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Converting excess low-price electricity into high-temperature stored heat for industry and high-value electricity production[☆]

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A B S T R A C T

The large-scale deployment of wind or solar energy results in electricity prices below the price of fossil fuels at times of high wind or solar output. Price collapse can be limited by using low-price electricity to heat firebrick to high temperatures, store the heat in firebrick, and provide hot air as needed to industrial furnaces, kilns, power plants and gas turbines. This sets a minimum price on electricity near that of fossil fuels.

1. Introduction

Most electricity is produced by burning fossil fuels. Economic variable electricity can be produced to match demand because most fossil plants have low capital costs and high operating costs. The cost of electricity does not increase rapidly for power plants operating at part load when the operating cost is the primary cost. Concerns about climate change require going to electricity generating technologies that do not emit carbon dioxide, such as nuclear, wind, and solar. These technologies have high capital costs and low operating costs (Table 1); thus, the cost of electricity increases rapidly if these capital-intensive plants are operated at part load. Because total energy costs for society are typically close to 10% of the gross national product, significant increases in energy costs implies significant decreases in the standard of living.

In deregulated markets the large-scale use of solar and wind results in electricity price collapse at times of high wind or solar input when electricity output exceeds demand. Collapsing revenue limits the economic use of solar, wind, and ultimately nuclear. A Firebrick Resistance-Heated Energy System (FIRES) is proposed (Stack et al., 2016; Stack, 2016) to limit electricity price collapse at times of high wind and solar output by converting excess low-price electricity into high-temperature stored heat that can be used as a substitute for fossil fuels by industry and to generate electricity at times of high prices. A minimum price of electricity is created near that of the price of fossil fuels used by industry. It is a mechanism to better utilize capital-intensive generating assets.

The article (1) defines and characterizes applications for FIRES, (2) describes FIRES' technical performance characteristics, (3) analyzes implications of large-scale deployment on electricity markets, and (4) estimates capital costs. The article reports on near-term applications such as heat to industry and long-term options such as coupling FIRES to gas turbines.

2. Electricity markets

In deregulated electricity markets, electricity generators bid a day ahead on the price that they are willing to sell electricity into the market—typically for each hour of the day. The grid operator accepts electricity bids up to the expected electricity demand for each hour. The bid ($/MWh) with the highest electricity price that is accepted sets the price for that hour and everyone who bids below that price gets the same price. Historically, most electricity has been generated using fossil fuels; thus, the price set for each hour was set by the fossil fuel plant operating at that hour with the highest operating costs (Table 1). The markets have a variety of other mechanisms to assure reliable electricity and remain within the technical constraints of the electricity grid.

In a perfect market, wind and solar will bid zero dollars per megawatt-hour (Table 1)—their variable operating and maintenance costs. The Massachusetts Institute of Technology (MIT) *Future of Solar Energy* (Massachusetts Institute of Technology, 2015) study provides an examination of the solar option and the challenge of moving from an electricity grid dominated by fossil fuel generation to a low-carbon grid. Fig. 1 shows market income for solar plants with increased use of solar. The average price of electricity received for the first few solar plants that are built is above the average yearly electricity price because the electricity is produced in the middle of the day when there is high

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Table 1
U.S. Energy Information Agency Estimated Levelized Cost of Electricity (LCOE) For New Generation Resources in 2020 using 2013 \$/MWh(e) (U.S. Energy Information Agency Annual Energy Outlook, 2016).

Plant Type	Capacity Factor (%)	Levelized Capital Cost (Plant and Transmission)	Fixed Operating and Maintenance	Variable O & M Including Fuel	Total System LCOE
Dispatchable Technologies					
Conventional Coal	85	61.6	4.2	29.4	95.1
Conventional CC[a]	87	15.6	1.7	57.8	75.2
Advanced CC with CCS[a]	87	31.3	4.2	64.7	100.2
Conventional Combustion Turbine	30	44.2	2.8	94.6	141.5
Advanced Nuclear	90	71.2	11.8	12.2	95.2
Non-Dispatchable Technologies					
Wind	36	60.8	12.8	0.0	73.6
Wind Offshore	38	174.4	22.5	0.0	196.9
Solar PV	25	113.9	11.4	0.0	125.3
Solar Thermal	20	197.6	42.1	0.0	239.7

[a] CC: Combined cycle; CCS: Carbon Capture and Storage.

