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# Mapping the Economics of U.S. Coal Power and the Rise of Renewables

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# Index

## Abstract

We have developed an online tool, CoalMap (coalmap.com), to help activists, regulators, and the general public explore the economic costs of existing coal-fired power plants in the United States. Drawing from publicly available datasets, the tool identifies U.S. coal plants that are particularly vulnerable to shutdown efforts by comparing each plant's average operating cost to the levelized cost of electricity (LCOE) for new utility-scale solar photovoltaic (PV) and wind generation in the same location. Users can apply different carbon prices and rates of cost decline for solar and wind, and observe the effects on the cost-competitiveness of renewable generation in future years. Our findings highlight the importance of sustained technology improvement and appropriate public policy in shifting the U.S. electricity generation mix toward low-carbon sources, and ultimately in achieving national climate-change mitigation targets. With 5% annual renewable cost declines and a carbon price equal to the U.S. government's social cost of carbon, new unsubsidized wind and solar PV generation at existing coal plant locations will be cost-competitive with fully amortized U.S. coal plants by 2019 and 2031, respectively.

## Introduction

### 1.1 Coal Power in the United States

In 1882, Thomas Edison built the first coal-fired power plant in the United States, the 600 kW Pearl Street Station plant in New York City[1]. Since that first demonstration, burning coal has become the world's preferred method for generating electricity at low cost. Today, coal is the single largest fuel source for electricity generation in the U.S. and worldwide.[2,3] By 2013, there were 518 active coal plants in the U.S., with a combined nameplate electric capacity of nearly 330 GW, corresponding to a net summer capacity of 306 GW.[4,5]* Many coal plants today have a nameplate capacity of over 500 MW, 1,000 times larger than Edison's Pearl Street plant. Each plant consists of one or more generating units.

The average U.S. coal-fired generator was 43 years old in 2013 (Figure 1).[6] Generating units are typically designed to last for at least 25 years with minimal modification. However, it is common to extend operational lifetimes to 40 years or more by replacing or upgrading components, since doing so is often far less expensive than building a new plant.[7] In part because many existing U.S. coal plants were built in the 1960s and 1970s, the average fleet-wide plant efficiency of about 35% has remained largely unchanged for the past 50 years.[8]

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*The net summer capacity is the peak load that a plant can support during summer months, after accounting for power used for internal plant operations. Summer capacity is typically lower than the nameplate capacity due to the increased temperature of cooling water supplies.

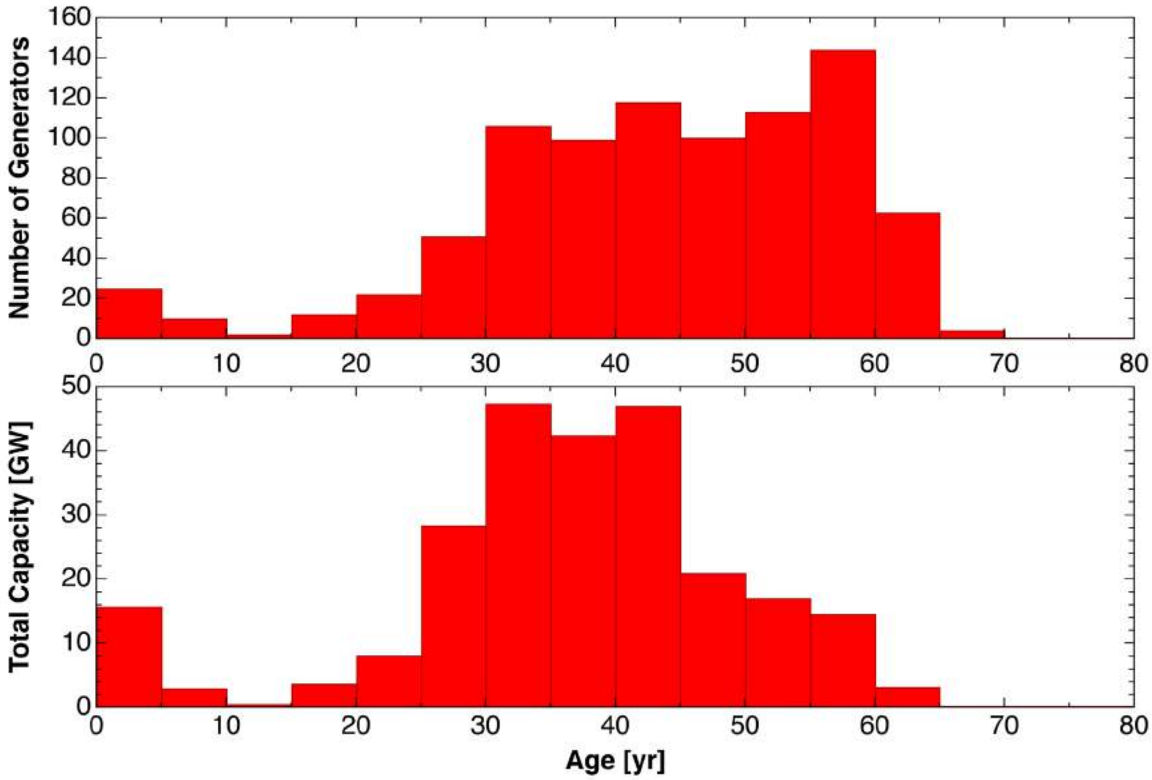


**Figure 1. Age distribution of U.S. coal-fired generating units and nameplate capacity in 2013.**[6] As of 2013, the average U.S. coal generator had been in operation for 43 years, far longer than the design lifetime of 25 years.

While the fraction of electricity produced from coal globally has increased slightly over the past 40 years—from 38% to 41%[9]—the role of coal in the U.S. generation mix has declined significantly. Prior to 2005, coal accounted for roughly 50% of U.S. electricity generation (Figure 2). By 2015, coal's contribution had dropped to 34% of total generation, and it is predicted to decline further.[10,11] The rapid recent decline in coal use in the U.S. can be attributed to the increased real and relative costs of burning coal, due to stricter environmental regulations, policy mandates, and decreasing costs of alternatives such as natural gas and renewables.

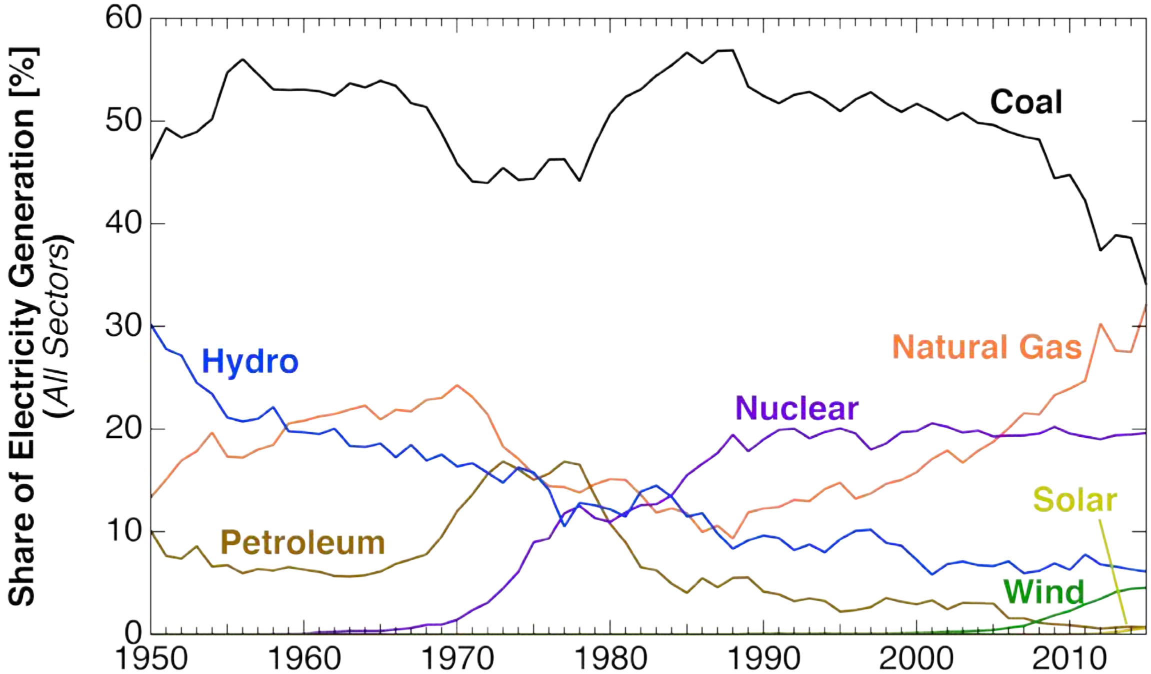


**Figure 2. Net U.S. electricity generation by fuel source.** Coal has historically accounted for 45–55% of U.S. electricity generation. In the past decade, increasing environmental regulation and falling natural gas prices have diminished the role of coal in the U.S. generation mix, down to 34% of total generation in 2015.[11] Data for 2015 is a 12-month running average through November 2015.[12] Data for solar generation only includes generation from utility-scale solar photovoltaic (PV) and concentrated solar power (CSP) plants. Distributed solar PV generation contributed 32% of total solar generation in 2015.[12]

## 1.2 Impact of U.S. Environmental Regulations on Coal Power

The contribution of coal to U.S. electricity generation is expected to continue to decrease as federal environmental policies place additional pressure on coal-fired power plants.[13] The U.S. Environmental Protection Agency's (EPA) Mercury and Air Toxics Standards (MATS) tightened emissions limits on existing generating facilities.[14] Since the Clean Air Act grandfathered in existing power plants—thus exempting them from the requirement to install the most modern pollution-control technologies—many of these plants are still using decades-old technology.[15] MATS is one of the EPA's strategies for addressing this gap. In July 2015, the U.S. Supreme Court sent MATS back to the D.C. Circuit Court of Appeals for further review. However, many coal plant operators have already decided to retire their aging plants rather than install the emission-control technologies required by MATS, resulting in 12.9 GW of coal retirements in 2015 alone.[16] By the end of November 2015, the net summer capacity of coal plants in the U.S. was about 286 GW, down from 306 GW in

December 2013.[5,12] The EPA's recently-finalized Clean Power Plan (CPP), which would require states to reduce carbon dioxide ($CO_2$) emissions resulting from power generation, is expected to place additional pressure on coal-fired power plants.[17,18] The U.S. Energy Information Administration (EIA) estimates that 90 GW of coal generation will retire between 2014 and 2040 if the CPP is implemented, compared to 40 GW without the CPP.[19]

Stricter environmental regulations stem from decades of mounting evidence of the detrimental impacts of fossil fuel consumption, and of coal in particular.[20] Coal accounts for about 46% of global $CO_2$ emissions and 27% of U.S. $CO_2$ emissions.[21,22] In addition to $CO_2$, coal plants emit substantial amounts of sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), mercury, and particulate matter. These emissions have serious negative impacts on human and environmental health. Observed human health impacts include respiratory illnesses, reduced life expectancy, increased infant mortality rates, and nervous system damage resulting in lower intelligence.[23–28] Furthermore, coal ash (the waste remaining after coal is burned) contains elevated levels of many toxic elements, including arsenic, lead, mercury, cadmium, and others.[29] Unintended release of these materials into the air or groundwater can cause cancer, damage to vital organs, and other health problems.[30–32] Local environmental impacts include acid rain and smog. In total, it has been estimated that the true societal costs of coal from public health and environmental damage amount to \$170B to \$520B per year.[28] These costs (externalities) are generally not included in the price of electricity from coal and instead are borne by the public.[20,28] The EPA has steadily tightened regulations to limit the harmful consequences of burning coal, setting limits on airborne concentrations of some of the worst pollutants.[13,33] For example, cap-and-trade programs have been used successfully to reduce the amount of acid rain and smog caused by $SO_2$ and $NO_x$.[34]

