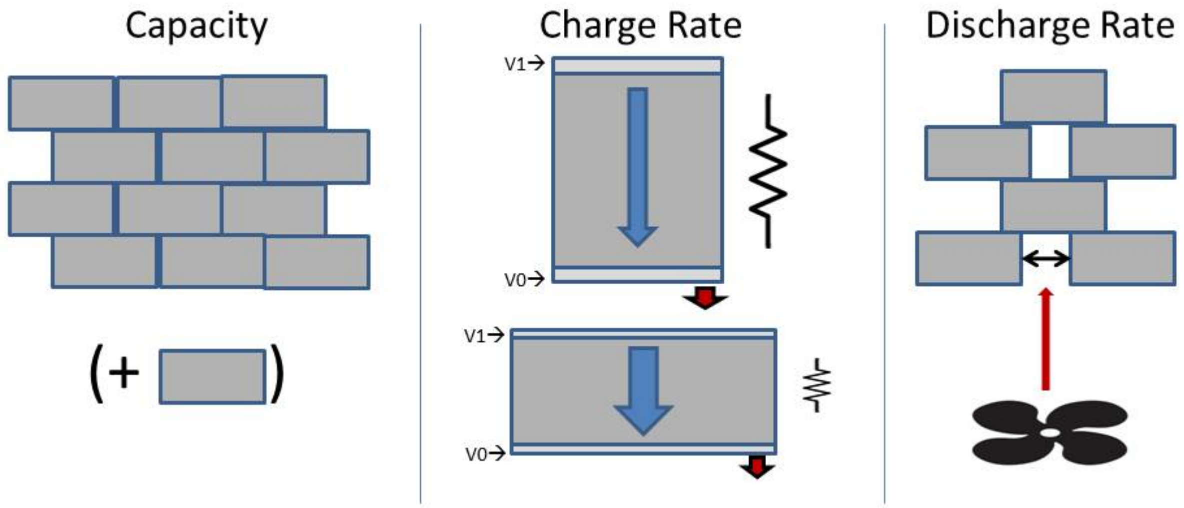

Fig. 5.3. The Heat Capacity, Charging Rate and Heat Discharge Rate are Chosen Based on Local Grid and User Conditions

- *Electricity input rate.* Heat input rate is determined by resistance heating capacity. Resistance heating is by an order of magnitude the cheapest way to use electricity. Heat input rate can be chosen to match peak power input (kW) that might be available on the market. The electricity input rate into FIRES when electricity price collapse is caused by solar would likely be larger than when electricity price collapse is caused by wind. Solar price collapse occurs in the midday as solar generation rapidly increases and decreases, providing a short window in time with low-price electricity thus high capacity heaters are needed to take advantage of this short window in time. High wind conditions and resulting electricity price collapse tend to exist over a period of many hours to days.

- *Heat storage capacity.* Storage capacity is determined independently by the amount of firebrick that is bought. The incremental firebrick cost is somewhere near \$1-2/kWh—about two orders of magnitude lower than the DOE battery goal of \$150/kWh and the Tesla battery at \$350/kWh. Very low heat storage costs are essential for wind where there are often several days of excess wind reducing electricity prices and creating the need for large heat storage capacities. The heat input rate may not be high but the heat storage capacity (kWh) needs to be large in such a situation.

- *Heat output rate.* Heat output is hot air that is controlled by the rate of air flow through the firebrick recuperator—that is, fan power. Because hot air is the output, FIRES can couple to most fossil-fueled kilns and furnaces. Flowing air through hot firebrick avoids the temperature limitations and temperature drops of heat exchangers enabling temperatures up to ~1800°C.

FIRES would provide heat primarily to the industrial market rather than commercial or residential market. Figure 5.4 shows the energy flows in the United States. Industry is the second largest user of electricity and a major user of natural gas for heat generation. Only the industrial market is large enough to absorb the quantities of low-price heat that would be generated with large-scale use of renewables There are large economics of scale associated with FIRES that favor its use in industry. Industrial markets provide a year-round market for heat while commercial and residential heat markets are seasonal. Doubling the number of storage cycles per year would reduce the effective capital costs per MWh(t) by half. Finally, FIRES could provide high-temperature heat—a unique capability and requirement for industry in a low-carbon world.

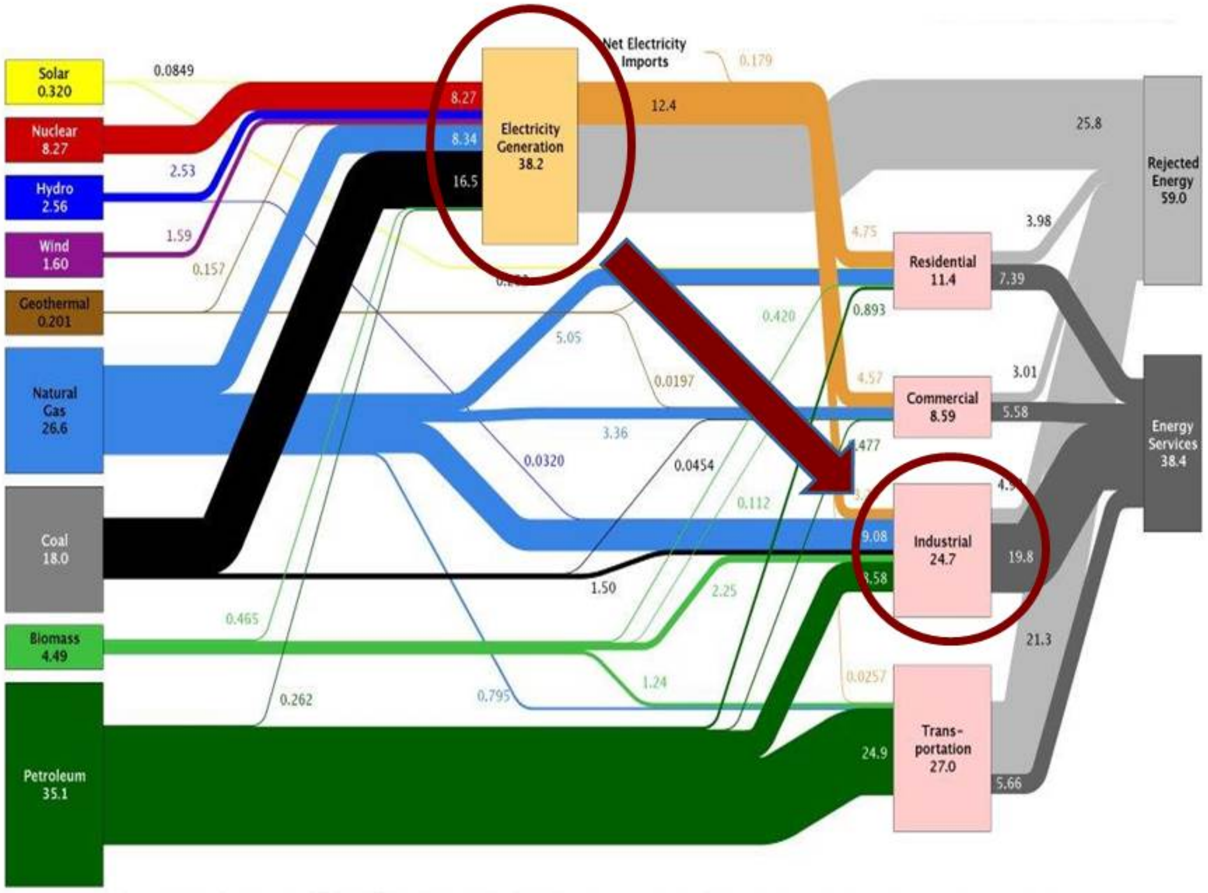

Fig. 5.4. Energy Flows (Quads/year) in the United States

There are several potential consequences of the successful deployment of FIRES based on its extremely low capital costs (estimated at <$5/kWh) that are far below the costs of other storage technologies (U.S. Department of Energy goals are for electricity storage devices are between $100 and $150 per kWh[37, 38]).

- FIRES may eliminate the sale of significant quantities of electricity at less than the heating value of natural gas—the preferred industrial fuel for heating purposes. It puts a limit on electricity price collapse, enabling the larger-scale use of low-carbon electricity generating technologies.
- FIRES may drastically reduce the need for batteries and similar devices for storage and additional long-distance power lines. Those technologies are based on the differences in electricity prices in time and space. FIRES could reduce the quantities of very cheap

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[37] U.S. Department of Energy, *Grid Energy Storage*, December 2013

[38] D. Bhatnagaret et. al, *Market and Policy Barriers to Energy Storage Deployment*, SAND13-7606, September 2013

electricity and, thus, the electricity price differences required for deployment of those technologies.
- If solar or wind costs go below the cost of fossil fuels, the market for these generators would rapidly expand if FIRES is able to transfer the electricity to the industrial sector as high temperature heat.

FIRES is a family of devices from low-temperature versions (<500°C) that are essentially off-the-shelf technology to high-temperature versions where added development work is required—particularly in the electrical heating systems (recuperators and hot-air ducts are existing technology). For some types of furnaces where radiation heat transfer is important, some natural gas may have to be burned because the carbon in the combustion gas increases radiation heat transfer from gas to boiler tubes. For some applications such as cement kilns, there will be large incentives to install FIRES. The production of cement requires the decomposition of calcium carbonate into calcium oxide and carbon dioxide. In such systems the carbon dioxide in the combustion gas retards the decomposition process so a low-carbon-dioxide hot gas would be more efficient in these processes than hot air heated with natural gas.

6. CHANGING THE ELECTRICITY PRICE CURVE BY STORING NUCLEAR AND SOLAR HEAT FOR ELECTRICITY PRODUCTION AT TIMES OF HIGH PRICES

At times of low electricity prices, heat from nuclear or solar thermal electricity generating systems can be sent to heat storage rather than being used to generate electricity. The stored heat used to generate peak electricity when needed. Figure 6.1 shows the implications to the electricity price curve.

