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Nuclear Energy Futures for a Low-Carbon World with Wind and Solar: Nuclear Co-generation with Heat Storage to Buy-Sell Electricity and Assure Peak Power

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Abstract—The characteristics of fossil fuels (low-cost storage, economic variable output enabled by low-capital-cost high-operating-cost power systems, etc.) have resulted in an energy system where fossil fuels separately supply energy to the electricity, industrial (heat) and transport (liquid fuels) sectors. World systems are undergoing a profound change driven by (1) large-scale addition of wind and solar and (2) the goal of a low-carbon electricity grid. Nuclear, wind and solar have high capital costs and low operating costs where the cost of energy increases rapidly if operate at part load. We examined integrating the electricity and industrial sectors by (1) nuclear co-generation with production of heat for industry and electricity and (2) addition of heat storage to increase reactor capacity factors.

This system design substantially reduces total energy costs by three separate mechanisms. Modeling of electricity and industrial energy systems shows nuclear cogeneration reduces energy costs by changing the hourly energy demand curves to better match production from low-carbon energy sources resulting in higher power-plant utilization. Cogeneration enables optimizing the electricity and industrial sector by varying industrial production to minimize total costs with added electricity sales at times of high prices. Heat storage increases plant capacity factors and thus lowers total energy costs.

Keywords Nuclear co-generation, Heat storage, Assured peak electricity generation

I. INTRODUCTION

Concerns about climate change may require reducing greenhouse gas emissions. Most decarbonization studies examine sectors of the energy economy that follow how the energy economy is organized today as shown in Fig. 1 for the United States. The economy is based on fossil fuels where fossil fuels are separately supplied to the electricity, industrial and transport sectors. These sectors have different characteristics. The electricity sector has large changes in demand with time on an hourly to seasonal basis that reflects residential and commercial electricity demand. The industrial sector primarily uses heat at a near constant rate. While the transport sector has a variable demand for energy, the energy input into fuels production (refineries, pipelines, etc.) is relatively constant. Fossil fuels excel at separately meeting these energy needs because (1) fossil fuels provide energy, storage of energy, and dispatchability of energy to meet these different requirements and (2) fossil fuel systems have low capital costs and high operating costs (fuel) allowing economic operation of power plants, furnaces, boilers, and cars at part load. Those characteristics enable fossil fuels to separately supply energy to the electricity, industrial and transport sectors.

Nuclear, wind and solar have high capital costs and low operating costs. Operating these technologies at part load increases energy costs. Because the economic characteristics of nuclear, wind and solar are different than fossil fuels, the “stovepipe” structure of the energy system as shown in Fig. 1 will change with more restrictive carbon emissions. We first describe that change and then the basis for changing the nuclear system design to reduce total energy costs.

II. LOW-CARBON-WORLD NUCLEAR SYSTEM DESIGN

The fundamental division between energy sources is whether they produce heat or work (electricity). Wind and solar photovoltaic (PV) produce electricity that defines their many of their characteristics. Nuclear energy produces heat that can be converted to electricity, directly used by industry or stored. Energy storage technologies are designed for either electricity (batteries, pumped hydro, capacitors, etc.) or heat (pressurized water, salt, concrete, oil, sand, etc.) This fundamental difference defines allowable system designs.