## 1.3 Pricing Carbon

Carbon pricing is widely accepted as the most economically efficient method for reducing $CO_2$ emissions and mitigating climate change.[35,36] A price on carbon can be enacted through a cap-and-trade mechanism or a direct tax on carbon emissions. Globally, 39 countries and 23 sub-national jurisdictions have implemented some form of carbon pricing policy.[37]

In the U.S., however, attempts to restrict $CO_2$ emissions have historically been less successful than efforts to limit other pollutants. The American Clean Energy and Security Act of 2009 (ACES), also known as the Waxman-Markey Bill, was a legislative attempt to implement a cap-and-trade program to limit U.S. greenhouse gases emissions.[38] Although the bill did not pass the U.S. Senate, the EPA is now using its authority under the Clean Air Act to limit the amount of $CO_2$ emissions from power plants. Their efforts include the Carbon Pollution Standards for new plants and the Clean Power Plan for existing plants, finalized in 2015.[39,40] These two mark the first significant regulations to limit U.S. $CO_2$ emissions. In the absence of a federal policy, states in the

Northeast created their own cap-and-trade program, the Regional Greenhouse Gas Initiative (RGGI), in 2009. The RGGI has been responsible for a 19% reduction in greenhouse gas emissions in participating states since 2005, roughly half of the total emissions reductions observed in the region.[41+] California has also implemented a similar statewide cap-and-trade program.[42]

Calculating the appropriate carbon price is a complex undertaking that relies on many assumptions.[43] A comprehensive estimate must consider all climate-change damages, including net impacts on agricultural productivity, human health, property value, and energy system costs. The correct carbon price is the present (discounted) value of the marginal economic cost incurred by an additional unit of $CO_2$ emissions; this price is known as the social cost of carbon (SCC). For planning purposes, the U.S. federal government has developed SCC estimates for different discount rates and years: in 2020, the estimated SCC is 12, 42, or 62 dollars per metric ton of $CO_2$ (\$/t$CO_2$) for a discount rate of 2.5%, 3%, or 5%, respectively.[44,45] Current U.S. government policy applies a SCC of roughly 40 \$/t$CO_2$.[46] If implemented immediately and globally, a carbon price at this level would keep the global average temperature rise below 2°C with a probability of 66%.[35]

Observed carbon prices vary widely, but the majority are between 1 and 30 \$/t$CO_2$.[37] For example, the carbon tax in British Columbia started at around 7 \$/t$CO_2$ in 2008 and increased annually to a limit of around 22 \$/t$CO_2$ in 2012. The European Union Emissions Trading System (EU ETS)—the first major cap-and-trade scheme—has faltered since its inception in 2005, with permit prices remaining below 10 \$/t$CO_2$ since 2011. A few countries have much higher carbon taxes—in Sweden, the price is 130 \$/t$CO_2$. In the U.S., regional and state carbon prices remain low: In December 2015, RGGI $CO_2$ allowances were priced at 8.27 \$/t$CO_2$ (7.50 \$/short ton $CO_2$).[47] In California, allowances are currently priced at around 13 \$/t$CO_2$.[48]

Due to the high carbon emissions associated with burning coal, a price on carbon can significantly increase the cost of coal-fired electricity. Pricing carbon appropriately is thus critical for determining the cost-competitiveness of renewable energy generation.

## 1.4 The Rise of Renewables

The decline of coal in the U.S. can be largely attributed to the rise of natural gas.[49] The advent of efficient combined-cycle gas turbines and the substantial decrease in natural gas prices have led to a major expansion in the capacity and use of gas turbines for electric generation.[50] From 2005 to 2008, U.S. Henry Hub natural gas

[+]The balance can be attributed to a combination of economic recession, declining natural gas prices, and policy intervention in the form of state renewable portfolio standards (RPSs).

prices averaged 7.85 \$/MMBtu, with several months above 10 \$/MMBtu.[51] From 2009 to 2015, however, prices dropped by over 50%, averaging 3.69 \$/MMBtu and reaching a low of 1.95 \$/MMBtu in April 2012.

Although new natural gas plants have replaced more U.S. coal capacity than any other source, renewable energy has also grown in importance in the last several years. Solar and wind together accounted for over 50% of added U.S. generation capacity in 2012, 2014, and 2015 (Figure 3). As with natural gas, renewable energy capacity additions have been driven largely by decreasing costs. Figure 4 shows the steady decline in average installed utility-scale system prices for both solar and wind, with a particularly steep drop in PV costs due to falling module prices.

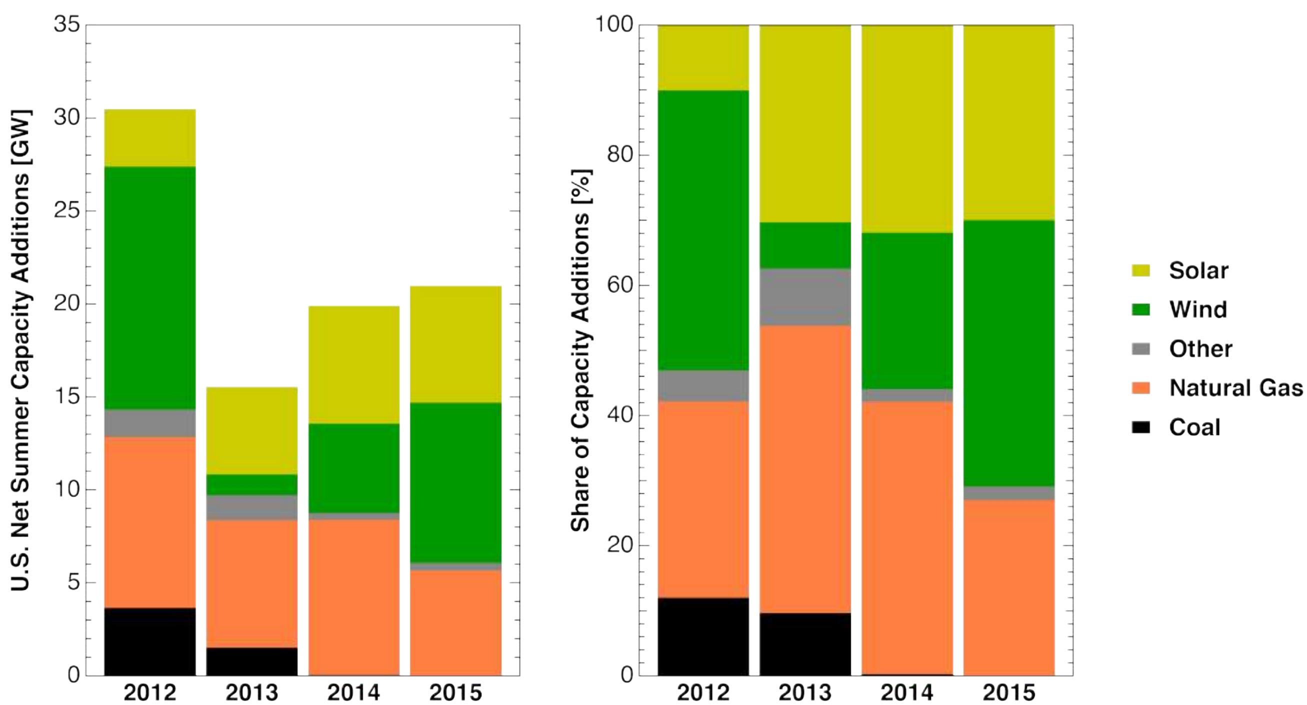


**Figure 3. Capacity additions to U.S. electric generation mix (2012 - 2015).** Annual net summer generation capacity additions (left) and fractional contributions (right) are shown for coal,[12,52] natural gas,[12,52] wind,[53] solar,[54,55] and other sources.[12,52] Efficiency losses of 15% (equivalent to an inverter loading ratio of 1.18) are used to convert the reported capacity of solar PV from DC to AC terms. Solar data include CSP, although total solar capacity is dominated by PV. Capacity additions for coal, natural gas, and other sources are shown through November 2015.

Both wind and solar have benefited significantly from government support policies for renewable generation. At the national level, the production tax credit (PTC) has been a major driver for U.S. wind power. However, PTC support lacks consistency, regularly requiring short-term extensions passed by Congress. This uncertainty creates massive year-to-year fluctuations in annual wind installations and increased market risk.[56,57] In contrast, consistent support for solar through the federal investment tax credit (ITC) has contributed to rapid growth of U.S. solar deployment since 2008.[58] In December 2015, the PTC for wind and ITC for solar were extended through 2019 and 2022, respectively, with gradual step-downs in the value of both tax credits.[59] These extensions make U.S. solar and wind investments more predictable and are expected to dramatically increase investment in both technologies. At the state level, renewable portfolio standards (RPSs) and net energy metering (NEM) policies have also contributed to the growth of renewable generation. While tax credits, renewable-energy mandates, and net metering are imperfect policy mechanisms for supporting low-carbon generation,[60] the combination of federal and state policy, technological improvement, and reduced cost has stimulated tremendous growth of U.S. wind and solar generation capacity in the past decade (Figure 4).

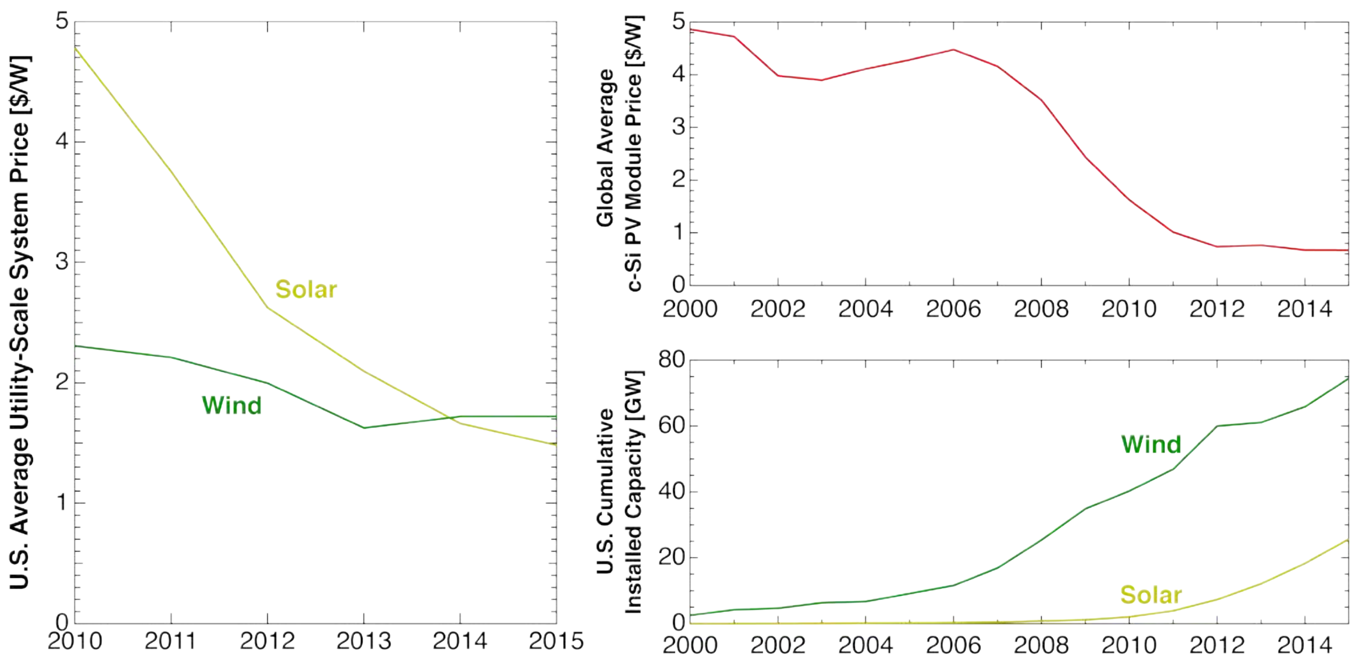


**Figure 4. Recent cost and capacity trends in solar PV and wind.** (left) Average installed prices for utility-scale solar PV [$/W$_{DC}$] and wind [$/W$_{AC}$] systems in the U.S.[61,62] (right) Global-average price for crystalline silicon PV modules[55,63] and U.S. cumulative installed capacity of solar PV [GW$_{DC}$][54,55] and wind [GW$_{AC}$],[53] showing rapid decline in PV module price and growth in installed capacity. All prices are shown in constant 2015 dollars.