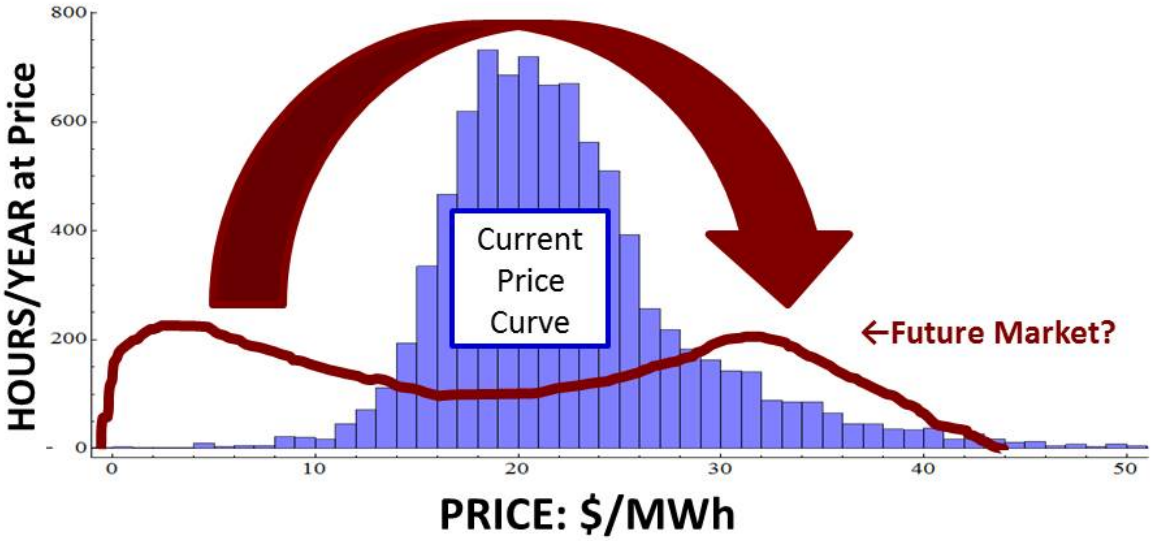

Fig. 6.1. Storing Heat to Produce Peak Electricity Reduces Electricity to the Grid at Low Prices and Provides More Electricity at Higher Prices—Reduces Hours of High-Priced Electricity

There are multiple thermal storage technologies (Table 6.1) applicable to nuclear and solar thermal systems for heat storage times of minutes to seasons. In many cases the systems are technically identical for coupling with nuclear or solar-thermal systems. Each has different characteristics.

Steam Accumulators: Direct Steam Storage

At times of low electricity prices, steam from the nuclear reactor or solar thermal plant is injected into insulated pressurized accumulator tanks partly filled with water. Steam injection continues until the hot water is at steam temperatures and pressures. At times of high electricity prices, valves from banks of accumulators are sequentially opened resulting in flashing of hot water to steam that is sent to a steam turbine to produce peak power. Abengoa® is currently building steam accumulators in South Africa coupled to solar power towers to maximize electricity production at times of high prices and to avoid revenue collapse at times of excess solar production. The operating conditions for solar and nuclear systems are similar.

Steam accumulators were developed in the 19th century when piston steam engines rather than electric motors were used in industry. The boiler produced steam, the steam was stored, and variable steam was then available to drive the steam engines to match demand. More modern versions coupled to steam turbines are used today.[39].Steam accumulators are capable of very fast response to demand, enabling their use to power steam catapults to launch aircraft aboard aircraft carriers. This rapid response capability implies the ability to match very rapid changes in electricity demand.

Studies were conducted in the 1970s on coupling large PWRs to steam accumulators to produce peak electricity.[40] In the 1970s, peak electricity was produced from oil. An oil embargo drove up oil prices, resulting in the need to develop alternative methods of peak electricity production. Under those conditions the technology was potentially competitive. Oil prices later dropped, causing work on nuclear-powered accumulators to stop. With renewables, the economic challenge is similar. In this case, the challenge is a drop in the price of electricity at certain times, making very low-price steam available to charge accumulators.

Nitrate Salt and Other Engineered Heat Storage

The second class of heat storage devices store heat in a liquid or solid media at atmospheric pressure. This implies that heat from high-pressure steam is transferred through a heat exchanger to a secondary low-pressure storage fluid. That secondary fluid heat capacity can be used to store the heat or used to heat a solid. To produce electricity, the process is reversed. The hot secondary fluid heats water to produce high-pressure steam that is sent to a peaking steam turbine. Depending on the specific design, this can be a separate set of heat exchangers or the same heat exchangers.

There has been a massive amount of work done on these types of systems for solar thermal power systems and the technology has been deployed at multiple solar power plants. The most common heat storage media today is a mixture of liquid nitrate salts that operate over the same temperature range as LWRs. While there are many possible storage fluids, the near-term option is the use of nitrate storage salts—exactly the same salts used in solar thermal power systems for the same technical and economic reasons.

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[39] W. Goldstern, *Steam Storage Installations*, Pergamon Press, 1970.

[40] P. V. Gilli and G. Beckman, "Steam Storage Adds Peaking Capacity to Nuclear Plants," *Energy International*, August 1973.

Hot Water Storage

The primary cost of a steam accumulator are the tanks associated with pressurized hot-water storage. Several concepts have been proposed[41, 42] to store hot water at pressure in mined underground rock caverns. The lithostatic pressure of the earth can be used to keep high-temperature hot water at pressure rather than tanks. Large high-pressure hot-water storage systems can be built by mining underground caverns and lining those spaces with insulation and a steel liner. The cost of such systems is strongly dependent upon the local geology. The economics of scale associated with underground mining imply large storage capacities—many GW-days or GW-months.

Hot Rock Storage

Recent studies[43] have examined the option of nuclear geothermal heat storage systems capable of storing a gigawatt-year of heat. This enables seasonal thermal-heat storage. At times of low electricity prices, hot pressurized water is injected underground to heat a zone of rock that has been fractured to increase its permeability to water flow. At times of high electricity demand, this hot rock zone becomes a manmade geothermal power system. The system has relatively slow response to demand but the storage costs ($/kWh) are extremely low relative to other options because the initial cost of the storage media is the cost of rock—essentially zero.

Because the rock zone can't be insulated, there are conduction heat losses. However, the heat losses are proportional to the surface area of the heat storage zone while stored heat is proportional to the volume of the heat storage zone. As the system size increases, the heat loss percentage decreases. Round-trip efficiencies compared to sending electricity directly to the grid are about 50%--but strategies to increase that to 70% have been identified. The minimum system scale is about 0.1 gigawatt-years to keep heat losses down to a few percent of the total heat being stored. Initial assessments indicate favorable economics in much of the U.S.

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[41] P. H. Margen, "Thermal Energy Storage in Caves," *Energy International*, October 1971.

[42] P. H. Margen, "Thermal Energy Storage in Rock Chambers," *Fourth International Conference on Peaceful Uses of Atomic Energy*, Vol. **4**, pp. 177, 1971.

[43] Charles Forsberg, "Hybrid Systems to Address Seasonal Mismatches Between Electricity Production and Demand in a Nuclear Renewable Electricity Grid," *Energy Policy,* **62***,* 333-341, November 2013.

Table 6.1. Alternative Heat Storage to Electricity Options for Nuclear Plants

Technology[44]	Description	Storage Time (Hr)	Size (GWh)
Liquid Heat Capacity	Store hot molten nitrate salt or other material at low pressure	10	<10
Steam Accumulator	Store high-pressure water-steam mix. Very fast response capability	1 to10	<10
Geothermal Hot Water	Store hot water 1000 m underground at pressure	100	100 to 1,000
Geothermal Rock	Heat rock to create artificial geothermal deposit	1000+	1,000 to 10,000

In most cases the economics and technologies of heat storage favor coupling heat storage with nuclear plants rather than solar thermal plants.

- *Storage costs.* Storage costs are driven by the number of storage cycles per year—double the number of storage cycles per year effectively cuts the capital cost per unit of heat storage in half. This implies that in a system with nuclear and solar thermal power systems, the heat storage under most circumstances would be preferentially coupled to the nuclear plants because the nuclear plants operate continuously year round and thus can support more cycles of storage per year with lower storage costs. Thermal energy storage systems are an order of magnitude less expensive than electricity storage systems with U.S. Department of Energy goals of $15/kWh(th).[45]

- *Assurance of recharge.* A nuclear plant with constant output can assure recharge of thermal storage systems each day; thus, the storage system can displace some quantity of dispatchable generating capacity. However, a solar thermal system can't make such assurances since its output is tied to the weather—days of low cloud cover will deplete any storage device coupled to a solar thermal system.

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[44] Existing commercial technologies are shown in red

[45] US Department of Energy, *Thermal Storage R&D for CSP Systems*, retrieved on 5 August 2015 from http://energy.gov/eere/sunshot/thermal-storage-rd-csp-systems

- *Geographical availability*. Solar thermal systems, unlike photovoltaics, require direct sunlight for mirrors to focus light on collectors. This requirement limits solar thermal systems in the U.S. to the southwest.

Monthly and seasonal heat storage options can substitute for dispatchable electricity generation and avoid the construction of additional power plants. All of the long-term heat storage options take advantage of deep underground spaces for long-term heat storage.

From a strategic perspective, RATHS seasonal storage may be central to a low-carbon world. Seasonal variations in energy demand are now met by fossil fuels. The only long-term seasonal zero-carbon storage options are heat or some storable fuel—hydrogen, biofuels, etc. One would expect heat to heat storage to electricity to be much less expensive than electricity to hydrogen or another storable form to hydrogen storage to electricity. There are fewer conversion steps with associated losses and costs. This implies potentially a massive role for geothermal heat storage in any low-carbon future.

7. CHANGING THE ELECTRICITY PRICE CURVE WITH A NUCLEAR TOPPING CYCLE (NUTOC) WITH FIRES

7.1 Concept Description

The concept of a nuclear reactor with a high-temperature topping cycles (NUTOC) is old. The Indian Point I reactor built in the 1970s in New Your state had a high-temperature topping cycle.[46, 47] Indian Point I was a pressurized water reactor where the steam from the nuclear plant went to an oil-fired super-heater to increase peak steam temperatures before going to a turbine. The characteristic of a topping cycle is that the heat-to-electricity efficiency of the incremental high-temperature heat addition is much greater than the efficiency of the total cycle. The Indian Point I topping cycle improved total heat-to-electricity efficiency by 21%. Near Lingen, Germany a boiling water reactor was built with an oil-fired super-heater that resulted in a 33% improvement in total heat-to-electricity efficiency. Topping cycles are economically attractive when there is a low-cost fuel source (uranium) for the lower-temperature heat and a higher-cost fuel source (oil) for the higher-temperature topping cycle. The Indian Point I plant was shut down due to the 1970s oil embargo that made oil too expensive to burn in a power plant.