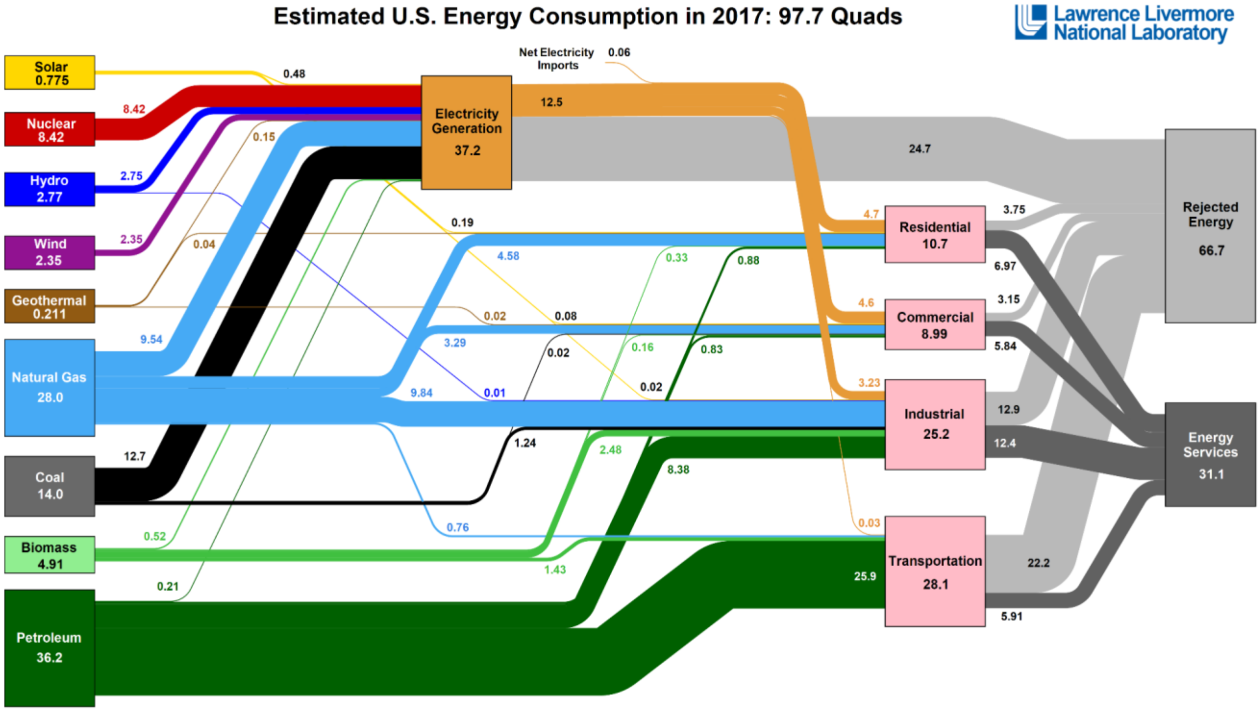

Fig. 1. 2017 Energy Flows in the United States [1]

Figure 2 shows the system design for heat generating technologies that applies to any heat generating technology (nuclear, concentrated solar power (CSP), geothermal and fossil fuels with carbon capture and sequestration). The red arrows are for energy flows of heat while the blue arrows are for energy flows of electricity. Unlike electricity generating technologies, heat storage and heat to industry require co-located facilities.

The reactor can send heat as steam in three directions depending upon demand to: (1) the turbine generator to provide dispatchable electricity generation, (2) storage and (3) industry if operating as a co-generation nuclear plant. At times of low electricity prices, a minimum amount of steam goes to the power cycle to keep the turbine-generator on line and allow rapid return to full power. The rest of the heat goes to heat storage and industry. There are multiple heat storage options [2-3]. At times of high electricity prices, steam from the reactor and added steam from storage goes to the power cycle to generate peak electricity output—substantially greater than the base-load electricity generating capacity of the reactor.

If electricity prices are low, electricity can be bought and converted into heat for heat storage using electric resistance heaters. Heat storage is an order of magnitude cheaper than electricity storage. The U.S. Department of Energy capital-cost goal for heat storage is $15/kWh while the capital cost goal for electric battery storage is $150/kWh. The power conversion equipment with batteries doubles that cost. The cost differences reflect the cost of raw materials for heat storage (pressurized water, salt, crushed rock, sand. concrete, oil, etc.) versus the cost of raw materials for electricity storage (lithium, cobalt, etc.). Technologies such as battery storage [4] are only viable for short storage periods—typically four hours.