## 1.5 Levelized Cost of Electricity (LCOE)

Public support policies and private investment decisions depend heavily on the relative cost of different energy technologies. The levelized cost of electricity (LCOE) is a commonly used metric for gauging the cost-competitiveness of renewable and conventional generation technologies.[64,65] The LCOE is the minimum real electricity price [$/kWh$_{AC}$] that a power plant must receive to break even on investment costs over the life cycle of the facility—in other words, the revenue per kWh needed to achieve a zero net present value over the facility's useful life. This metric accounts for all physical assets and resources required to produce one unit of electricity, including plant capital expenses, cost of capital, and operating expenses. Like all other capital-intensive investments—including new thermal generation facilities—new solar and wind projects may face a higher effective cost of capital than smaller investments, such as life extension for an existing facility. We acknowledge but do not attempt to address here the complex issues involved in the financing of large capital-intensive projects.

All costs can be classified as upfront investment (typically proportional to capacity), fixed operations and maintenance (O&M; proportional to capacity), or variable O&M (proportional to generation). Different generation technologies have their costs distributed differently among these categories. For example, the cost of coal generation is divided roughly evenly between upfront capital and variable O&M costs.[66] In contrast, the cost of solar, wind, and other renewable technologies is dominated by upfront capital costs, with very low fixed and variable O&M.[++] Because these costs are incurred at different times in the facility life cycle, they cannot be used as a direct metric of economic competitiveness.

LCOE can be calculated according to $LCOE = c \cdot \Delta + f + v$ where $c$ is the unit cost of capacity, $\Delta$ is the tax factor (mark-up), $f$ is the lifetime-average fixed cost per kWh, and $v$ is the lifetime-average variable cost per kWh. We follow the approach outlined by Reichelstein and Yorston.[67] The individual terms above are defined as follows:

$$c = \frac{SP}{G}$$

$$\Delta = \frac{1 - i - \alpha(1 - \delta i) \sum_{t=1}^{T^0} x_t \cdot \gamma^t}{1 - \alpha}$$

$$f = \frac{\sum_{t=1}^{T} F_t \cdot \gamma^t}{G}$$

$$v = \frac{Y \sum_{t=1}^{T} V_t \cdot x_t \cdot \gamma^t}{G}$$

[++]For this reason, solar and wind are often considered to be zero-marginal-cost generators, which bid into wholesale electricity markets at the top of the merit order.

where $SP$ is the DC system price, $G\left[\frac{kWh_{AC}}{kW_{DC}}\right] = Y \cdot \sum_{t=1}^{T} x_t \cdot \gamma^t$ is the discounted lifetime AC generation per unit DC capacity (with $Y$ = 8760 · capacity factor = first-year AC generation per unit DC capacity (or energy yield), $T$ = system lifeline, $x_t$ = system degradation factor in year t as a fraction of first-year generation, and $\gamma = 1/(1 + \text{interest rate})$ = discount factor), i is the investment tax credit, $\alpha$ = 40% is the effective income tax rate, $\delta$ = 0.5 is the asset capitalization factor,[67] $T^0$ is the system lifetime for tax purposes, $F_t$ is the fixed cost in year t per unit DC capacity [$/kW$_{DC}$], and $V_t$ is the variable cost in year t per unit AC generation [$/kWh$_{AC}$].

LCOE is a simple but imperfect metric for evaluating the cost-competitiveness of different generation sources. It is strictly valid only when the competing technologies serve the same segments of the load duration curve (e.g., when comparing baseload technologies). When technologies serve different load segments, they operate with different capacity factors—the LCOE thus fails to capture the true cost of generation, and merely represents the cost of serving different parts of the load curve. Intermittent technologies such as solar and wind are particularly challenging to assess—they serve an arbitrary subset of load segments depending on resource availability, obscuring which technologies they are competing with and changing the load segments for all generators.

One possible alternative metric for cost-competitiveness is the power purchase agreement (PPA) price. PPAs are contracts that specify the terms (e.g., start and end dates, price, and delivery schedule) for the sale of electricity, typically from an independent power producer (IPP) to a utility. PPA prices reflect the amount of post-incentive revenue required for a project to be viable. Compared to calculated LCOEs, observed PPA prices have one key advantage: They are actual data points that reflect real market conditions, including costs, incentives, financing, electricity demand, and competition. In a competitive wholesale market, long-term PPA prices should approximate the post-incentive LCOE. However, it is often difficult to obtain current and granular PPA data: Such agreements are often proprietary and data are available only where PPAs have been signed. State- or region-averaged PPA prices fail to capture local differences in resource availability, siting considerations, and availability of transmission and distribution resources. Furthermore, since PPA prices reflect near-term market conditions, they are not necessarily representative of long-term cost trends. This analysis does not consider PPA prices, but regional PPA price data for wind are shown in the Supporting Information as a point of reference (Figure S6).

Even though solar and wind electricity are often sold under long-term, fixed-price contracts (PPAs), the value-adjusted LCOE is still useful for comparing costs, as PPA prices are generally linked—either directly or indirectly—with the market value of the electricity.[60] PPAs price terms are often indexed to wholesale prices, and some vary with the time of day at which power is delivered. Furthermore, the power purchaser, who bears all the price risk, is unlikely to pay more for electricity under a PPA than its true market value (i.e., the discounted expected value of future prices) plus any subsidy.

It is important to recognize that the average market value of intermittent generation depends on the level of grid penetration. Electricity demand, wholesale market prices, and the output of solar and wind generators all vary on the time scale of hours. In the absence of energy storage, the value of variable generation depends on the extent to which that generation (e.g., available sunlight and wind) is correlated on average with the market price of electricity. A positive correlation means that the intermittent source is more valuable than constant baseload generation, while a negative correlation means that the intermittent source is less valuable than baseload. At low penetrations, solar output tends to be positively correlated with demand and with market prices, and hence is more valuable than LCOE alone would suggest (by a so-called value factor of 1–1.3).[68] At higher penetrations, solar systematically reduces market prices during daytime hours, reducing its own value and eventually making it less competitive than LCOE would indicate. For wind, typical value factors are below 1 even at low penetration, and decline further with increasing penetration.

In practice, the viability of a new generating facility depends on many factors: the local demand profile, the existing generation mix, transmission and distribution grid infrastructure, market prices, availability of financing, and government policies. While some of these factors are discussed above, this analysis does not attempt to address the full range of issues governing investment decisions. Instead, we focus on the LCOE of representative solar and wind generators in the U.S., varying the available energy resource to gauge cost-competitiveness at different locations.

## 1.6 CoalMap

We have created an online interactive tool—CoalMap—for comparing the cost of electricity from existing U.S. coal plants and from new utility-scale solar PV and wind systems at or near the locations of those plants, based on publicly available datasets. Complementary tools include the Sierra Club coal plant tracker—which highlights the operational status and toxic pollutant emissions of U.S. coal plants[69] —and the Institute for Local Self-Reliance (ILSR) solar grid parity map—which compares solar PV generation costs with retail electricity rates for U.S. residential and commercial customers.[70]

Details of the cost calculations are given below in Section 2. Briefly, using 2013 data from the U.S. Energy Information Administration (EIA), including fuel and other O&M expenditures, we calculate the average variable operating cost for each U.S. coal plant in $/kWh. Based on the latitude and longitude of each plant, we identify the closest available solar and wind resource data and simulate the cost of solar and wind generation in those locations (Figure 5). Annual solar PV generation is simulated using the System Advisor Model (SAM) software development kit (SDK) from the National Renewable Energy Laboratory (NREL), with hourly solar radiation data from the National Solar Radiation Database (NSRDB).[71,72] Based on the resulting annual capacity factor, the solar LCOE is then calculated using custom code. Wind generation costs are similarly calculated based on average capacity factors from the NREL Eastern and Western Wind Integration Study datasets.[73]

The purpose of CoalMap is to help activists and regulators plan for a coal-free future by mapping the current and future costs of U.S. coal-fired and renewable electricity generation. We seek to identify the coal plants that are most economically vulnerable to renewable energy generation, environmental activism, and climate-change regulation, and to provide a tool to assist people in pushing such plants toward retirement.

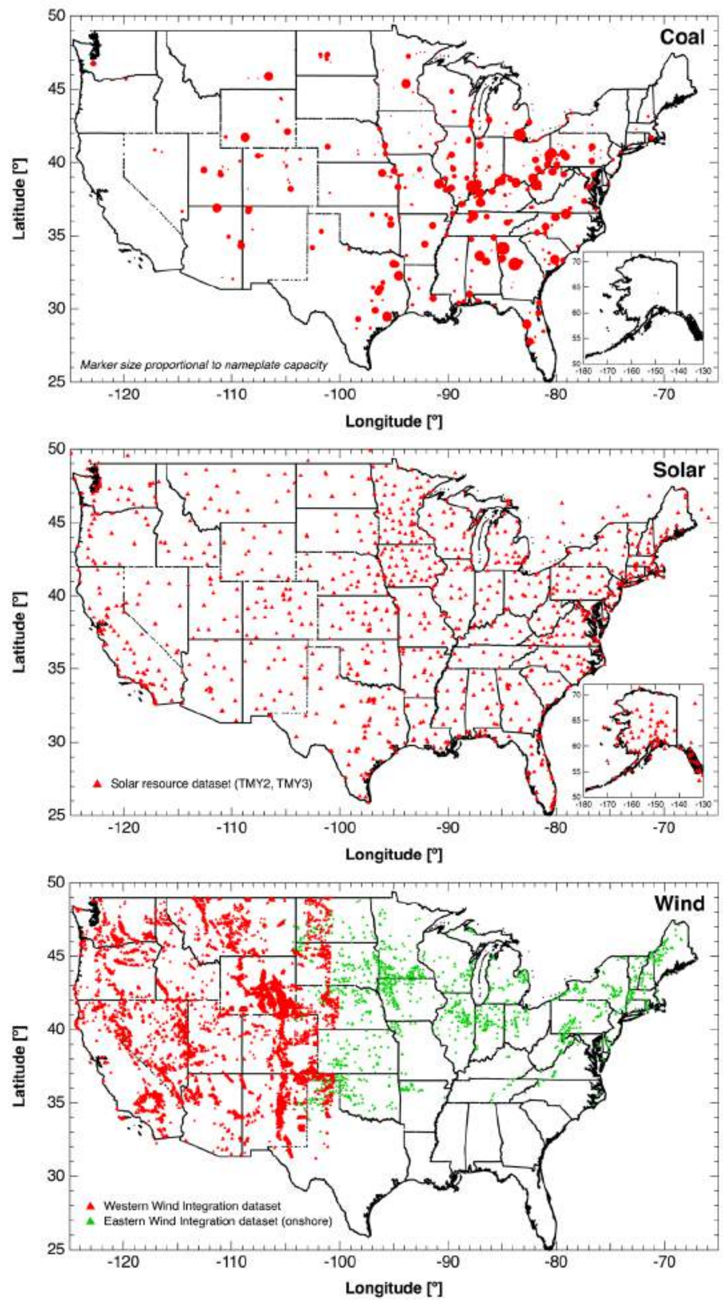


**Figure 5. Map of U.S. coal-fired power plants, solar resource sites, and wind resource sites.** Solar data are typical meteorological year (TMY2, TMY3) datasets from NSRDB (1259 sites in the U.S.). Onshore wind data are from the NREL Eastern and Western Wind Integration datasets (1326 and 32,043 sites, respectively).