Since that time there has been a revolution in natural-gas combined cycle technologies that enables NUTOC to be applied to high-temperature reactors coupled to Nuclear air-Brayton Combined Cycles (NACC)[48, 49, 50]. Development work is underway. The NACC topping cycle is shown in Fig. 7.1. When operated at base-load on reactor heat, air is compressed, heat is added from the reactor, the hot compressed air goes through a turbine producing electricity and the warm air exits through a heat recovery steam generator (HRSG) with the steam used to produce added electricity—the same basic power cycle as a natural gas plant. If coupled to a Fluoride-salt-cooled High-temperature Reactor (FHR), an advanced reactor under development, the heat-to-electricity efficiency is 42%. This is a good heat-to-electricity thermal efficiency for a nuclear, solar thermal, or coal power plant.

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[46] D. J. McCormick and W. P. Gorzegno, "The separately fired superheater--a nuclear application at Indian Point," *ASME Transactions, ASME-IEEE National Power Conference.* Albany, New York, 1965.

[47] N. Lior, "Energy, Exergy and Thermoeconomic Analysis of the Effects of Fossil-Fuel Superheating in Nuclear Power Plants," *Energy Conversion and Management*, **38**, No 15-17, 1585-1593, 1997

[48]. C. Andreades, R. O. Scarlat, L. Dempsey, and P. F. Peterson, Reheating Air-Brayton Combined Cycle Power Conversion Design and Performance Under Normal Ambient Conditions", *J. of Engineering for Gas Turbines and Power*, *136*, June 2014.

[49] C. Andreades, L. Dempsey, and P. F. Peterson, "Reheating Air-Brayton Combined Cycle Power Conversion Off-Normal and Transient Performance", *J. of Engineering for Gas Turbines and Power*, *136*, July 2014

[50] C. Andreades, *Nuclear Air-Brayton Combined Cycle Power Conversion Design, Physical Performance Estimation and Economic Assessment*, PhD Thesis (Nuclear Engineering), University of California at Berkeley, Summer 2015.

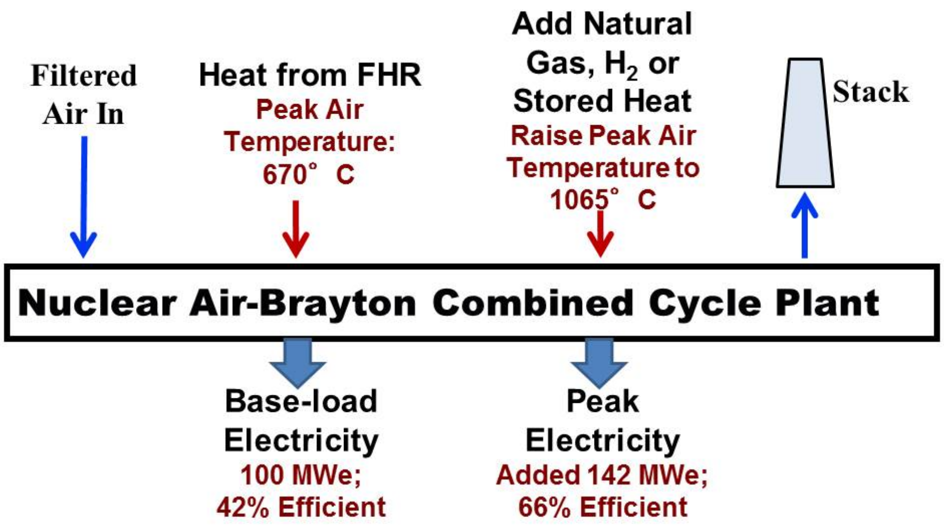

Fig. 7.1. Nuclear Air-Brayton Combined Cycle (NACC)

In a gas turbine there is the option of adding additional heat after the nuclear heat to further raise compressed gas temperatures before entering a power turbine from 670°C to 1060°C in this specific example. The incremental heat-to-electricity efficiency depending upon the design is between 66 and 70%--the most efficient system on earth to convert incremental heat to electricity and substantially higher than a stand-alone natural gas plant. The added high-temperature heat to raise the temperature of the compressed air can be provided by (1) FIRES, (2) injecting another fuel such as natural gas, biofuels, or hydrogen into the hot compressed air or (3) a combination of the two options. In this specific example the peak temperature would be 1060°C—a result of using a design based on the GE 7FB gas turbine optimized for base-load electricity with conservative design assumptions. Incremental heat-to-electricity efficiency will increase with the same reactor and turbine peak temperature limits if NACC is optimized for peak power rather than base-load power. Alternatively, if the reactor temperatures are allowed to increase and peak gas turbine temperatures are increased (1230°C)[51], incremental heat-to-electricity efficiencies are ~70%.

Advanced gas turbines have peak temperatures above 1300°C, implying that an advanced design could have significantly higher incremental heat-to-electricity efficiencies by operating at higher temperatures. While the incremental heat-to-electricity efficiency is very high, the total plant efficiency ([total electricity / [nuclear + peak added heat]) is much lower.

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[51] C. Andreades, R. O. Scarlat, L. Dempsey, and P. F. Peterson, Reheating Air-Brayton Combined Cycle Power Conversion Design and Performance Under Normal Ambient Conditions", *J. of Engineering for Gas Turbines and Power*, *136*, June 2014.

In the operation of this system (1) the reactor would operate at base-load, (2) electricity would be purchased when prices are low and stored as high-temperature heat using FIRES—including the electricity generated by base-load reactor operations during times of low prices, and (3) the FIRES high-temperature heat would be used to raise compressed air temperatures before the turbine to produce peak electricity at times of high prices. Peak power production is more than base-load electricity production. If the reactor has a base-load output of a 1000 MWe, the site might go from -2000 MWe (electricity purchased from the grid and electricity from base-load operations to FIRES) to +2000 MWe.

Normally it would be expected that the efficiency of a storage system that converts electricity to heat to electricity would be low. *That is not true here because the heat is added as a topping cycle above "low-temperature" 700°C nuclear heat that results in compressed air temperatures of 670°C.* The efficiency is similar to many other storage technologies (pumped hydroelectric) but uses low-cost heat storage. The round-trip efficiency is expected to improve with improvements in gas turbine technology. In this context a NUTOC using NACC technologies has unique capabilities. This has several implications:

- *Compete with natural gas*. NACC may enable advanced nuclear plants to compete with lower-cost natural gas. In peak power mode the nuclear plant incrementally uses less natural gas per kWh of electricity generated than a stand-alone natural gas plant. If the electricity market price is set by stand-alone natural gas plants, this implies more revenue for NACC.
- *FIRES*. The gas turbine can use FIRES as the high-temperature auxiliary heat source for peak electricity production—transferring low-priced electricity into heat for peak electricity production when needed.
- *Power cycle for peak hydrogen in a zero-carbon grid*. Hydrogen has long been proposed as the peaking fuel for a low-carbon grid by producing hydrogen at times of low electricity prices with electrolysis and using it for peak electricity at times of high electricity prices. Because it is storable, it could help address the seasonal storage challenge associated with a low-carbon grid. The technical challenge is that the calculated efficiencies in converting electricity-to-hydrogen-to-electricity have been significantly under 50%. The low efficiency implies high costs. If NACC can achieve the predicted high efficiency for converting incremental fuel to electricity then use of hydrogen as a peaking fuel would become more economic.

There is a long history of thermodynamic topping cycles. In the 1930s General Electric developed a coal plant with a steam bottoming cycle and a mercury topping cycle. The Indian Point I reactor had lower temperature nuclear heating and a topping cycle using an oil-fired super heater. In both of these systems the efficiency was limited by the peak temperature capabilities of the boiler tubes that transferred heat from the fuel to the steam, mercury or other working fluid.

The gas turbine eliminates this materials constraint. High-temperature incremental heat is transferred directly to the compressed air by burning a fuel (natural gas, hydrogen, biofuels) or heating with hot firebrick in FIRES. Heat is not transferred through a heat exchanger. Instead, the air is heated to very high temperatures and power is extracted via the turbine. The peak compressed gas temperatures far exceed the limits of any practical boiler-tube materials. Because of the small quantities of materials, turbine blades can be made of exotic high-temperature materials. In addition, many turbine blades are internally cooled with a ceramic outer layer and thus can extract work from hot gas at temperatures that would cause the turbine blade to fail if it is not actively cooled. This allows 1300°C hot gas to flow over a turbine blade that would fail far below 1300°C.

The high temperatures imply high efficiency—higher than any other heat engine. The air-Brayton combined cycle coupled to a high-temperature nuclear reactor becomes a transformational technology. The baseline concept has NACC and FIRES coupled to an FHR with projected commercialization dates of ~2030 in China. The option could not have existed 15 years ago because the gas turbine technology was not good enough.

7.2 Impact on the Grid

The impact of NUTOP on the electricity price curve is shown in Fig. 7.1. Low price electricity is transferred from the grid to FIRES for peak electricity production. However, incremental peak electricity can also be produced by burning any fuel.

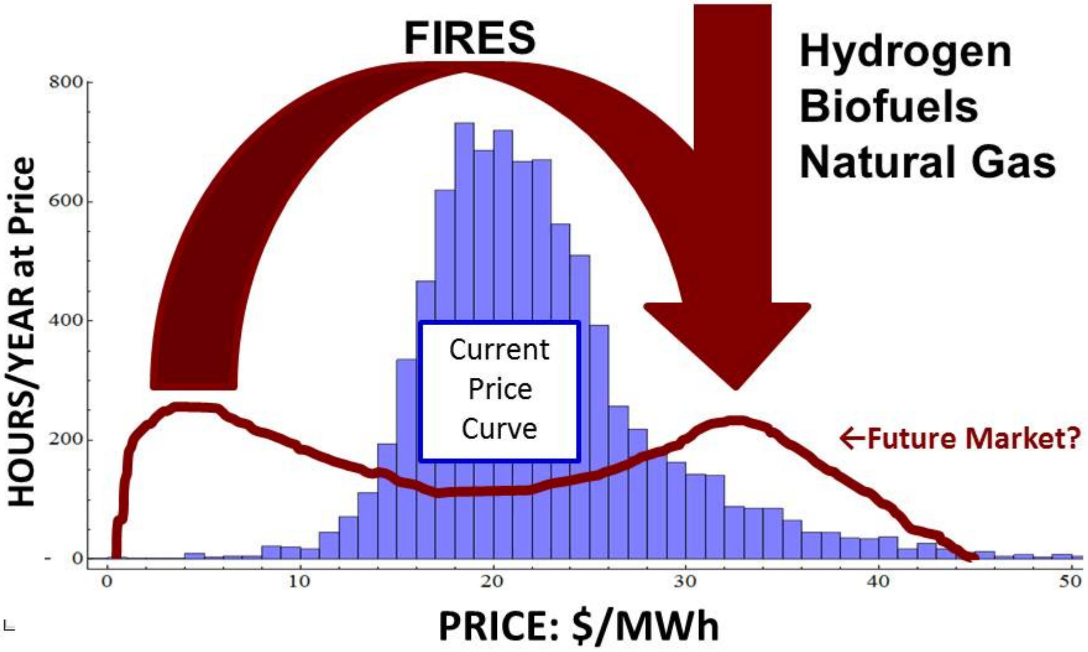

Fig. 7.2. Impact of High-Temperature Nuclear Reactor with Thermodynamic Topping Cycle (FIRES, Hydrogen, Biofuels, or Natural Gas)

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

The NUTOC concept has been developed for coupling with the FHR, so a short description is provided herein. The FHR is a new reactor concept[52] that combines (1) a liquid salt coolant, (2) graphite-matrix coated-particle fuel originally developed for High Temperature Gas-cooled Reactors (HTGRs), (3) a NACC power cycle adapted from natural-gas combined-cycle plants and (4) FIRES. The FHR concept is a little over a decade old and has been enabled by advances in gas turbine technology and HTGR fuel. The Chinese plan to build an FHR test reactor by 2020.