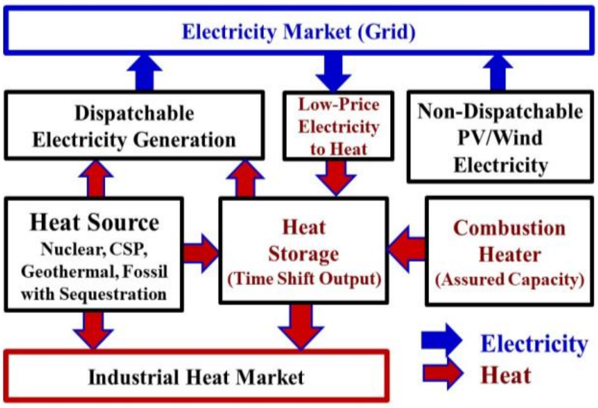

Fig. 2. Integrated Nuclear-Renewable Co-generation System with Heat Storage [2]

To provide assured peak generating capacity if storage is depleted, a combustion furnace provides the heat equivalent that comes from storage to the power cycle for peak electricity production. Capital costs [2, 5] for such a boiler are estimated at $100-300/kWe, less than the cost of a simple gas turbine ($500-600/kWe); the next cheapest alternative for assured generating capacity. The boiler can burn natural gas, biofuels or hydrogen.

III. MINIMIZING ELECTRICITY COSTS IN A LOW-CARBON WORLD

To examine these options [6] we first ask the following questions: What would be the optimum mix of technologies to minimize total cost of electricity for different constraints on carbon dioxide emissions per unit of electricity produced? This assumes today's organization of the electric sector, which is separate from the industrial sector. We then ask what is required to decarbonize the industrial sector, including the option to electrify the industrial sector and its impact on the electricity sector and electricity costs.

Recent studies [7-9] show that a mixture of dispatchable (nuclear, fossil fuels with sequestration, etc.) and non-dispatchable energy sources minimize the costs of electricity production in a low-carbon world. We extend this work to understand how nuclear plants would be operated to minimize total electricity costs using the load-following capabilities of nuclear plants. We used GenX [10], a power system decision support tool, to explore the optimal electricity generation mix based on minimizing the total system cost of electricity generation for a set of pre-specified scenarios. Each scenario is characterized by a carbon emission limit, a year-long hourly demand profile, year-long hourly availability profiles for solar and wind resources, and a set of investment and operational costs that model different systems under different carbon emission targets. The optimization is based on minimizing the average cost of electricity.

We consider electricity futures with and without nuclear energy for six areas of the world: (1) Texas, (2) New England, (3) Tianjin, Beijing, and Tangshan (T-B-T), China, (4) Zhejiang, China, (5) France and (6) and the United Kingdom. This includes electricity grids with excellent (Texas) and poor (New England) solar and wind resources. It includes countries with high (U.S. and U.K.) and low (China) capital costs for nuclear power plants.

Five different levels of carbon constraints were considered measured in carbon dioxide released per kilowatt-hour (gCO_2/kWh) of electricity produced: 500, 100, 50, 10 and 1 gCO_2/kWh. The energy technologies included energy production technologies (natural gas, coal, fossil fuels with carbon sequestration, nuclear, wind, solar) and storage technologies (hydro and batteries).

Figure 3 shows average electricity costs for the six regions as carbon dioxide emissions are reduced and including all technologies for five different levels of carbon emission constraints. Fig. 4 shows average electricity costs if nuclear energy is excluded from the generating mix.