## Generation Cost Calculations

### 2.1 Coal

In 2013, there were 518 operational coal plants in the U.S., accounting for about 328 GW of nameplate generation capacity.[6] Of these 518 plants, 392 were operated by electric utilities or IPPs to supply electricity to the grid (i.e., not combined heat and power systems). The locations of these plants are shown in Figure 5.

Plant locations, nameplate capacities, and annual $CO_2$ emissions by state and region are shown in Figure 6. The majority of U.S. coal plants and total generating capacity are located in the Interior, Southeast, and Midwest regions. The U.S. average coal nameplate capacity is 828 MW; the largest plant is the 3564 MW Scherer facility in Juliette, GA. The average annual $CO_2$ emissions per plant is 3.9 $MtCO_2$/yr. A list of coal plants scheduled for partial or full retirement (111 of 392 total) was compiled from a variety of sources, including the EIA, SourceWatch, and local news.[16,74]

To calculate operating costs for each plant, we use generator-level data from the EIA, including location and nameplate capacity from Form EIA-860[6] and fuel consumption, fuel costs, total O&M costs, and total generation from Form EIA-923.[77] Data for plants with multiple generating units are unified. Missing specific fuel cost [cents/MMBtu] and $CO_2$ emissions [lbs. $CO_2$/MMBtu] data are filled with fleet-wide average values weighted by fuel consumption and typical emission rates for different coal types (anthracite, bituminous, lignite, and sub-bituminous). Annual values are then calculated as follows:

$$Annual\ fuel\ cost\ \left[\frac{\$}{yr}\right] = Fuel\ consumption\ \left[\frac{MMBtu}{yr}\right] * Average\ fuel\ cost\ \left[\frac{\$}{MMBtu}\right]$$
$$Annual\ emissions\ \left[\frac{tCO_2}{yr}\right] = Fuel\ consumption\ \left[\frac{MMBtu}{yr}\right] * Average\ emissions\ \left[\frac{tCO_2}{MMBtu}\right]$$

Annual O&M costs are calculated as a sum of individual O&M expense categories: collection/abatement, disposal/abatement, and other.[+++] Average variable operating costs are then calculated by combining fuel costs, O&M costs, and an optional carbon tax with annual net generation for each plant:

$$Coal\ operating\ cost\ \left[\frac{\$}{MWh}\right] = \frac{Annual\ fuel\ cost\ \left[\frac{\$}{yr}\right] + Annual\ O\&M\ cost\ \left[\frac{\$}{yr}\right] + \left(Annual\ emissions\ \left[\frac{tCO_2}{yr}\right] * \ Carbon\ tax\ \left[\frac{\$}{tCO_2}\right]\right)}{Annual\ net\ generation\ \left[\frac{MWh}{yr}\right]}$$

[+++]The cost of allowances for $NO_x$ and $SO_2$ emissions have been highly variable in recent years, but in all cases they constitute only a small fraction of the total operating cost of coal-fired generators. Furthermore, as more coal plants have retired, the price of these allowances has decreased. We therefore omit these costs from our calculations.

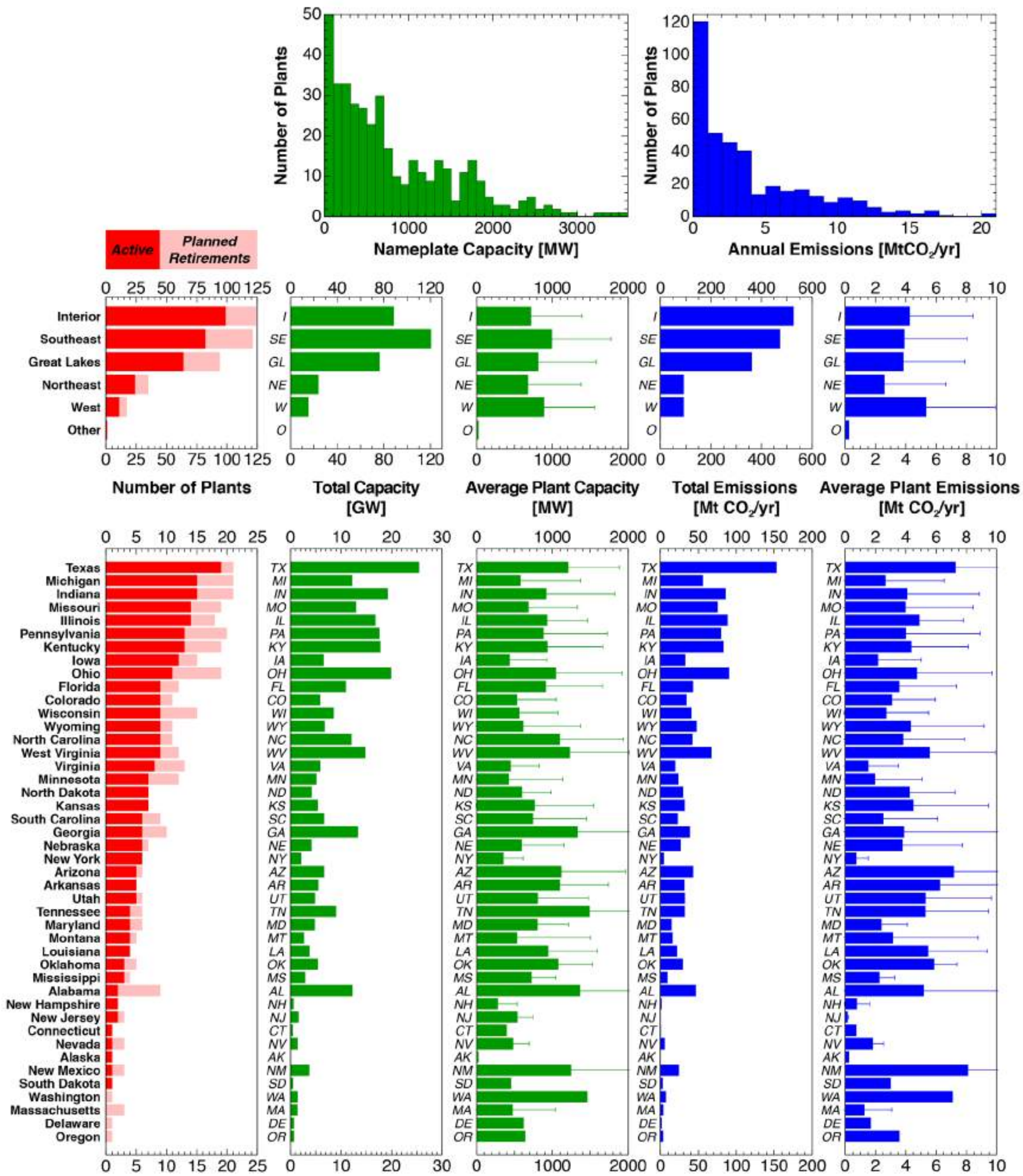


**Figure 6. Distribution of U.S. coal plant locations, nameplate capacities, and annual $CO_2$ emissions by region and state.** Capacity and $CO_2$ emissions data include plants scheduled for retirement (light red in left histograms). Error bars represent one standard deviation.

## 2.2 Solar

We evaluated three approaches for calculating the LCOE of new solar PV generation in the U.S., all based on publicly available solar insolation datasets and tools associated with NREL's System Advisor Model**:

- Method 1: PVWatts + SAM – This method uses NREL's PVWatts Version 5 application programming interface (API) to calculate the first-year AC energy output [kWh/yr] for a given location. We use the SAM graphical user interface (GUI) to estimate the typical annualized first-year cost (i.e., the roughly location-independent product of 2 SAM output parameters: real LCOE [$/kWh] and first-year AC output [kWh/yr]). Dividing the generic first-year cost by the location-specific first-year generation gives an estimated real LCOE in $/kWh.
- Method 2: SAM only – This method uses the SAM SDK to directly calculate the real LCOE for each location of interest.
- Method 3: SAM + custom LCOE code – This method uses the SAM SDK to calculate the first-year AC generation in each location. This value is then translated into an annual capacity factor, which is used as input to a custom LCOE calculation following Reichelstein and Yorston.[67]

Method 1, based on PVWatts, is the simplest to design and program because it does not require the SAM SDK, which is incompletely documented and requires trial-and-error experimentation to use effectively. However, the PVWatts interface restricts substantially the set of system design choices available to the user. In contrast, the SAM SDK allows much more detailed and accurate modeling of PV system performance and economics, including specific PV module and inverter choices, inverter loading ratios, array layout, detailed DC and AC losses, and financing parameters. Methods 2 and 3, which use SAM to calculate PV generation, incorporate system degradation rates and discounted cash flows over multi-year time scales, which are needed for accurate cost calculations.

We chose Method 3 as our primary approach for calculating solar LCOE. Our custom code allows sensitivity analyses to be performed more easily than with SAM, and can calculate LCOE when hour-by-hour weather data are not available—only an annual capacity factor is required.

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**The NREL SAM, sponsored by the U.S. Department of Energy, is a computer model that simulates the performance and financial metrics of renewable energy systems—including solar PV and wind systems at residential, commercial, or utility scale—in great detail. SAM allows project developers, policymakers, and researchers to evaluate technological and financial design options for individual systems in various locations. The standard SAM graphical user interface (GUI) is straightforward and easy to use for single-project simulations, but is not amenable to larger-scale investigations of multiple system configurations. The SAM SDK provides a software toolkit for incorporating individual SAM simulation modules (e.g., standard PV system performance model, weather data validation model, and IPP financial model) into custom software, with wrappers for Python, C, C++, C#, Java, and MATLAB. NREL's online PVWatts application uses one such module—in conjunction with location-based weather file lookup—to provide a simplified subset of SAM's PV simulation capabilities. Here we use the SAM SDK, along with PVWatts and custom code, to calculate solar LCOE in various locations.

Similar solar LCOE distributions are obtained with each of the three methods described above, as shown in the Supporting Information (Figure S3 and Figure S4).

Key input parameters for our solar and wind LCOE calculations are shown in Table 1. We assume an upfront PV system price of 1.90 $/W_{DC}$, near the low end of installed prices surveyed by LBNL[75] and comparable to prices observed by GTM[62] for U.S. utility-scale PV systems installed in 2014. SAM simulations used to obtain annual capacity factors assume a 20 MW system with PV module efficiency of 18.7%, temperature coefficient of –0.386%/°C, fixed latitude tilt, inverter efficiency of 97.6%, and nominal losses of 4.44% DC, 1% AC, and 5% for soiling. We note that system capacity is not an input to the LCOE calculation. The system size should not affect upfront price or LCOE significantly, as long as the system is larger than the estimated 5 MW threshold[75] for economies of scale in procurement, installation, and O&M, and smaller than the apparent >100 MW threshold for diseconomies of scale.