The liquid salt coolant was originally developed for use in molten salt reactors (MSRs) where the fuel is dissolved in the salt. The original MSR program was part of the Aircraft Nuclear Propulsion Program of the 1950s to develop a jet-powered nuclear bomber. Consequently, the fluoride salt coolant was developed to transfer high-temperature heat from a nuclear reactor to an air-Brayton aircraft gas turbine. Advances in utility gas turbines over 50 years have now reached the point where it is practical to couple a salt-cooled reactor to a commercial stationary combined-cycle gas turbine with heat delivered from the FHR between 600 and 700°C. It is that combination that enables the FHR to potentially have the transformational capabilities. It is also why fluoride-salt cooled reactors most efficiently couple to gas turbines—that was what they were designed to do.

A commercial FHR point design[53,54] has been developed with a base-load output of 100 MWe to match the capabilities of the GE 7FB gas turbine—the largest rail transportable gas turbine made by General Electric. FHRs with higher output could be built by coupling multiple gas turbines to a single reactor or using larger gas turbines. Utility combined-cycle gas turbines are growing rapidly in size and the new H-Class gas turbines have about twice the output of the F-Class gas turbines. The development of an FHR will require construction of a test reactor—this size commercial machine would be a logical next step after a test reactor. This point design describes the smallest practical FHR for stationary utility power generation. The market would ultimately determine the preferred reactor size or sizes.

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[52] C. Forsberg et al., *Fluoride-Salt-Cooled High-Temperature Reactor (FHR) Commercial Basis and Commercialization Strategy*. MIT-ANP-TR-153, Massachusetts Institute of Technology, Cambridge, MA, Dec. 2014. At: http://web.mit.edu/nse/people/research/forsberg.html and http://fhr.nuc.berkeley.edu/

[53] C. Andreades et al., *Technical Description of the "Mark 1" Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR) Power Plant*, UCBTH-14-002, University of California at Berkeley, September 20, 2014. At: http://web.mit.edu/nse/people/research/forsberg.html and http://fhr.nuc.berkeley.edu/

[54] C. Andreades, *Nuclear Air-Brayton Combined Cycle Power Conversion Design, Physical Performance Estimation and Economic Assessment*, PhD Thesis, Nuclear Engineering, U. of California at Berkeley, Summer 2015.

Fig. 7.3 shows the FHR coupled to a NACC with FIRES. In the power cycle external air is filtered, compressed, heated by hot salt from the FHR while going through a coiled-tube air heat exchanger (CTAH), sent through a turbine producing electricity, reheated in a second CTAH to the same gas temperature, and sent through a second turbine producing added electricity. Warm low-pressure air flow from the gas turbine system exhaust drives a Heat Recovery Steam Generator (HRSG), which provides steam to either an industrial steam distribution system for process heat sales or a Rankine cycle for additional electricity production. The air from the HRSG is exhausted up the stack to the atmosphere. Added electricity can be produced by injecting fuel (natural gas, hydrogen, etc.) or adding stored heat after nuclear heating by the second CTAH. This boosts temperatures in the compressed gas stream going to the second turbine and to the HRSG.

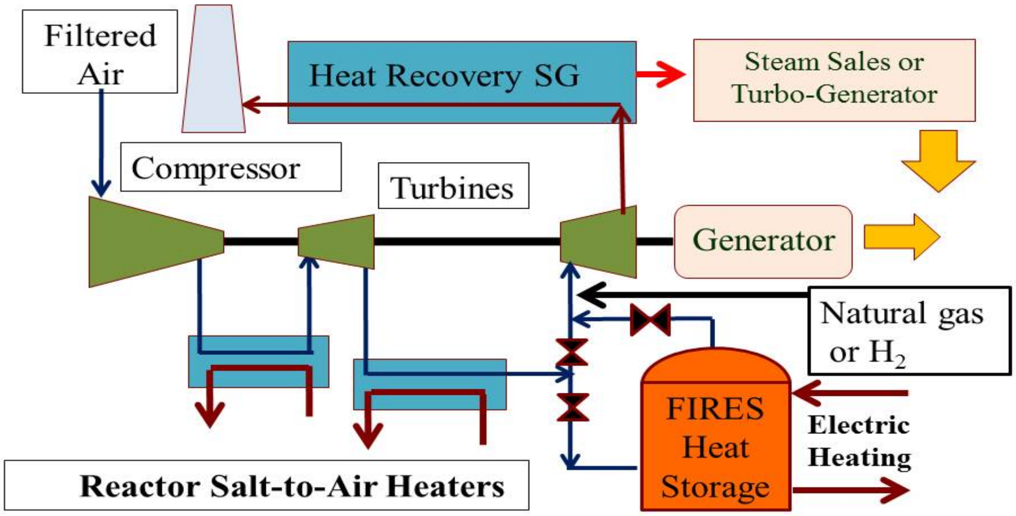

Fig. 7.3. Nuclear Air-Brayton Combined Cycle (NACC) with FIRES

The incremental natural gas, hydrogen, or stored heat-to-electricity efficiency is 66.4%--far above the best stand-alone natural gas plants because the added heat is a topping cycle. For comparison, the same GE 7FB combined cycle plant running on natural gas has a rated efficiency of 56.9%. The reason for these high incremental natural gas or stored heat-to-electricity efficiencies is that this high temperature heat is added on top of "low-temperature" 670°C nuclear heat (Fig. 7.4). For a modular 100 MWe FHR coupled to a GE 7FB modified gas turbine that added natural gas or stored heat produces an additional 142 MWe of peak electricity.

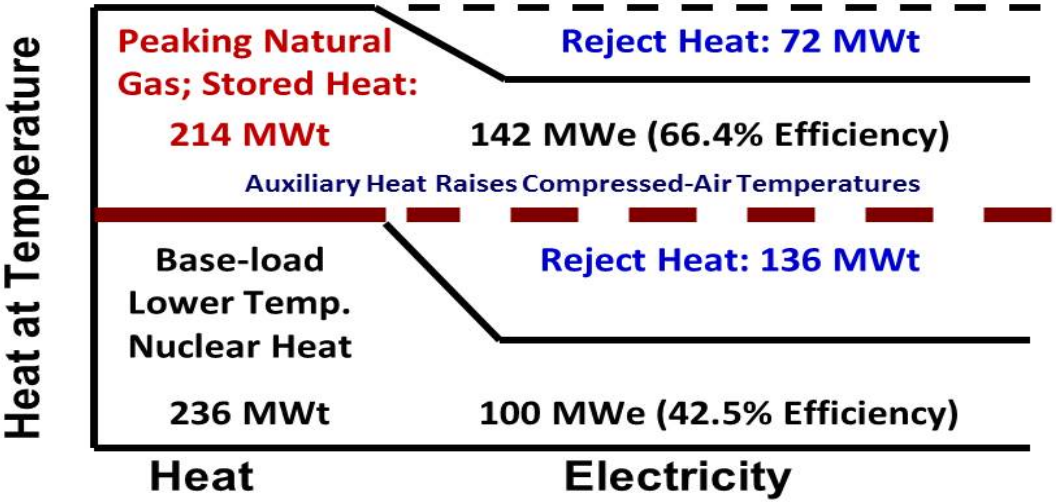

Fig. 7.4. Heat and Electricity Balance for NACC and FIRES

The heat storage system consists of high-temperature firebrick heated to high temperatures with electricity at times of low or negative electric prices. The hot firebrick is an alternative to heating with natural gas. The firebrick, insulation systems, and most other storage system components are similar to high-temperature industrial recuperators. The round-trip storage efficiency from electricity to heat to electricity is ~66%--based on ~100% efficiency in resistance electric conversion of electricity to heat and 66% efficiency in conversion of heat to electricity. That efficiency could be near 70% by 2030 with improving gas turbines.

The plant output is shown in Fig. 7.5. When electricity prices are low (less than the price of natural gas), electricity from the FHR is sent to FIRES. In addition, up to 242 MWe of electricity is bought from the grid. The buy capability of the FHR matches the sell capability and thus does not require upgrades to the grid. Because electricity is used to heat the firebrick, firebrick can be heated to 1800°C to minimize the quantity of firebrick required. The hot compressed gas from FIRES is lowered to the turbine limits by either steam injection or mixing with lower-temperature compressed air.

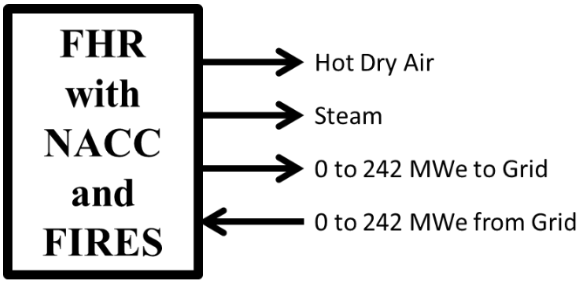

Fig. 7.5. Capability of Modular FHR with NACC and FIRES

Much of the technology to integrate FIRES into a gas turbine is being developed by a General Electric-RWE project Adele (Fig. 7.6 and Fig. 7.7) to develop an adiabatic compressed air storage system for deployment in Germany. RWE is the largest German utility. Adele is an alternative to battery storage of electricity. When electricity prices are low, the air (1) is compressed 70 bar with the adiabatic compression raising the compressed gas temperature to 600C, (2) is cooled by flowing through a brick recuperator, and (3) stored as compressed air in salt domes deep underground. The compressed air must be cooled to avoid overheating the salt and causing structural failures of the underground works. When electricity prices are high, the compressed air flows back through the firebrick and is reheated and enters a turbine where it produces electricity before being exhausted to the atmosphere. The first demonstration project is to be completed in several years. As a result of this project, a firebrick recuperator is being incorporated into a modern large gas turbine. There are differences, for NACC with FIRES the gas temperatures are higher, the peak pressures are lower, and the firebrick is heated electrically. However, much of the technology is being developed including how to integrate a gas turbine with a firebrick recuperator.