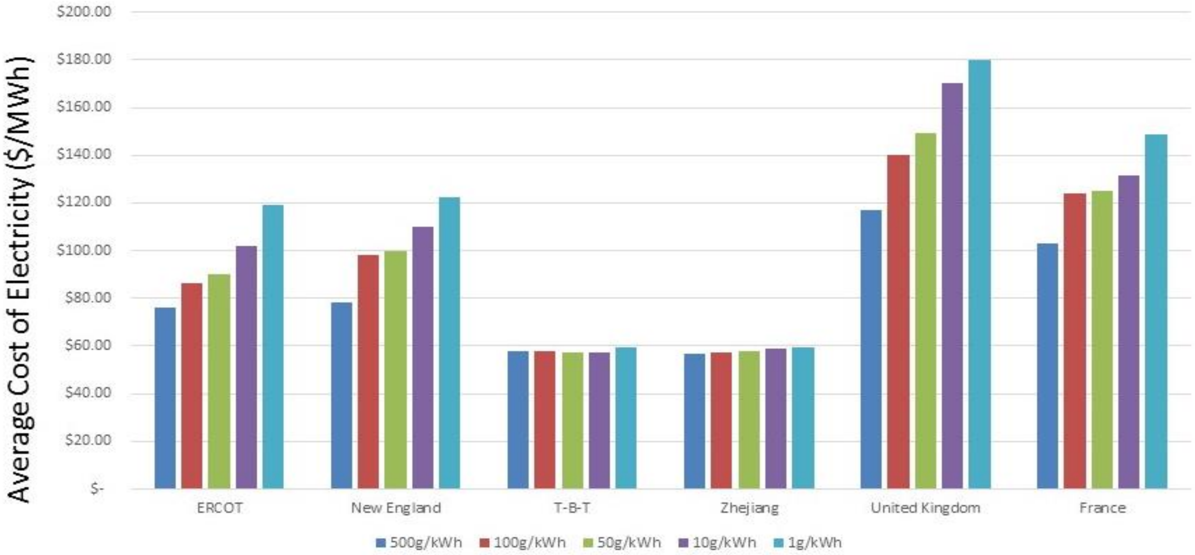

Figure 3. Average Cost of Electricity (All Technologies Allowed) Versus Carbon Constraint

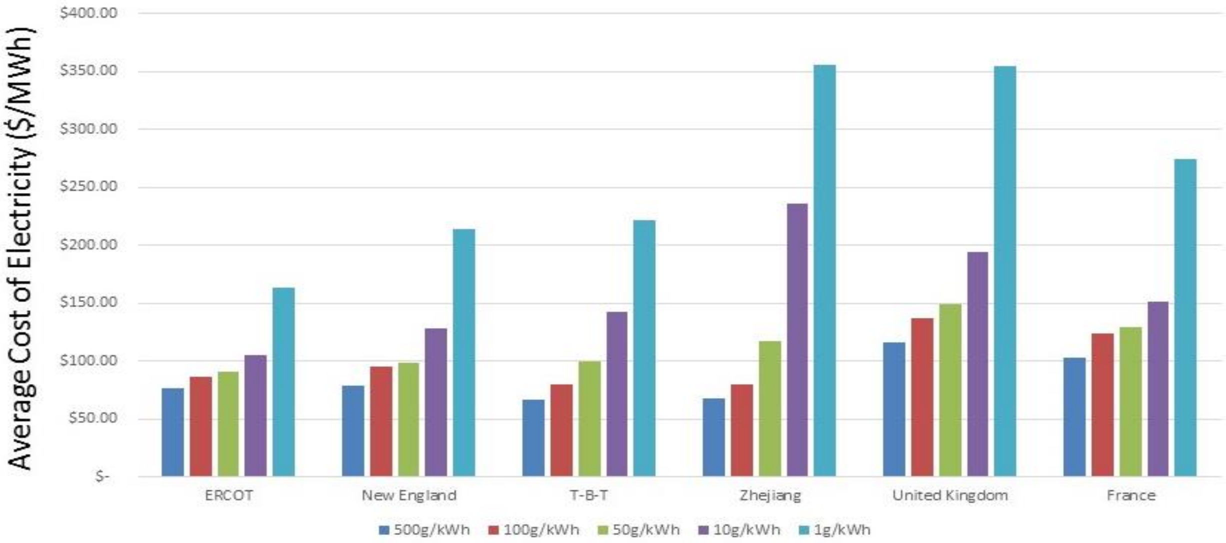

Fig. 4. Average Cost of Electricity for Non-Nuclear Scenarios versus Carbon Constraint