Table 1. Input parameters for solar and wind LCOE calculations.

| Parameter | Solar PV | Wind |
|---|---|---|
| **System lifetime** | 25 years | |
| **Annual degradation** | 0.5%/year | 0%/year |
| **System price** | 1.90 $/$W_{DC}$ | 1.90 $/$W_{AC}$ |
| **Fixed O&M cost** | 15 $/$kW_{DC}$/year | 0 |
| **Variable O&M cost** | 0 | 0.02 $/$kWh_{AC}$/year[a] |
| **Discount rate** | 7.5%[b] | |
| **Incentives** | 30/10/0% ITC[c] | 30/0% ITC<br>23/0 $/MWh PTC[d] |
| **Depreciation** | 5-year accelerated depreciation (MACRS)[e] | |

[a] Reflects actual wind operating costs reported by public companies with significant U.S. wind assets built in the 2000s[61]
[b] Typical weighted-average cost of capital (WACC) for electric generation facilities (e.g., as assumed for OECD countries and China in Ref. 76)
[c] The U.S. federal investment tax credit (ITC) for solar generating facilities is scheduled to expire at the end of 2016.
[d] There has historically been substantial uncertainty in the year-to-year continuity of the ITC and production tax credit (PTC) for wind. In calculations where a non-zero PTC is used, we take a simple deduction from the calculated LCOE. This approach assumes that the PTC applies for the entire project lifetime, although the current PTC applies only for the first 10 years of operation.
[e] Modified Accelerated Cost Recovery System (MACRS) 5-year depreciation schedule: 20%, 32%, 19.2%, 11.52%, 11.52%, 5.76%. Half-year depreciation is used in the first and last years.

### 2.3 Wind

Methods similar to those described above for solar PV can be used to calculate LCOE for wind generation. SAM can simulate wind turbine and system performance, but the SAM SDK does not offer a direct method for obtaining location-specific wind resource data. Furthermore, translating raw resource data into annual generation and capacity factors is a much more complex procedure for wind than for solar.[#]

Here we use average wind capacity factors for over 30,000 U.S. locations from NREL's Eastern and Western Wind Integration datasets. For each location of interest, we identify the nearest resource data available and use the custom code described above to calculate real LCOE. Input parameters for wind LCOE calculations are shown in Table 1. We assume an upfront system price of 1.90 $\$/W_{AC}$, roughly equal to the U.S. average installed cost for wind projects completed in the last several years.[61] The effect of varying capacity factor and federal subsidies for wind power is shown in the Supporting Information (Figure S5 and Figure S6).

## The CoalMap Interactive Tool

Each marker on the CoalMap represents a coal plant operated by an electric utility or IPP, excluding the few combined heat and power generators (Figure 7). Our analysis includes the 392 U.S. plants in operation in 2013, the most recent year for which complete data were available.[77] The marker color represents the lowest-cost electricity generation option at a given location. A red marker indicates that existing coal generation is cheaper than new wind and solar. A yellow or green marker indicates that solar or wind is the cheapest option, respectively. Black or gray markers represent plants that were operational in 2013 but have already retired or are scheduled to retire, respectively.

We used several publicly available software tools to develop the online CoalMap tool (coalmap.com). Data preparation, cost calculations, API calls, and various analyses were carried out using Python and associated packages, including in particular the *pandas* data analysis library. The online map and charts were produced with the Google Maps API and Charts API. The website was written in Javascript (with jQuery), CSS, and HTML, with a design based on the Bootstrap framework. The project is open source and currently hosted on Github.[##] We encourage interested readers to fork and help us improve the CoalMap project.

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[#] In a given location, wind speeds generally increase with altitude, so the choice of tower height directly affects the available wind resource. By varying the size of the turbine blades relative to the generator's nameplate capacity, a turbine designer can achieve nearly any desired capacity factor, although these parameters are typically chosen to optimize the system utilization and minimize generation cost.

[##] https://github.com/verysure/coalmap

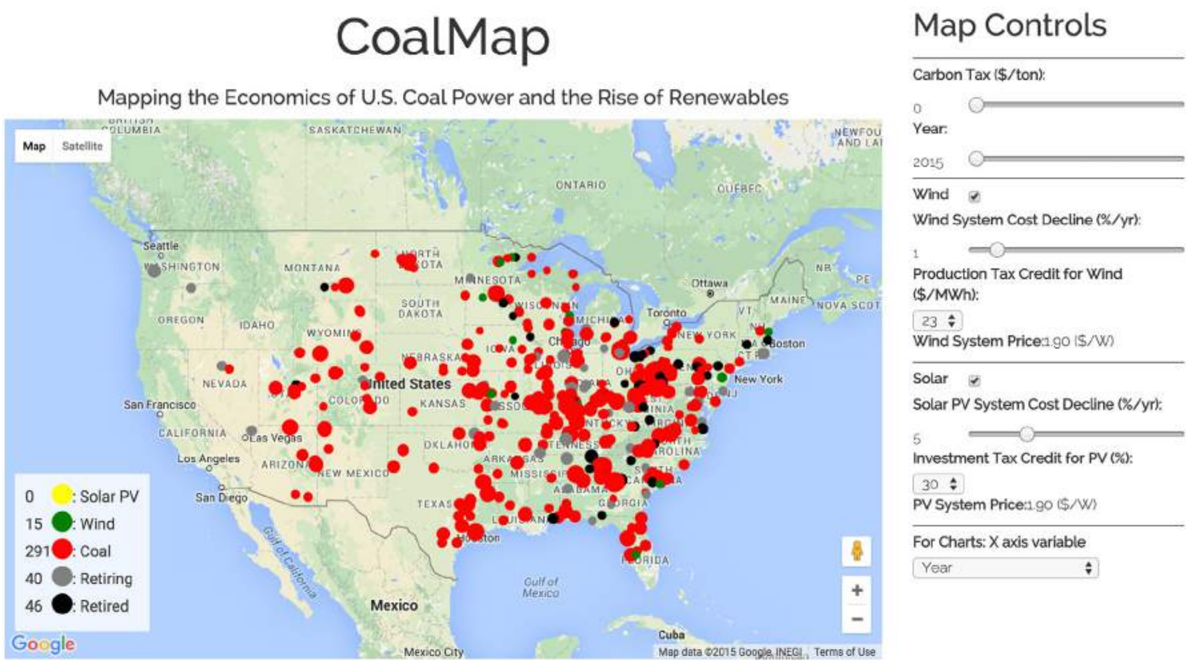


**Figure 7. Screenshot of the CoalMap web interface.** Users can change the carbon tax, rate of wind and solar cost decline, ITC, and PTC to explore the impact of these factors on the cost-competitiveness of renewables in the selected year.

## Results

Our calculations show that existing U.S. coal plants—under the current regulatory regime—can provide electricity at substantially lower average costs than new solar PV and wind generation facilities in the same locations. New renewable generators must pay off their large upfront investment and can be profitable today only at relatively higher market prices.` As shown in Figure 8 and Table 2, new utility-scale solar systems at the sites of current U.S. coal plants have an average LCOE of (102 ± 12) \$/MWh, assuming a 30% ITC. This value is 200% higher than the unweighted-average marginal cost of existing coal generation, (33 ± 17) \$/MWh. New U.S. wind generation has an average subsidized LCOE of (61 ± 8) \$/MWh—85% higher than coal.

This analysis may paint an unfairly pessimistic picture of the cost-competitiveness of solar and wind generation in the U.S. The cost of renewable electricity is tied to resource availability, which varies strongly across the continental U.S. (by up to a factor of 2 for solar). Coal plant locations are not chosen to maximize sunlight and wind—in fact, most plants are concentrated in the Southeast and the Midwest, which have the lowest solar and wind resource. In contrast, existing solar and wind generating facilities are mostly located in

`A new coal plant in the U.S. would have a substantially higher LCOE (around 100 \$/MWh, according to the EIA) than the average coal operating cost calculated in this work.

the Southwest and Great Plains, respectively, where the available resource is largest. Thus it is not surprising that some observed average PPA prices—as low as ~50 $/MWh for solar[75] and 23.5 $/MWh for wind[61]—are much lower than the average LCOE values calculated here.``

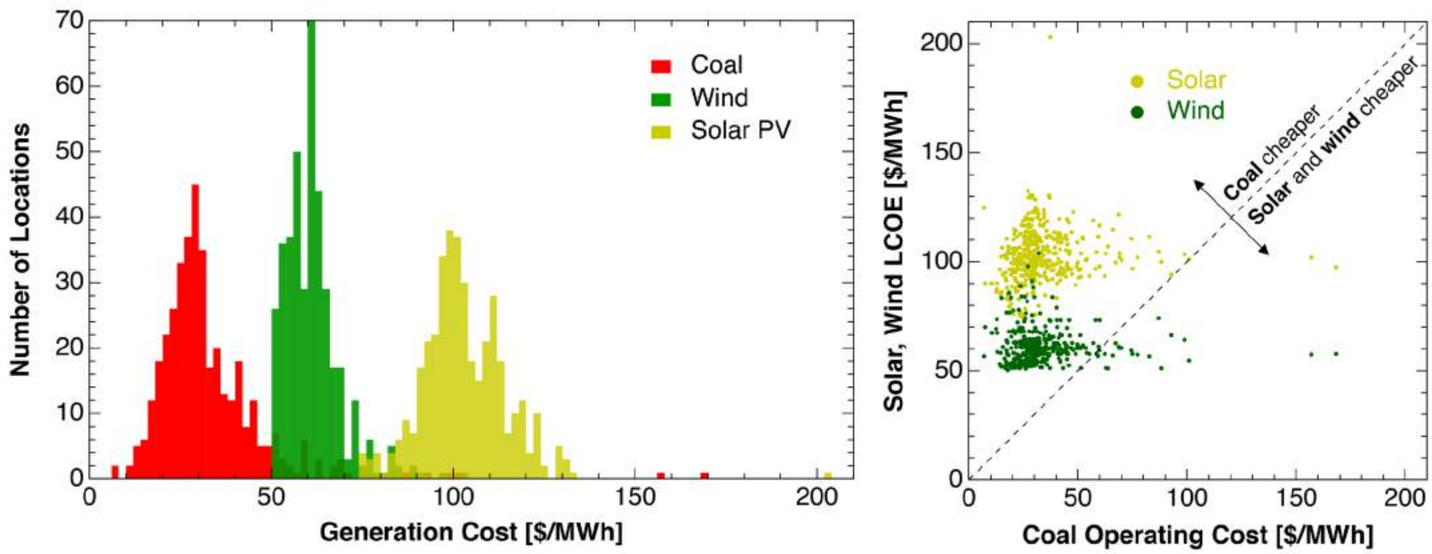


**Figure 8. Distribution of coal, solar, and wind generation costs at U.S. coal plant locations.** Coal cost calculations assume the current regulatory regime. Solar and wind LCOE calculations assume a 30% ITC. Very few fully amortized coal plants are economically threatened by new solar and wind generation today, even in the absence of financing limitations. We note, however, that many U.S. coal plants are already shutting down in response to new and expected environmental regulations.