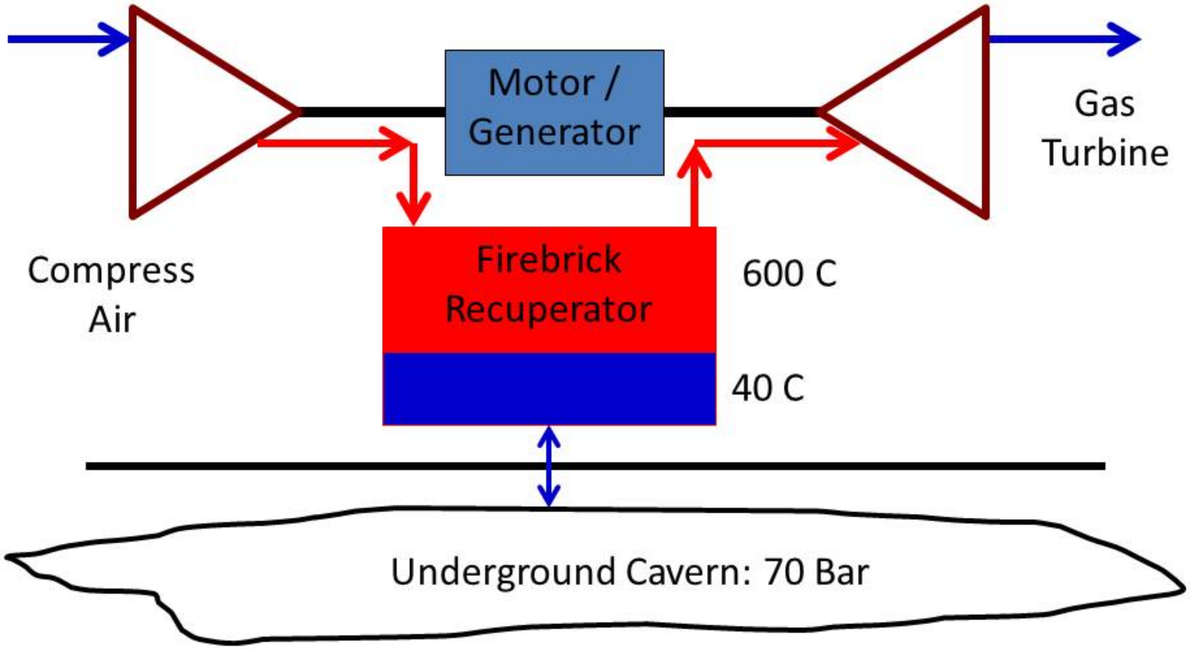

Fig. 7.6. Adiabatic Compressed Air Storage (Project Adele)

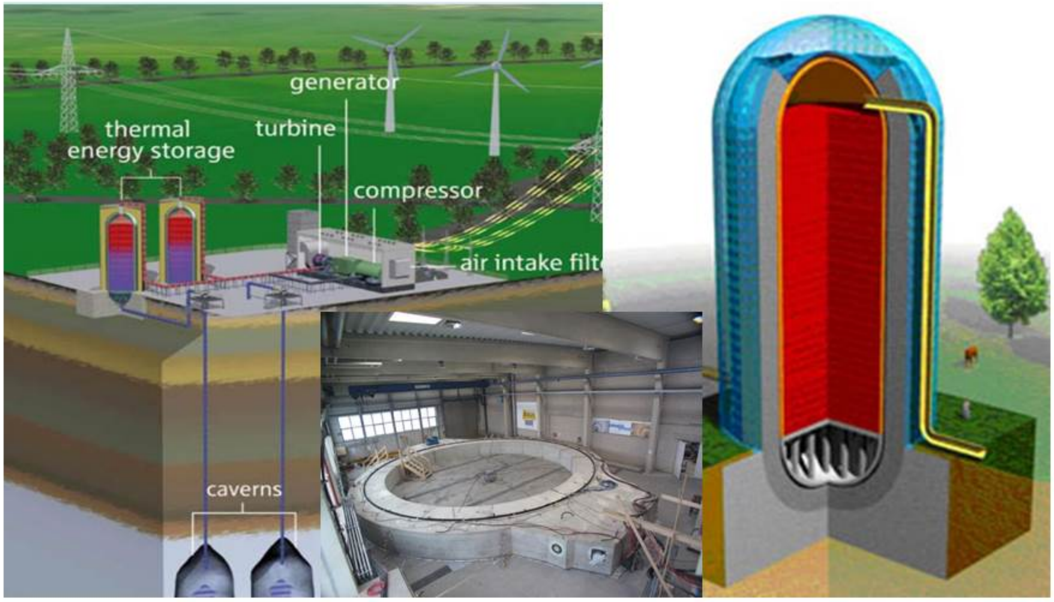

Fig. 7.7. Project Adele: Plant Layout, Test Section for Concrete Pressure Vessel for Firebrick and Drawing of Concrete Pressure Vessel with Firebrick (Courtesy of General Electric)

A second schematic of NACC for a low-carbon world is shown in Figures 7.8. The combined cycle plant allows steam sales to industry if desired.

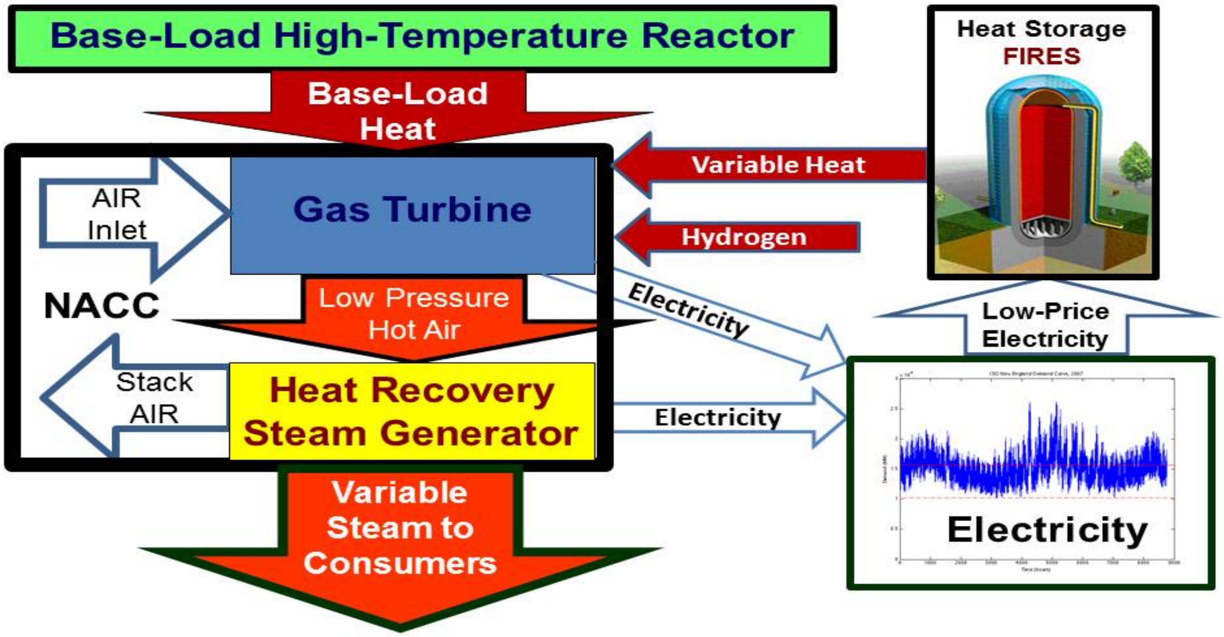

Fig. 7.8. Schematic of NACC for a Low-Carbon World with Peak Electricity Production using FIRES or Hydrogen

In the existing Texas and California grids, the revenue for an FHR with NACC would be 50% higher than a base-load nuclear plant because of the capability to produce more electricity at times of peak demand and prices. For each market, the starting point is the hourly price of electricity. This price was used to determine net revenue for that hour for: (1) the FHR operating under base-load conditions and (2) the FHR producing peak electricity. Net revenue for peak electricity production is the revenue from electricity sales for that hour minus the price of natural gas that was burned. The plant was assumed to operate each hour in the mode that produced the most net revenue. Total yearly revenue was obtained by summarizing revenue for each hour over the year. The difference in revenue between a base-load plant and an FHR with NACC increases with natural gas prices. Figure 7.9 shows the U.S. Energy Information Agency estimates on the costs of different methods to produce electricity including a base-load nuclear plant. Increasing revenue potentially makes the FHR with NACC competitive with natural gas—assuming similar capital and operating cost to an LWR.

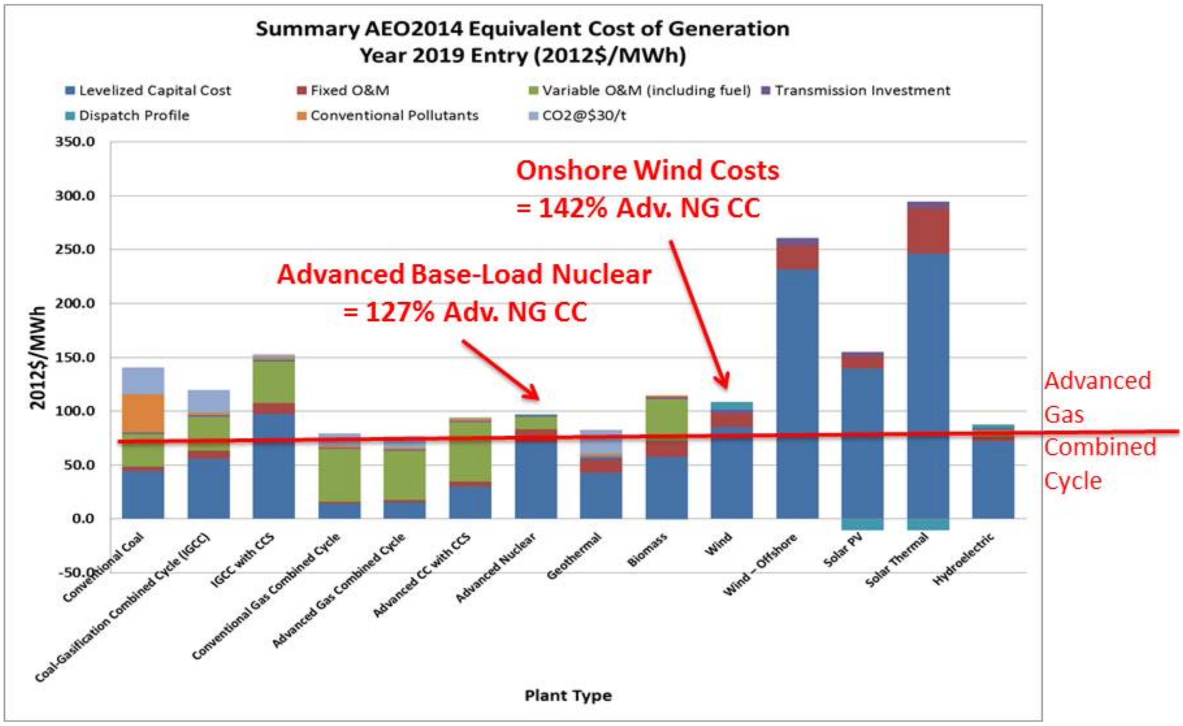

Fig. 7.9. Energy Information Agency Estimates of Levelized Cost of Electricity from Different Electricity Generating Technologies.