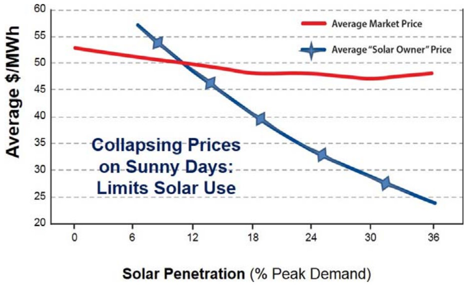

Fig. 1. Solar PV Market Income and Average Wholesale Electricity Prices versus Solar PV Penetration.

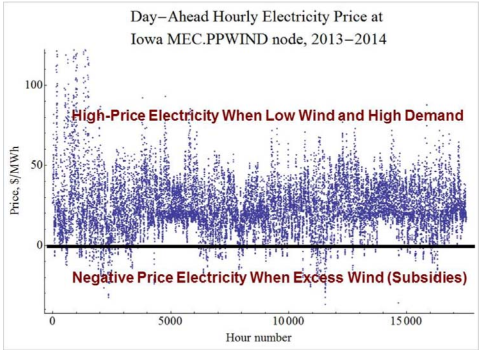

Fig. 2. Hourly Wholesale Electricity Prices in Iowa over Two Years.

demand and prices are high. As more solar plants are built, electricity prices at times of high solar output collapse; thus, solar revenue collapses as solar production increases. This limits unsubsidized solar capacity to a relatively small fraction of total electricity production even if there are large decreases in solar capital costs.

At the same time there are only small changes in the average price of electricity. Other power plants are required to provide electricity at times of low solar output—but these plants operate for fewer hours per year. Investors will not build new power plants to meet this need unless the price of electricity increases at times of low solar output to cover the costs of a power plant that operates only part of the time.

The same effect occurs with wind. Recent studies have quantified this effect in the European market (Hirth, 2013, 2015). 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 h per year when wind could provide the total electricity demand, the price of electricity would be near zero, and 28% of all wind energy would be sold in the market for prices near zero.

To use a real example, Fig. 2 shows wholesale prices for electricity in western Iowa, a state with a large installed wind capacity. One can see negative prices enabled by wind subsidies on days of high-wind conditions. When there are negative prices, the electricity generator pays the grid to take the electricity. Wind operators are willing to pay the grid to take electricity because their subsidies are tied to electricity produced. Without subsidies, prices would go to zero but not negative except under limited circumstances. In this specific example the price of electricity is less than the local industrial price of natural gas for over half the time.

Analysis (Forsberg, 2013) indicates that significant price reductions occur on a grid when solar provides over 10% of all electricity produced, wind provides over 20% of all electricity produced, and nuclear provides over 70% of all electricity produced. The different levels of solar, wind, and nuclear penetration before significant revenue collapse reflects the relative mismatch between electricity production for each of these technologies and demand. There is a large literature on the other market effects of adding solar and wind to the grid (International Energy Agency, 2016; Nuclear Energy Agency, 2012) and limits on use of electricity storage to address this challenge (Braff et al., 2016; de Sisternes et al., 2016; Brick and Thernstrom, 2016).

The revenue collapse is a consequence of going from low-capital-cost, high-operating-cost fossil systems to high-capital-cost, low-operating cost solar, wind, and nuclear systems. Revenue collapse at times of high solar and wind input favors the use of low-capital-cost, high-operating-cost fossil fuel electricity generation at times of low wind or solar output. This expanded the use of coal in Germany and natural gas in the United States as renewables are added to the grid.

Societies can choose to subsidize particular energy systems for social reasons, but because energy is such a large fraction of the global income, this has large impacts on standards of living. What is required is low-cost methods to productively use low-operating-cost excess generating capacity when available to reduce electricity price collapse under high wind or solar conditions and thus expand use of low-carbon solar, wind and nuclear electricity generating technologies.

3. FIRES for industrial heat

3.1. Technical description

FIRES (Fig. 3) consists of a firebrick storage medium with a relatively high heat capacity, density and maximum operating temperatures up to ~1800 °C (Stack et al., 2016; Stack, 2016). The firebrick is "charged" by resistance heating with electricity at times of low or negative electricity prices. Low electricity prices are defined as electricity prices that are less than the competing fossil fuel—that is natural gas in