**Table 1. Input parameters for solar and wind LCOE calculations.**

| Technology | Scenario | Generation Cost [$/MWh] |
|---|---|---|
| Coal | | 33 ± 17 |
| Solar PV | 30% ITC | 102 ± 12 |
| | 10% ITC | 139 ± 16 |
| | No subsidies | 157 ± 18 |
| Wind | 30% ITC | 61 ± 8 |
| | 23 $/MWh PTC[a] | 63 ± 12 |
| | No subsidies | 86 ± 12 |

[a] Our PTC calculation is a simplified estimate assuming that the subsidy is received for the full lifetime of the wind plant (rather than for the first 10 years only).

``PPA prices also include the effect of federal and local subsidies, as discussed above.

The costs of coal, solar, and wind generation vary with location (Figure 9), although not always predictably. Coal operating costs tend to be highest in the Southeast and lowest in the Interior. Solar and wind LCOEs are primarily determined by resource availability (in particular because we assume location-independent upfront costs and subsidies), although temperature-related system losses also contribute for solar. As expected, solar PV levelized costs are lowest in the sunny western states, while wind costs are lowest in the windy central U.S. states.

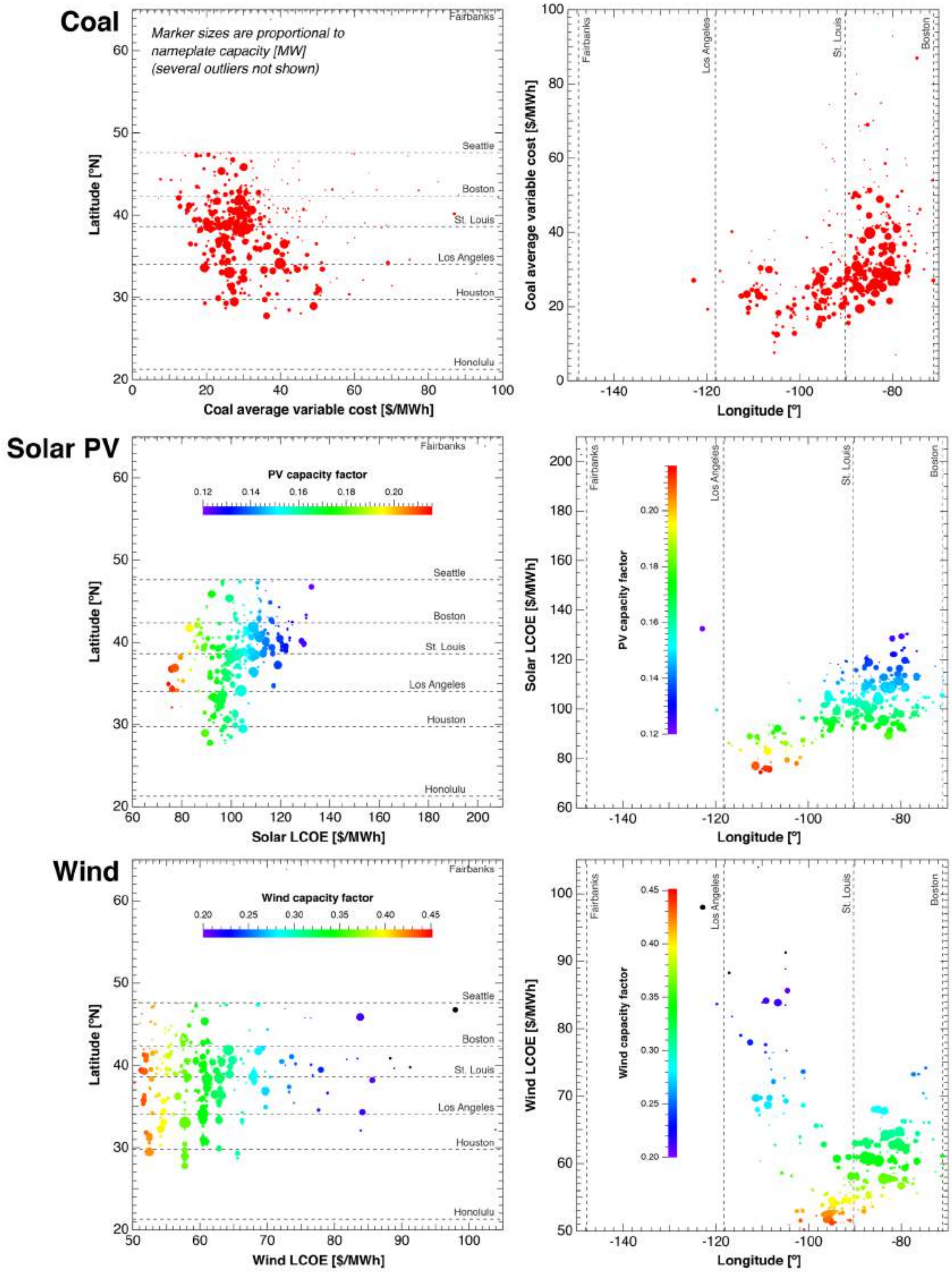


**Figure 9. Geographical variation of generation costs for coal, wind and solar in the U.S.** Coal average operating cost, solar PV LCOE, and wind LCOE are shown at the location of each existing coal plant. PV and wind calculations assume a 30% ITC.

Although it appears to be much cheaper to continue operating U.S. coal plants than to replace them with solar PV and wind, one should consider long-term cost trends in making long-term planning decisions.[78] Since around 1940, the cost of U.S. coal power has been dominated by fuel costs, which show no long-term downward trend and present a cost floor for coal-fired electricity.[66]

In contrast, solar PV and wind system costs have declined rapidly in recent years: Average utility-scale PV system prices in the U.S. decreased from 4.78 $/W in 2010 to 1.48 $/W in 2015 (21% compound annual reduction).[62] Average U.S. wind system prices decreased from 2.31 $/W in 2010 to 1.72 $/W in 2015 (6% annual reduction).[61] More importantly, solar and wind electricity prices have decreased as well—average U.S. solar PPA prices fell from 154 $/MWh in 2009 to 53 $/MWh in 2014 (19% annual reduction),[75] while wind PPA prices fell from 70 $/MWh to 23.5 $/MWh over the same period (20% annual reduction).[61] While these cost declines are unlikely to continue at their current rates, further reductions are expected with technological improvement and maturation of financing and policy support mechanisms. Recent projections by NREL, the International Energy Agency (IEA), and the European Photovoltaic Industry Association (EPIA; now SolarPower Europe) predict levelized cost declines of roughly 1%/year for wind[79] and 2–10%/year for solar[80] out to 2030.

If realized, sustained cost reductions could dramatically change the competitiveness of renewables compared to coal and other fossil fuels. In Figure 10, we show the effect of varying rates of cost decline—from 0%/year to 10%/year—on the median LCOE of solar PV and wind at the sites of U.S. coal plants. We emphasize that these numbers are based on unsubsidized system costs (no ITC or PTC). Despite the high cost of unsubsidized solar PV today, a compound annual cost reduction of 10% would make solar generation cheaper on average than fully amortized U.S. coal plants by 2031, with a LCOE of 29 $/MWh. Solar PV would then be by far the lowest-cost option for new electric generation in the U.S. and in most of the developed world.

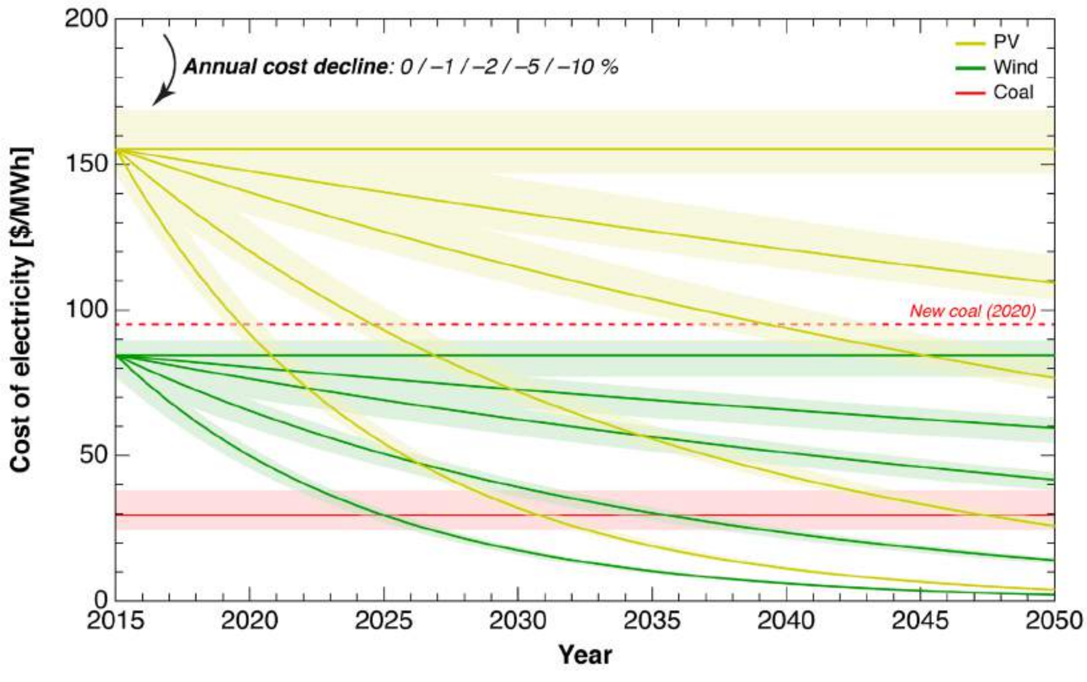


**Figure 10. U.S. cost of electricity from coal, solar, and wind vs. time with varying rates of cost (LCOE) decline.** Light-colored bands span the 25th and 75th percentiles for each scenario. The estimated U.S. average levelized cost of new coal plants entering service in 2020 is shown for reference.[64]

A price on carbon would further improve the economics of low-carbon solar and wind generation compared to coal (Figure 11). Over the full plant life cycle, a typical utility-scale solar PV system or onshore wind generator is responsible for greenhouse gas emissions of 41 $gCO_2$-eq/kWh or 11 gCO2-eq/kWh, respectively, far lower than the 915 $gCO_2$-eq/kWh reported for U.S. coal plants from 1997–2012.[81,82] Applying the U.S. government's social cost of carbon of 40 $/$tCO_2$ increases the cost of coal generation from 30 $/MWh to 71 $/MWh, close to the median LCOE of unsubsidized wind. This result suggests that a price on carbon would have a significant impact on renewable investment decisions and coal plant retirement schedules.