The economics of adding FIRES depends on how many hours per year the price of electricity is below the price of natural gas. The economics are expected to be favorable in the California market by 2020. By then there will be sufficient renewables to drive electricity prices below those of natural gas for significant periods of time. It enables replacement of “expensive” natural gas with cheaper electricity. FIRES enables buying massive quantities of electricity when the price is low. Unlike batteries and other electricity storage devices, resistance heaters are inexpensive and thus the system can absorb massive quantities of low-price electricity even if available for short periods of time.

Gas turbine technology is developing rapidly. The first “H-Class” natural-gas-fired combined cycle plants are coming online with outputs above 500 MWe and higher efficiencies. A NACC deployed in 15 years will have higher efficiency than current designs and will be able to couple efficiently to much larger reactors. The incremental heat-to-electricity efficiency will also substantially increase. Some reactors today have multiple steam turbines—there is the option to couple a large high-temperature reactor to multiple NACC to enable any size high-temperature reactor to use NACC. More recent work[55,56,57,58] suggests that NACC may also be applicable to other high-temperature reactors including sodium-cooled fast reactors.

Several final observations should be made about the FHR with NACC. It is enabled by the remarkable technology and commercial advances in natural-gas combined cycle plants. This variant of a nuclear topping cycle couples efficiently with a zero-carbon nuclear renewable electrical grid because it’s the first reactor concept with design goals to (1) enable competition with low-cost natural gas and (2) enable a zero-carbon electrical grid. Until a decade ago, no though had been given to such design goals. Whether there are other such nuclear options is unknown. Last, as a new concept there are many unknowns.

7.4 Cryogenic Energy Storage (CES)

There is another class of NUTOC based on a very different approach where LWR heat is the topping cycle and air is the working fluid. In a cryogenic energy storage (CES) system[59] electricity is used to produce liquid air using current industrial processes. The cryogenically cooled air is stored at atmospheric pressure. At times of high electricity demand, the liquid air is compressed, heated with steam from a light water reactor (LWR) to produce high-pressure air, sent through a turbine, and exhausted to the atmosphere. The round trip efficiency would exceed 70%. The peak power is about three times the rated electrical power of the LWR. The efficiency

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[55] C. Forsberg, P. McDaniel, and B. Zohuri, “Variable Electricity and Steam from Salt, Helium, and Sodium Cooled Base-Load Reactors with Gas Turbines and Heat Storage”, Paper 15115, Proc. *International Congress on Advanced Nuclear Power Plants (ICAPP15),* Nice, France, May 3-6, 2015.

[56] B. Zohuri, *Innovative Combined Brayton Cycle Systems for the Next Generation Nuclear Power Plants*, PhD Thesis, University of New Mexico, May 2014.

[57] P. McDaniel and C. Forsberg, “Nuclear Air-Brayton Combined Cycles for Sodium Cooled Fast Reactors, Paper 15355, *Trans. American Nuclear Society 2015 Winter Meeting*, Washington D.C., November 8-12, 2015

[58] C. Forsberg and P. McDaniel, “Air-Brayton Systems with Salt, Sodium, and Helium Base-Load Reactors with Variable Electricity, Steam and Hot-Air Output”, Paper 15200, *Trans. 2015 American Nuclear Society*, Washington D.C., November 8-12, 2015.

[59] Y. Li et al., “Load Shifting of Nuclear Power Plants Using Cryogenic Energy Storage Technology,” *Applied Energy*, **113**, 1710-1716, 2014.

is obtained by starting with an extremely cold fluid rather than going to extremely high temperatures.

8. CHANGING THE ELECTRICITY PRICE CURVE WITH HYBRID ENERGY SYSTEMS: PRODUCING ELECTRICITY AND A SECOND PRODUCT

Hybrid energy systems (Fig. 8.1) produce two or more products—one being electricity. The second product is an energy-intensive storable product such as hydrogen or a liquid fuel. The nuclear, wind, and solar systems are used at full capacity. When production of electricity exceeds demand, heat from nuclear and solar thermal systems with electricity are used to produce a second product—reducing electricity to the grid. It is a way to transfer excess energy generating capability, when available, to the industrial, commercial, and residential sectors—helping those sectors meet zero carbon goals. Recent reports have described the potential of hybrid systems.[60]

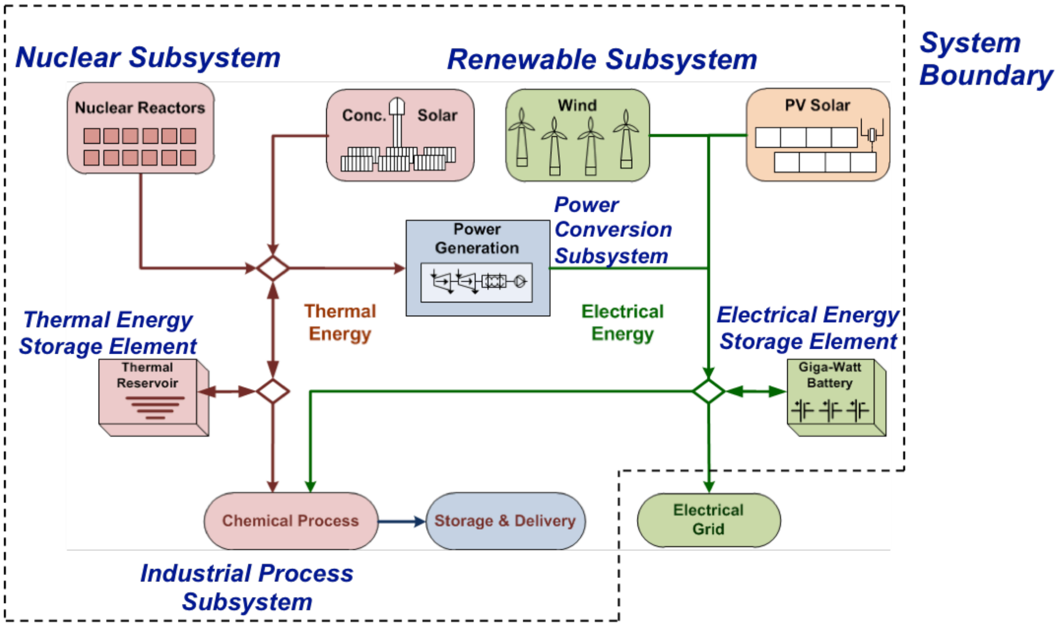

Fig. 8.1. Generalized Nuclear-Renewable Hybrid Energy System, Showing the System Boundary and Grid Connection.

Hybrid systems may include heat storage. These systems can have major advantages over energy storage by productively using excess energy from nuclear, solar, and wind, when available, with the potential to address seasonal mismatches between energy production and demand. With the production of a second product, there is the potential to be more economic than other strategies because one minimizes storage costs and associated inefficiencies.

The historical example is cogeneration where the nuclear plant provides variable amounts of electricity and steam for industry or district heating. While the cogeneration concept is old, new

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[60] W. R. Deason, R. D. Boardman, and S. M. Bragg-Sitton, *Integrating Nuclear-Renewable Hybrid Energy Systems: Current Energy Market Status Report*, INL/EXT-15-35446, June 2015.

technologies are changing its characteristics. In particular, advances in pipe insulation may allow hot water transport as far as 200 km—enabling nuclear plants to provide heat for large cities.[61]

Potentially the largest future hybrid systems would be those producing hydrogen and electricity. An example is a nuclear wind hydrogen system located in areas of low-cost wind (high Great Plains) where hydrogen is produced via high-temperature electrolysis and transported by long distance pipeline to industrial customers.[62, 63, 64] It is a method to efficiently use isolated low-cost wind resources, meet local electricity demands and create a valuable transportable commodity. Figure 8.2 shows the system structure that is applicable to nuclear-wind-hydrogen or nuclear-solar-hydrogen hybrid systems.