There are several conclusions from these figures. There is a large increase in costs in low-carbon scenarios if nuclear is excluded. The vertical axis ($/MWh) is twice as high in Fig. 4 (no nuclear allowed) compared to Fig. 3 (nuclear allowed). In a low-carbon world there are large differences in energy costs with location because of the large variability of renewable resources and costs of nuclear power plants. Chinese electricity costs do not change with carbon constraints because nuclear power is the low-cost option.

The large increases in electricity costs with tighter carbon constraints is driven by the need to provide assured peak generating capacity. When there are no carbon constraints, this peak capacity is provided by low-cost fossil plants operating at part load. In the U.S. this is the simple gas turbine burning natural gas. As carbon constraints are imposed, peak power is provided by a mixture of storage systems (batteries, etc.) and nuclear power plants operating in a load-following mode [11]. When nuclear is not allowed (Fig. 4), peak assured capacity is provided by overbuilding wind and solar combined with addition of battery storage [12-13]—an expensive option.

Using the GenX model we then conducted a thought experiment of integrating the electricity sector and industrial sector. We assumed a strategy of using electric resistance heaters to provide heat to industry where one unit of electricity (kWh(e)) is converted into one unit of heat (kWh(h)). The U.S. industrial heat input is 22 quads (Fig. 1)—almost twice the 12.5 quads of electricity output from the electricity sector. This implies that the industrial heat demand is 22/12.5 times the current electricity output for the grid. We add an industrial electricity heat demand (MWh) that is 22/12.5 times the total electricity demand delivered at a constant rate over 8760 hours per year. This creates a massive base-load electricity demand under the current variable electricity demand.

Figure 5 shows the average cost of electricity in Texas for four cases: (1) no-nuclear with the nominal electricity demand, (2) no nuclear with the nominal plus industrial electricity demand, (3) nuclear-allowed with the nominal electricity demand and (4) nuclear-allowed with nominal plus industrial electricity demand.

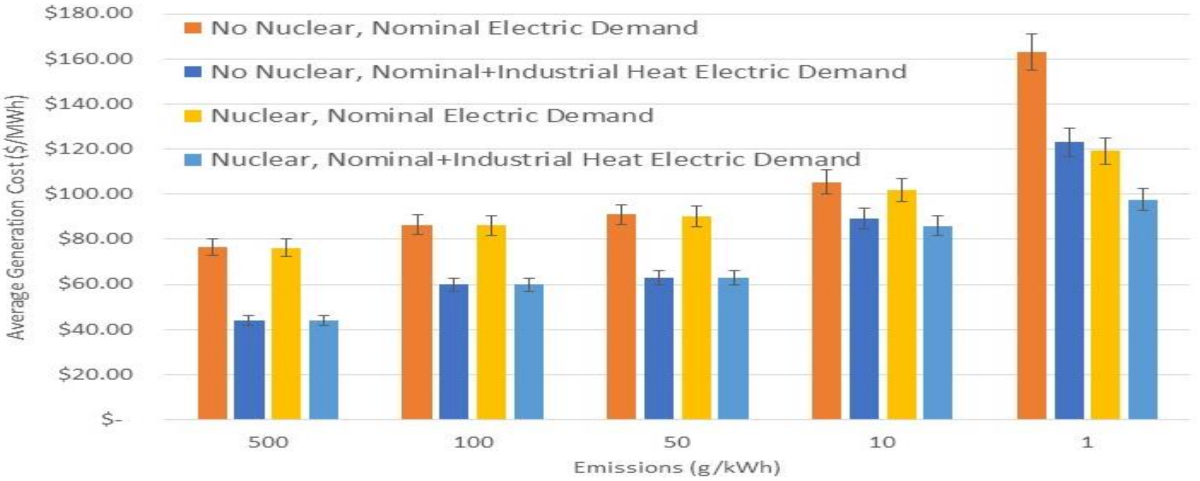

Fig. 5. Average Texas Electricity Costs versus Emissions Limits for Alternative Electricity Demand and Generating Scenarios