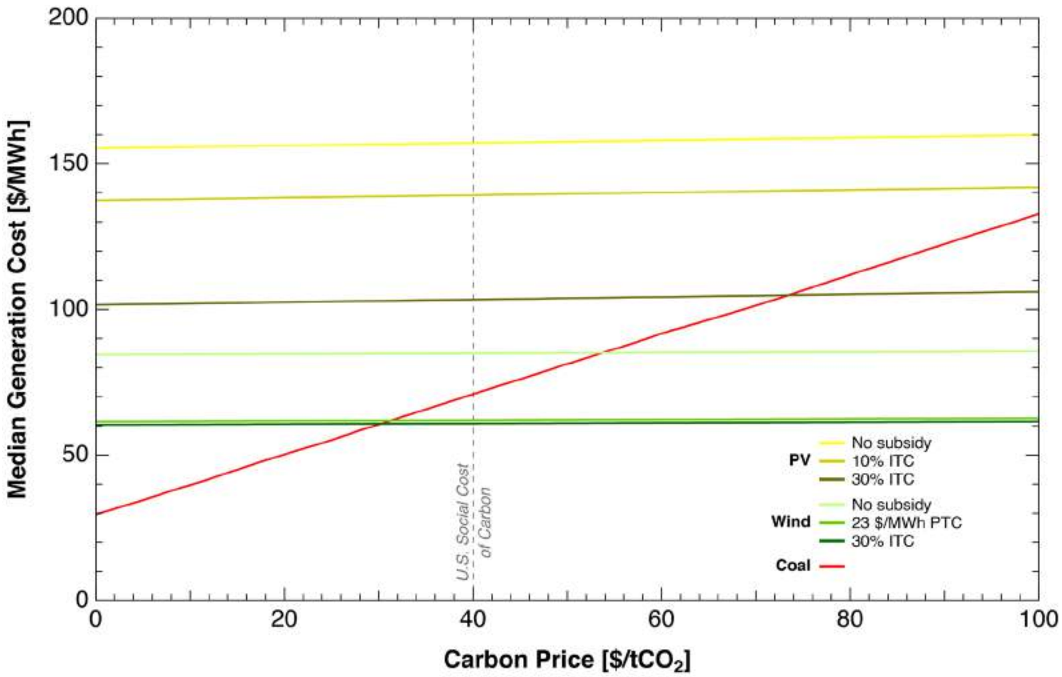


**Figure 11. Effect of carbon price on the median cost of electricity from existing U.S. coal plants and new solar PV and wind plants.** The social cost of carbon used by the U.S. government (40 $/$tCO_2$) is shown (gray dashed line). Solar and wind cost calculations assume current system prices and performance parameters (Table 1). Imposing a price on carbon would make new solar and wind facilities significantly more competitive with coal power, even without major cost reductions.

The combined impact of renewable cost declines and a carbon price on the cost-competitiveness of solar and wind is dramatic. In Figure 12, we focus on the *crossover year*, the first year in which the median cost of unsubsidized solar or wind electricity is cheaper than the median operating cost of fully amortized coal plants. Under different assumptions for the rate of solar and wind cost decline and the price on carbon emissions, we find dramatic shifts in the crossover year. Increasing the rate of cost decline is important but yields diminishing returns beyond a rate of few percentage points per year. Increasing the price on carbon has a significant and near-linear effect on crossover. For example, raising the price on carbon from 0 $/$tCO_2$ to 40 $/$tCO_2$ shortens the time to crossover by 17 years (from 2048 to 2031 for solar; 2036 to 2019 for wind) at a renewables cost decline rate of 5%/year.

The coal generation costs shown here are a lower-bound estimate of actual coal plant operating costs, as these calculations do not account for the cost of the more stringent emissions controls needed to comply with new and expected environmental regulations. With such regulatory impacts fully accounted for, one would expect existing U.S. coal plants to be shut down far earlier than predicted by this analysis.

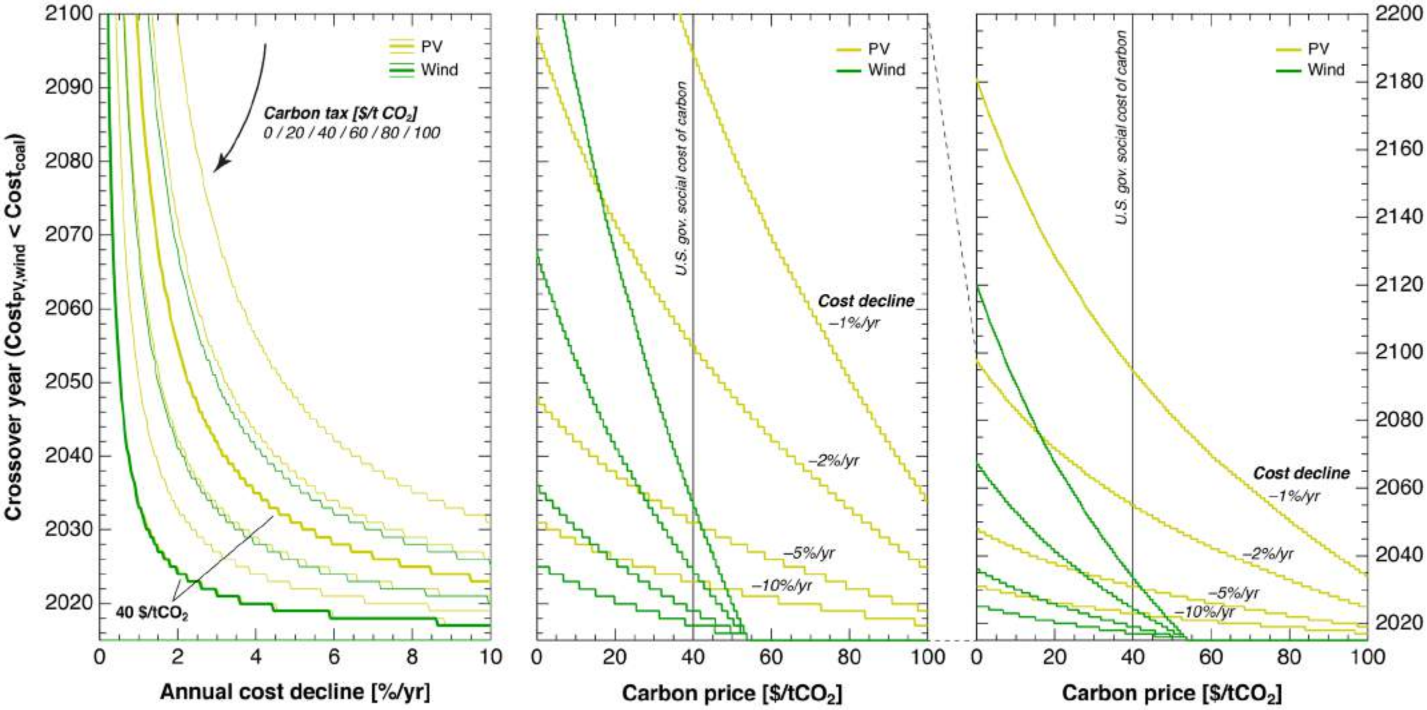


**Figure 12. Crossover year (median cost of solar or wind electricity < median cost of coal-fired electricity) for varying rates of renewable cost decline and carbon prices, with no subsidies for solar and wind.** Introducing a price on carbon significantly shortens the time to crossover between the cost of coal and renewables.

## Conclusions

We have developed an online tool, CoalMap, to help activists, regulators, and the general public explore the economic costs of existing coal-fired power plants across the United States. By comparing coal generation costs to the LCOE of new solar PV and wind generation in the same location, the tool identifies coal plants that are particularly vulnerable to shutdown efforts. Users can apply different carbon prices and rates of cost decline for solar and wind, and observe the effects on the cost-competitiveness of renewable generation in future years.

Our findings highlight the importance of technology improvement and appropriate public policy in achieving climate-change mitigation targets. The combination of cost reductions and carbon pricing is particularly potent: If high rates of solar and wind cost reduction are sustained through technological and financial innovation, and if carbon emissions are appropriately priced through a carbon tax or cap-and-trade regime, new low-carbon generators could help send the aging U.S. coal fleet off to a well-deserved retirement within the next two decades.

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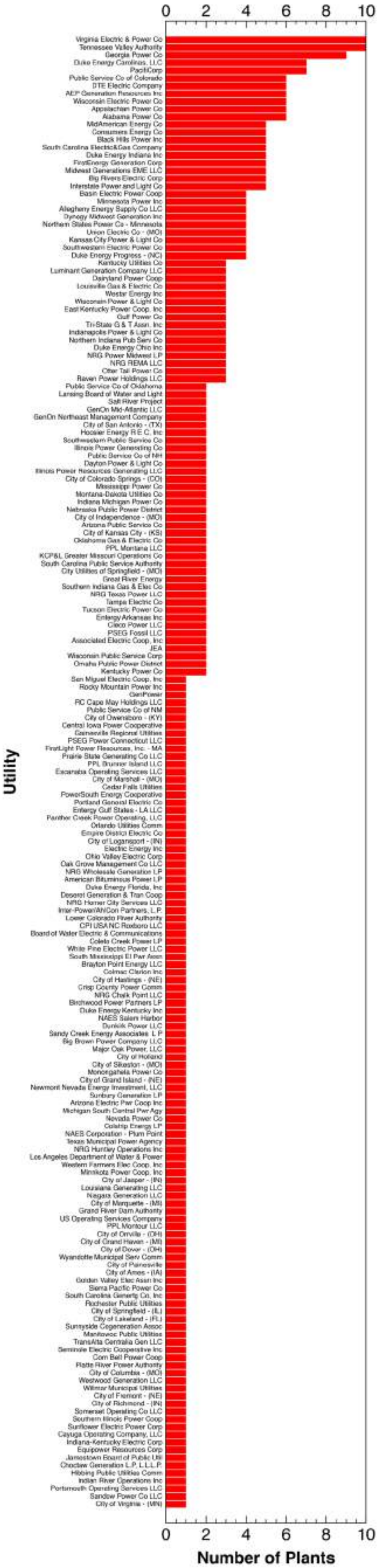
## Supporting Information



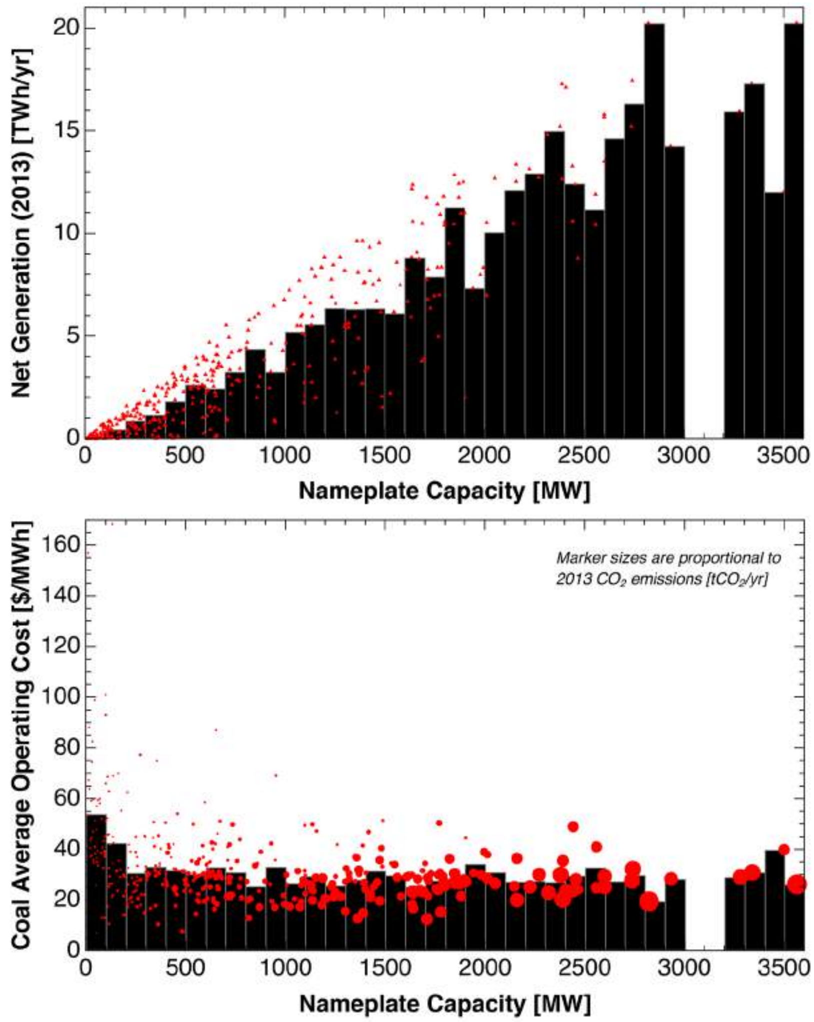




**Figure S1 (above). Scale effects on annual net generation and average variable operating cost of U.S. coal plants.** Annual net generation increases roughly linearly with nameplate capacity, as expected. Economies of scale are observed for coal plants with nameplate capacities exceeding roughly 200 MW.