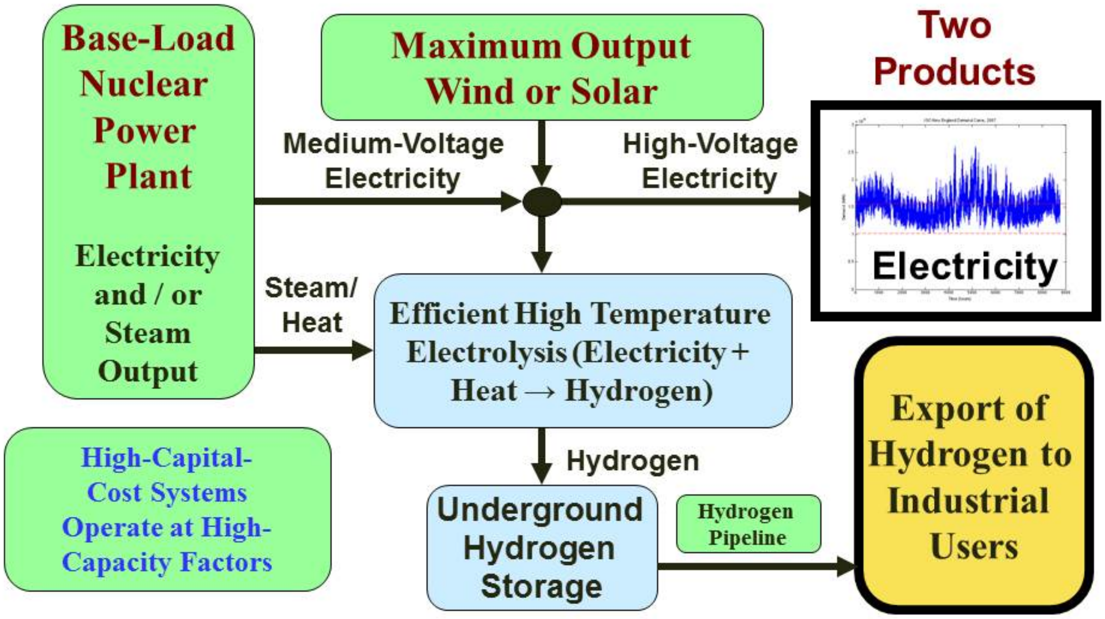

Fig. 8.2. Nuclear Wind/Solar Hydrogen Hybrid System

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[61] H. Safa, "Heat Recovery from Nuclear Power Plants", *Electrical Power and Energy Systems*, **42**, 553-559 (2012)

[62] G. Haratyk, C. W. Forsberg, and M. J. Driscoll, *Nuclear-Renewables Energy System for Electricity and Hydrogen Production: A Case Study of a Nuclear Wind Hydrogen System for the Midwest Electrical Grid*, MIT-NES-TR-012, Center for Advanced Nuclear energy Systems, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2011

[63] G. Haratyk, G., *Nuclear-Renewables Energy System for Electricity and Hydrogen Production*, Department of Nuclear Science and Engineering Master's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2011

[64] G. Haratyk, C. W. Forsberg, 2012. "Nuclear-Renewables Energy System for Hydrogen and Electricity", *Nuclear Technology*, **178** (1), 66-82, 2012

The nuclear-wind-hydrogen hybrid system has the following features:

- *Capital utilization*. Capital intensive nuclear and wind systems operate at full capacity
- *Electricity*. Nuclear and wind systems produce all electricity required for variable regional electricity demand. The nuclear plants can meet peak electricity demand even if there are low-wind conditions.
- *Hydrogen*. At times of high wind conditions, steam from the nuclear plants and excess electricity from the grid are used to produce hydrogen via high-temperature electrolysis—steam electrolysis. Steam electrolysis is more efficient than conventional electrolysis but requires heat and electricity.
- *Storage*. Hydrogen is stored locally in underground systems—the same technology used to store hydrogen in bulk today and the same technology used to store natural gas. Large-scale hydrogen storage is a low-cost technology.
- *Shipment.* Hydrogen is shipped by pipeline with the hydrogen storage to enable full use of pipeline capacity.

Features of this system are full utilization of capital-intensive assets (wind, nuclear, and long-distance pipeline), a zero-carbon local electricity grid, and export of a low-cost local resource (wind) as hydrogen to national markets. In this example hydrogen is the storage medium to match electricity production with demand.

Hydrogen may be a long-term fuel for peak electricity production for a zero-carbon grid. The challenge is the round-trip efficiency of electricity to hydrogen to electricity. High-temperature electrolysis is the most efficient method to produce electricity. A nuclear topping cycle (NUTOP) is the most efficient method to convert hydrogen to electricity.

9. ELECTRICITY TRANSMISSION AND DISTRIBUTION

Transmission costs are the other major cost associated with electricity and can be a third or more of the total cost of electricity to the residential consumer. The above options are partly in competition with added transmission capability but also can also reduce transmission costs. Electricity transmission grids serve multiple purposes. They connect electricity generators to consumers. Electricity grids lower peak electricity demand and reduce required generating capacity by (1) averaging loads of different customers and (2) moving electricity across time zones where peak demands occur at different times. Transmission brings lower-cost electricity from one area to areas with higher-cost electricity.

The costs of adding electricity generating capacity to the grid depends upon the electricity generating technology. Table 9.1 shows these estimated costs for the United States for different types of electricity generation. These costs assume the existing grid system. As a basis of comparison, the EIA estimate for the generating cost of electricity in 2018 is $67.10 /MWh. If 30% of the electricity is generated by wind or solar, the added grid costs for these renewables can approach a third the existing cost of generating electricity from natural gas and thus major are contributors to the total cost of electricity.

Table 9.1. Incremental Grid-Level System Costs in the United States ($/MWh)[65]

Technology	Nuclear		Coal		Gas		Onshore Wind		Offshore Wind		Solar	
Penetration Level	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%	10%	30%
Backup Costs	0.00	0.00	0.04	0.04	0.00	0.00	5.61	6.14	2.10	6.85	0.00	10.45
Balancing Costs	0.16	0.10	0.00	0.00	0.00	0.00	2.00	5.00	2.00	5.00	2.00	5.00
Grid Connection	1.56	1.56	1.03	1.03	0.51	0.51	6.50	6.50	15.24	15.24	10.05	10..5
Grid Reinforcement & Extension	0.00	0.00	0.00	0.00	0.00	0.00	2.20	2.20	1.18	1.18	2.77	2.77
Total	1.72	1.67	1.07	1.07	0.51	0.51	16.30	19.84	20.51	28.26	14.82	28.27

These costs are broken into categories. The backup costs for times of low wind or solar in the United States are for natural gas generating capacity. Balancing costs[66] refers to the ability to maintain system performance on a minute-to-minute basis in the presence of uncertainty in

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[65] Nuclear Energy Agency, *Nuclear Energy and Renewables: System Effects in a Low-Carbon Electrical Systems*, Paris, France, 2012.

[66] E. Ela et al. *Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation*, NREL/TP-5D00-61765, National Renewable Energy Laboratory, September 2014.

supply and demand. Grid connection costs are high for offshore wind and solar but for different reasons. Offshore wind connection costs reflect the costs of undersea power cables. Higher solar connection costs are a consequence of several factors including solar capacity factors are ~20% versus 90% for nuclear—implying more than four times as much grid is required to move a kWh of electricity.

There is a specific challenge with solar grid costs depending upon the type of solar deployed. Large-scale distributed (rooftop) solar has significantly larger transmission and distribution costs[67] than utility-scale solar. The electricity distribution system today is sized for peak electricity demand recognizing that not all houses or commercial establishments will have simultaneous peak electricity demands. If one installs distributed solar on a large scale, the distribution grid must be sized for peak electricity output that does occur simultaneously in an area. Peak electricity output with significant solar deployment will be larger than peak electricity demand and thus the need for added electricity distribution capacity. While distributed solar reduces line losses, as penetration increases those savings are generally outweighed by investments to maintain power quality. Figure 9.2 shows the results of the detailed analysis.

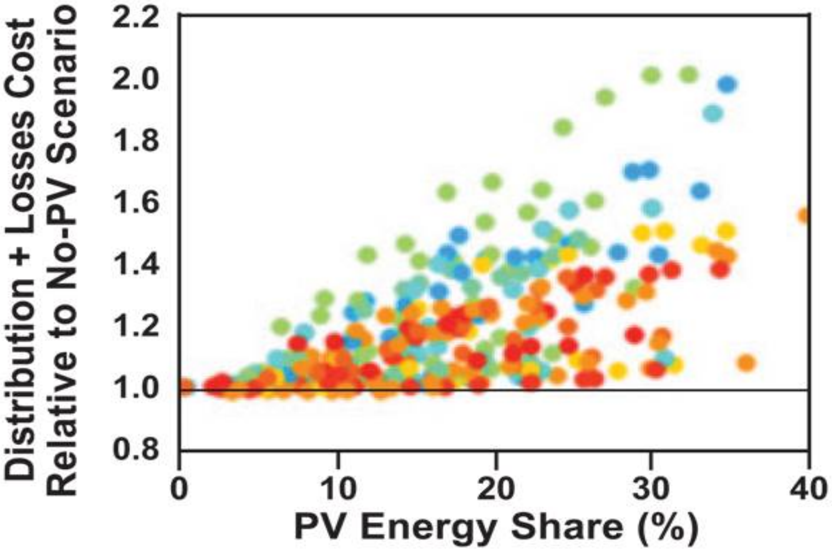

Fig. 9.1 Average Total Costs with Increased Distributed PV Penetration Under Different Assumptions About Design Standards and Generation Mix.

In some cases, distributed solar will double distribution system costs by the time 30% of all electricity is produced by solar. The costs of moving a kWh of electricity in the distribution system with distributed power generation is much larger than moving a kWh of electricity on the transmission grid from utility-scale solar systems. In addition, the technologies required for

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[67] Massachusetts Institute of Technology, *Future of Solar Energy*, 2015

addressing seasonal variations in solar are large-scale technologies that can’t be deployed in a cost-effective manor on a small distributed scale. That implies moving electricity from distributed generating sources to storage and back—an option that maximizes electricity grid costs.

The coupling between the five classes of technologies discussed in this report and transmission-distribution is complex. Many but not all of the added transmission-distribution costs associated with wind and solar can be reduced by these technologies. There are also two potentially larger global impacts. Technologies that can transfer excess thermal energy from the electricity sector (RATHS, NUTOP, Hybrid) to the industrial sector reduce the total need for transmission and distribution. Second, the hybrid energy systems that produce hydrogen provide an alternative strategy to move energy long distances—pipelines rather than transmission lines.

10. COMPARISON OF OPTIONS: IMPLICATIONS FOR RESEACH AND DEVELOPMENT

10.1 Option Space

The five options are compared in Table 10.1 based on five characteristics. The third column is the relative ability to prevent price collapse in a grid with large-scale solar, wind or nuclear. The fourth column is the relative amount of electricity sent to the grid at times of high demand. Some options do not have the ability to send added electricity to the grid. The fifth column is the ability of the system to replace dispatchable generating capacity and avoid the construction of added power plants—this may only apply to some technologies within a category. The sixth column is where the energy goes from the electric sector. These are approximate judgments and significant work will be required to provide good quantitative analysis.

Table 10.1. Classes of Systems to Match Electricity Production to Demand and Impact on Electricity Price Curve

Option	Method to Use Excess Low-Price Electricity	Limit Price Collapse	Electricity To Grid (Relative)	Replace Gen. Capacity (MW)	Storage Times
Electrics: Electricity Storage (Battery and functionally equivalent)	Grid Electricity →Stored Work →Electricity	Limited	1	Limited (Future Grid)	Hour to Day
FIRES: Electricity to Heat Storage to Industry	Grid Electricity →Stored Heat →Heat to Industry	Very Good	0	No	Hour to Week
RATHS: Reactor Associated Heat Storage (Solar thermal storage option)	Reactor Heat →Stored Heat →Electricity	Limited	1-2	Yes	Hour to Season
NUTOC: Nuclear Reactor Topping Cycle using FIRES Heat Storage	Grid Electricity →Stored Heat in FIRES Reactor Heat + FIRES Heat →Peak Electricity	Good	1-2	Yes	Hour to Day, Seasonal with Stored H_2
Hybrid: Co-Produce Electricity and Second Product	Reactor Heat + Grid Electricity → Electricity + Second Product	Good to Very Good	0	No	Hour to Season

10.2 Key Observations

Structuring options by functional characteristics helps define the roles of wind, solar, and nuclear in a zero-carbon grid. It provides a way to develop R&D portfolios and defines unexplored areas of research. Several observations are derived from this analysis.