In the nuclear and no-nuclear cases, adding a base-load industrial electricity demand resulted in large reductions in the cost of electricity. What happened? The change in the electricity demand curve resulted in favoring generating technologies that can produce base-load electricity operating at higher capacity factors. With no emission limits on natural gas (500 g/kWh), this favors low-cost efficient combined-cycle natural gas plants operating at high capacity factors on cheap natural gas rather than simple gas turbines operating at low capacity factors and lower efficiencies. As emission constraints are tightened, burning fossil fuels with carbon capture and nuclear are favored. These are high capital cost generating systems where the cost of electricity is dependent upon the capacity factor. If one doubles the capacity factor, the generating costs dramatically decrease. The hourly to seasonal shape of the electricity demand curve has a massive impact on the mix of preferred generation technologies and the cost of energy.

This has massive implications going forward. In fossil fuel systems most of the cost is associated with the fuel—the capital cost of the power plant is small. One can afford to operate power plants at low capacity factors with little impact on the cost of energy. In a low carbon world all of the energy technologies (nuclear, wind, and solar) have high capital costs and low operating costs. If one operates these technologies at half capacity, the costs double. In a low-carbon society there are large economic incentives to improve the match between the energy generating technology and the demand to lower the cost of energy. One way to do that is to couple the energy demands of the electricity sector to the industrial sector—breaking the stovepipe characteristics of today's fossil fuel system.

There are two ways to supply heat to industry: (1) supply electricity that is converted into heat as described above or (2) directly supply heat from the reactors. In either case one is better matching energy output with energy demand—the strategy to minimize costs. However, if one is to directly supply heat to industry, the nuclear plant that provides variable electricity and heat to industry must be a co-generation plant co-located with the industrial plant.

The economic strategy for supplying heat to the industrial sector with low-carbon dioxide emissions is to provide heat from nuclear reactors, not electricity. That is because heat is the output of a nuclear plant whereas electricity is the output of wind and PV systems. Table 1 shows the levelized cost of electricity from different generating technologies [14] and a nominal levelized cost of heat. Wind has the lowest cost: \$30 to 60/MWh(e). The efficiency of converting electricity into heat is near 100%; thus, the cost of heat from wind is about \$30 to 60/MWh(t). However, one must then add the cost of the electricity grid. A recent analysis of those costs [15] estimated those costs at \$15/MWh(e) if wind provided 10% of all electricity and \$27/MWh(e) if wind provided 30% of all electricity. The grid costs of solar are higher. Those grid costs can more than double the cost of delivered heat. Nuclear electricity costs are estimated between \$112 and 183/MWh(e). The efficiency of converting heat to electricity in a light-water reactor is about 33% so the cost of heat from the reactor is \$37 to 61/MWh(t). However, one does not need the heat-to-electricity systems (turbine hall, etc.) or the grid so the cost of heat from a nuclear plant is below this number. This reality is seen in prices for heat versus electricity. U.S. electricity prices are 4 to 6 times that of natural gas per unit of heat.

Table 1. Unsubsidized Levelized Cost of Electricity (LCOE) for new plants in \$/MWh(e)) [14] and unsubsidized Levelized Cost of Heat (LCOH) for new plants in \$/MWh(t).