**Figure S2 (left). Utilities served by U.S. coal plants.**

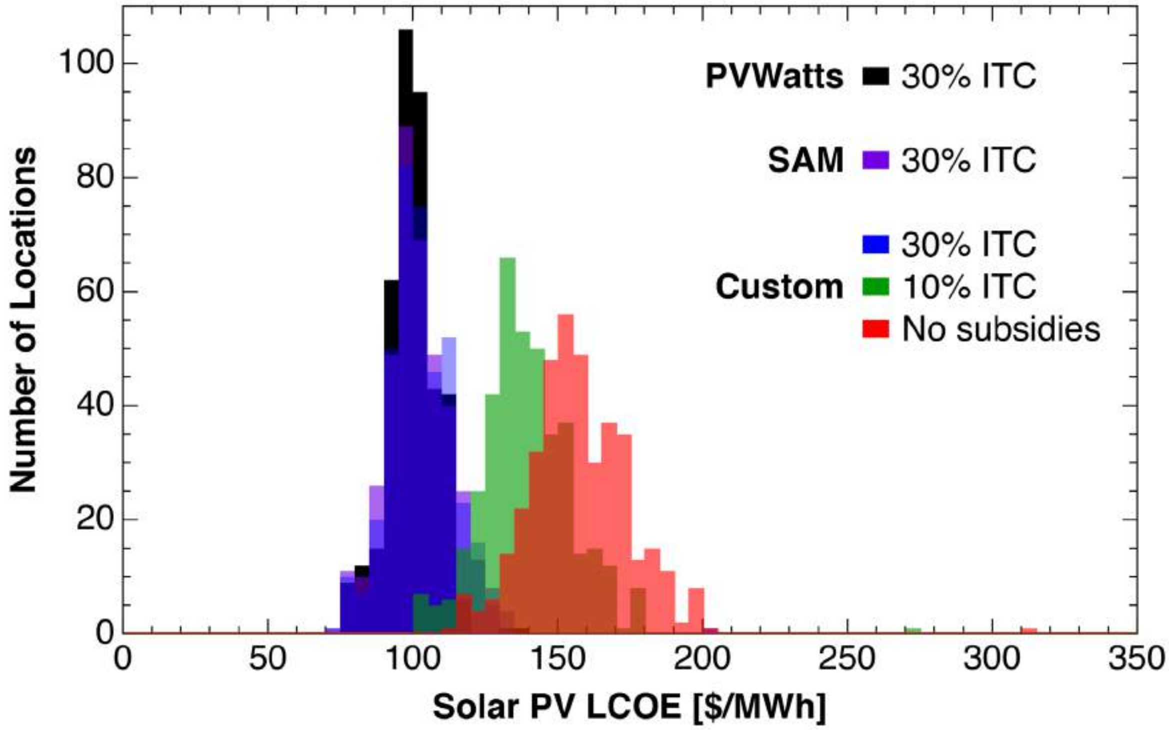



Figure S3. Solar PV LCOE distributions with varying ITC levels, calculated by PVWatts, SAM and custom code.

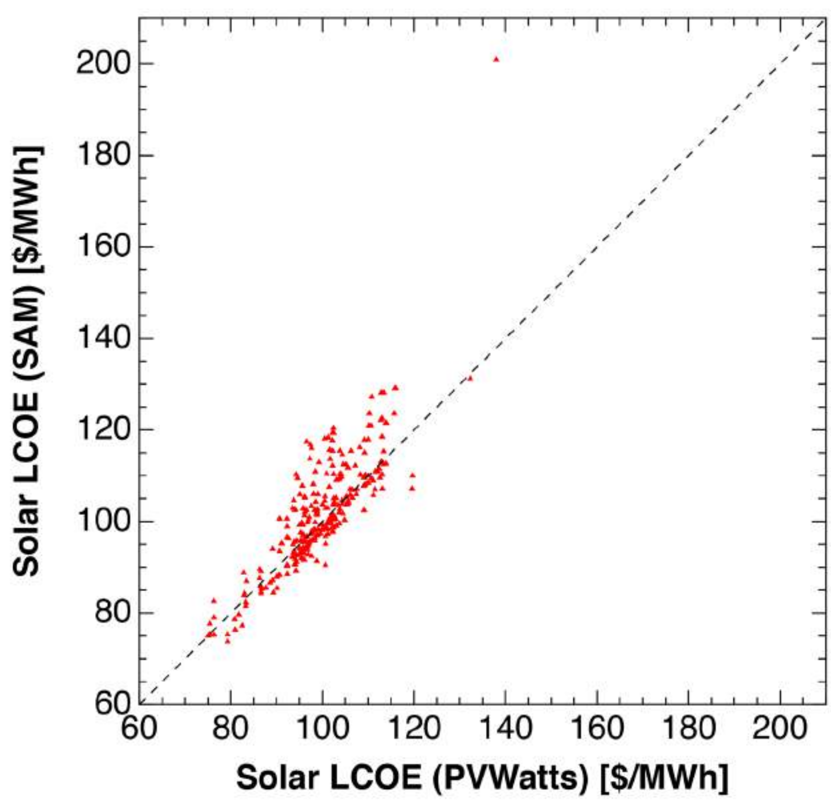



Figure S4. Comparison of LCOE calculated with SAM and with PVWatts for solar PV systems in the location of U.S. coal plants.

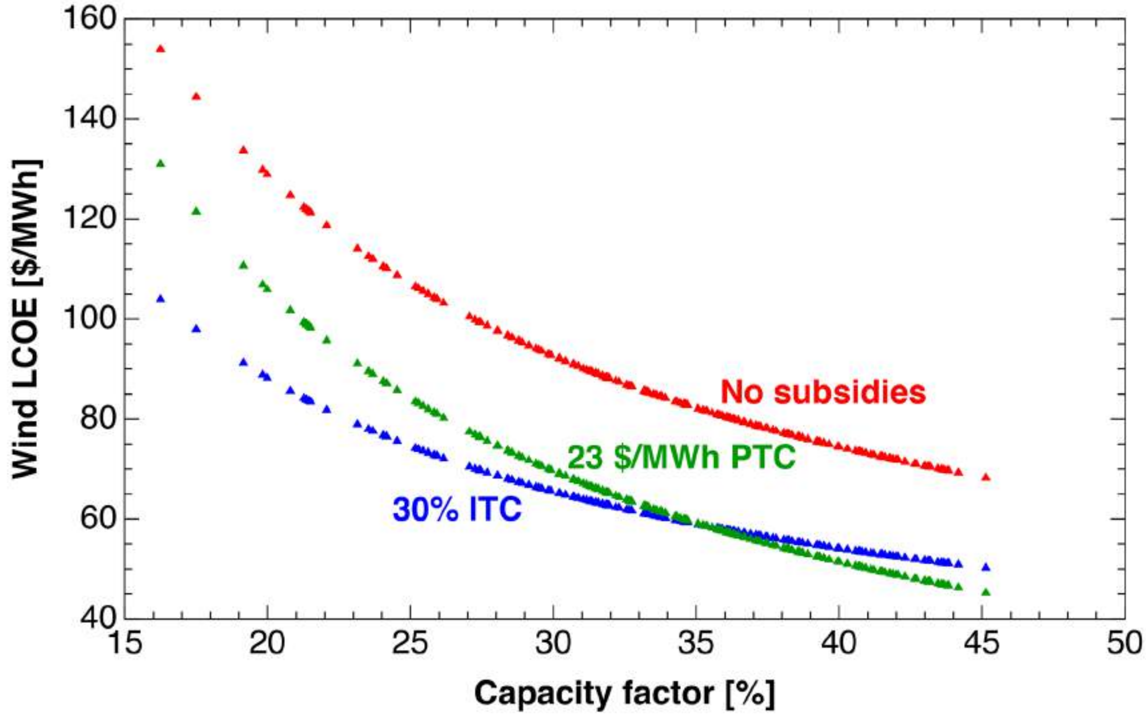



Figure S5. Effect of wind capacity factor on LCOE under different federal subsidy scenarios. At low capacity factors, the 30% ITC is more valuable than the 23 $/MWh PTC. With increasing capacity factor, the total output-based PTC subsidy increases, making it more valuable than the investment-based ITC.

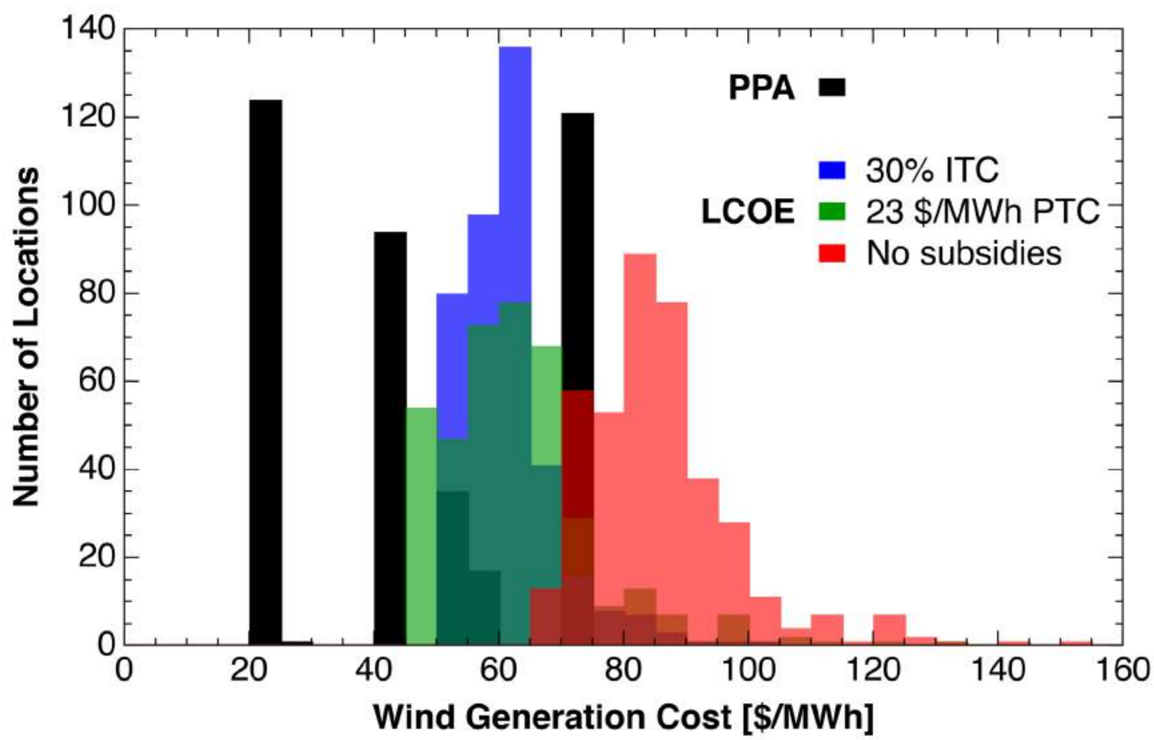



Figure S6. Comparison of observed wind PPA prices and the LCOE calculated for wind systems in the location of U.S. coal plants. Three federal subsidy scenarios are considered: 30% ITC, 23 $/MWh PTC, and no subsidies.