- *Electricity price collapse in a deregulated electricity market is the central challenge when (1) transitioning from an electrical system dominated by low-capital-cost high-operating-cost fossil fuel generating capacity to (2) an electrical system dominated by high-capital-cost low-operating-cost nuclear, wind and solar electricity generating technologies.* Electricity price collapse limits the use of low-carbon technologies. Massive subsidies or “special rules” can hide price collapse but does not change the fact that the value of electricity is very low if production exceeds demand. The total societal cost of energy (price plus subsidies) will be very high unless efficient methods to fully utilize capital-intensive electricity generating technologies are developed. This is just as important as reducing the capital cost of nuclear, wind, and solar systems in a low-carbon world. A nuclear, wind, or solar plant operating at 50% versus 100% capacity is equivalent to doubling the capital cost of that technology.

- *FIRES could limit electricity price collapse associated with the large scale renewables deployment and thus improve the economics of wind, solar, and nuclear by converting low-price electricity into valuable high-temperature stored heat for industry*. Because FIRES is a low-cost technology it can set a minimum price for electricity near the cost per unit heat of fossil fuels used in industrial furnaces and kilns. FIRES is a possible coupling technology to allow buying large quantities of heat at rates greater than immediately needed for industrial furnaces when the electricity prices are low. It is the changing characteristics of the electricity price curve that creates the incentives to deploy FIRES. If FIRES is successfully deployed, there are other implications for the electricity sector:

    - If solar or wind systems can reduce costs to match fossil fuels per unit of heat, there would be a massive market demand for these technologies to deliver heat to industry through FIRES.
    - FIRES could enable a low-carbon electric sector to partly decarbonize the industrial sector and may ultimately provide a large fraction of heat to the industrial sector.
    - FIRES could limit the growth of traditional electrical energy storage systems, such as batteries, and long-distance transmission lines. The economics of batteries and long distance transmission lines are based on large differences in the price of

electricity respectively in time and location. FIRES could reduce these electricity price variations.

- *Heat storage (RATHS) is cheaper than electricity storage, has the capability to meet weekly to seasonal electricity storage requirements, and can partly replace the need for electrical generating capacity.* Weekly and seasonal storage is not economically feasible with electricity storage technologies. Thermal storage is cheaper when coupled with nuclear than solar thermal, and nuclear plants can be built in most locations whereas solar thermal power plants require direct sunlight (southwest U.S.). This implies that nuclear energy coupled to heat storage may be an enabling technology for economic large-scale use of wind and solar by reducing renewable-induced electricity price (revenue) collapse and providing electricity at times of low wind or solar conditions.

- *Hybrid systems have the potential to be the low-cost option*. Storage has associated costs and inefficiencies. Hybrid systems can potentially minimize storage. Hybrid systems with hydrogen production deserve special attention because of the potential ability to transfer low-price energy to the industrial and transport sectors where there is a growing demand for hydrogen.

- *NUTOP: Grid Electricity to FIRES Heat Storage with Stored FIRES Heat for Peak Power.* This is the wildcard among the five categories and the newest set of options—systems that act like electric storage (batteries, pumped storage, etc.) but have the capability to produce peak power using auxiliary natural gas or ultimately hydrogen, thus providing dispatchable electric capacity like a base-load nuclear plant. All of the other sets of options have existed for decades and thus are much better understood.

- *The relative use of the five classes of technologies will vary with location because of the geographic variation in renewable resources and differences in electricity demand.*

10.3 Recommendations

The analysis of the grid and possible options to enable full utilization of wind, solar, and nuclear leads to a set of research and development recommendations. This is a preliminary set with the observation that there have been very limited examinations of the options space including categorization of options by their general characteristics.

Need for Firebrick Resistance Heated Energy Storage (FIRES) or Equivalent

The central feature of a low-carbon grid dominated by high-capital-cost low-operating-cost technologies in a deregulated market is price collapse when production exceeds demand—unless there are technologies to match production with demand. Technology advances will have little impact on the large-scale use of renewables unless this challenge is addressed. Price collapse impacts solar, wind, and nuclear. Price collapse drives the grid toward use of low-capital-cost high-operating cost technologies such as natural gas turbines. The challenge is greatest with solar because most of the excess electricity is available in a period of a few hours with the need for a technology capable of economically absorbing very large quantities of low-priced electricity in a short period of time. Thus far, FIRES is the only technology identified with those characteristics.

Need for Technologies that Provide Electric Generating Capacity That Economically Couples Production and Demand

Short-term electricity storage, short-term thermal energy storage for peak electricity and other similar approaches do not address the long-term challenge of creating a low-carbon affordable electrical system. Any electrical grid built on short-term energy storage can have catastrophic blackouts (non-resilient) if there are prolonged periods of (1) high electricity demand (long heat waves, long cold periods, etc.), (2) extended cloud cover that shuts down solar, or (3) extended low wind conditions. The challenge is the energy equivalent of the 100-year flood, except such events cover very large geographical areas and, thus, are more damaging to society than highly localized 100-year floods. There is not yet a good understanding of the variability of weather with climate change.

The potential technological options are those that provide more generating capacity: seasonal thermal storage, mega-scale hybrid systems that produce mega-quantities of storable fuels such as hydrogen, and nuclear topping cycles. Future low-carbon energy systems must have the capability to assure energy even if unexpected weather.

Need to Determine if the Existing Energy Policies Are Creating a Policy Trap where It Is Extremely Difficult to Progress Toward a Zero-Carbon Energy System

The current electricity policy in the U.S. is subsidies to wind and solar, betting on natural gas to provide electricity when the wind does not blow and the sun does not shine (Fig. 10.1). It is a monoculture system where if the price of natural gas goes up or as a society we must get off natural gas because of climate changes, electricity prices climb rapidly. There are very few incentives to create the required technologies if there are no restrictions on natural gas and very high costs to change policies. It is a set of policies that may be hard to reverse.

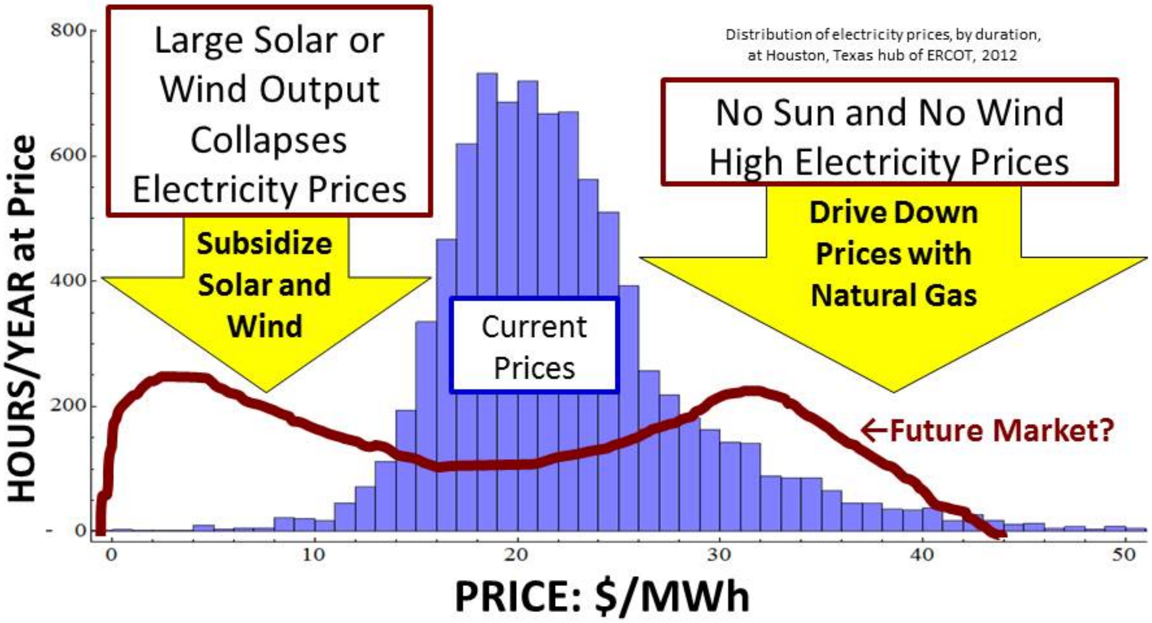

Fig. 10.1. Current U.S. Electricity Policy

11. CONCLUSIONS

The U.S. is in a transition from an electricity system based on low-capital-cost high-operating-cost fossil fuel plants to one based on high-capital-cost low-operating-cost plants using nuclear, wind and solar. To minimize costs to society we need to fully utilize this generating capacity although the electricity output of nuclear, wind, and solar plants does not match electricity demand.

There are many technologies that can help match electricity production with demand (storage, hybrid systems, etc.). These technologies have not been developed or deployed at a significant scale in the past because the electricity systems were dominated by fossil fuel plants. In an electrical grid dominated by fossil fuel power plants, the economic solution to meet variable electricity demand has been to operate fossil plants at partial load. This is viable because fossil generating costs are dominated by the cost of the fuel, not the cost of the plant.

A categorization of technology options to match electricity production with demand in a low-carbon electricity system was developed based on whether heat or work is stored. This resulted in five classes of options where each class can be considered a “black box” with certain characteristics. This categorization system is used as a basis to think about options and will be used in future modeling of system options. A set of R&D recommendations directly flows from this analysis.

Nuclear energy is a major component of future low-carbon electricity grids, partly because three of the five sets of options that enable efficient matching of low-carbon electricity production with demand couple with steady-state heat sources. That is the functional description of a nuclear reactor. It also implies that nuclear energy is likely the enabling technology for large-scale use of wind and solar. One unique feature of nuclear energy is its potential ability to couple with technologies that address seasonal energy storage requirements—requirements that are easy to meet with a fossil system but difficult to meet in a low-carbon world.

Large-scale use of wind and solar implies large geographical variations in preferred energy choices because of the large geographical variations in those resources. That variation also implies large differences in the relative importance of any of the five classes of technologies discussed in this report. Different constraints will result in different mixtures of energy sources with large variations across the United States and the world.