Technology	**LCOE: \$/MWh(e)**	**LCOH: \$MWh(t)***	**Dispatchable**
Solar PV: Rooftop Residential	187–319	187-319	No
Solar PV: Crystalline Utility Scale	46–53	46-53	No
Solar PV: Thin Film Utility	43–48	43-48	No
Solar Thermal Tower with Storage	98–181	33-90	No
Wind	30–60	30-60	No
Natural Gas Peaking	156–210		Yes
Natural Gas Combined Cycle	42–78		Yes
Nuclear	112–183	37-61	Yes

[*] Conversion of electricity to heat ~100%. Nuclear is a heat source that converts heat to electricity. With LWR, the conversion efficiency is ~33% implying the cost of heat about a third the cost of electricity. The same efficiency is assumed for CSP

The GenX model shows large reductions in average electricity costs if one adds a massive base-load demand—the industrial demand. That benefit is from coupling the electricity and industrial sectors which changes the energy demand curve. It can be done with electricity but it can also be done with co-generation where the heat from nuclear plants is used to provide heat to industry or heat to produce electricity. Heat is less expensive than electricity; thus, the reduction in electricity prices will be smaller than the GenX thought experiment of electrifying the industrial sector. If one sends nuclear heat to the industrial sector, the number of reactors required will be a half to a third the number required to send electricity to industry because sending heat directly to industry avoids the losses of converting heat to electricity and back to heat.

Fossil-fuel [16] co-generation is used in the U.S. and elsewhere in the world. There is a limited use today of nuclear co-generation [17-18] and none in the U.S. There have been two historical incentives for co-generation.

- *High-efficiency conversion of heat to electricity*. For industrial plants that need low-temperature steam, co-generation plants can produce high-temperature steam, send that steam through a high-pressure turbine to produce electricity and send the low-pressure steam to the industrial process.
- *Disposal of excess fuel*. Refineries, chemical plants, paper mills, and other industrial facilities burn wastes producing electricity and steam. Excess energy beyond that needed by the facility is converted into electricity that is sold as electricity.

In the context of a low-carbon energy system with large-scale wind and solar, nuclear co-generation couples the electricity and industrial sectors. This has major implications in terms of meeting industrial demand for a low-carbon energy source and providing dispatchable electricity to the grid—what makes low-carbon electricity grids expensive.

If fossil-fuel cogeneration plants have excess capacity, they sell added electricity to the grid at times of high prices. Some fossil co-generation plants reduce industrial production to produce added electricity for the grid when prices are high. Some industrial plants schedule annual shutdowns for maintenance at times of annual highest electricity prices to sell more electricity from their co-generation facilities. These same strategies enable a nuclear co-generation plant in a low-carbon grid to increase revenue while providing added assured lower-cost electricity generation for the grid when required.

Until recently there have been limited incentives for co-generation facilities to vary electricity output in response to wholesale electricity prices. The variability in wholesale electricity prices is limited in systems dominated by fossil fuels that sets a minimum price on electricity based on the cost of fuel. The change in the electricity markets from (1) the addition of wind and solar [19-20] and (2) constraints on carbon emissions create large economic incentives for the industrial sector with nuclear cogeneration to change operational modes to boost profits by selling high-price electricity—assured peak generating capacity that lowers the cost of decarbonization. Figure 6 shows the impact of adding solar PV to the California grid between 2012 and 2017. There are large incentives to buy electricity and convert to heat at times of low prices and sell electricity at times of high prices.

Fig. 6. Changes in wholesale electricity prices in California on a spring day due to the addition of solar PV

IV. CONCLUSIONS

The characteristics of fossil fuels (low-capital cost and high-operating (fuel) cost) have created an energy stove-piped world with fossil fuels supplying energy separately to the electricity and industrial sectors. The characteristics of low-carbon nuclear, wind and solar systems (high-capital cost and low-operating cost) create large incentives to boost capacity factors to reduce energy costs. That can be done with nuclear systems via three mechanisms (1) nuclear co-generation that couples the energy demands of the electricity and industrial sector to provide an energy demand that better matches production—assuming no change in energy demand by either sector, (2) nuclear co-generation that enables variation in industrial production to fully optimize the electricity and industrial sectors to minimize total costs and (3) low-cost heat storage to enable base-load reactor operation with variable heat to industry and electricity to the grid. The system design is changed.

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