Cost of electricity by source

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In electrical power generation, the distinct ways of generating electricity incur significantly different costs. Calculations of these costs at the point of connection to a load or to the electricity grid can be made. The cost is typically given per kilowatt-hour or megawatt-hour. It includes the initial capital, discount rate, as well as the costs of continuous operation, fuel, and maintenance. This type of calculation assists policy makers, researchers and others to guide discussions and decision making.

The **levelised cost of electricity** (**LCOE**) is a measure of a power source which attempts to compare different methods of electricity generation on a consistent basis. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to break-even over the lifetime of the project.

Contents

Cost factors

While calculating costs, several internal cost factors have to be considered.[1] (Note the use of "costs," which is not the actual selling price, since this can be affected by a variety of factors such as subsidies and taxes):

- Capital costs (including waste disposal and decommissioning costs for nuclear energy) - tend to be low for fossil fuel power stations; high for wind turbines, solar PV; very high for waste to energy, wave and tidal, solar thermal, and nuclear.
- Fuel costs - high for fossil fuel and biomass sources, low for nuclear, and zero for many renewables. Fuel costs can vary somewhat unpredictably over the life of the generating equipment, due to political and other factors.
- Factors such as the costs of waste (and associated issues) and different insurance costs are not included in the following: Works power, own use or parasitic load - that is, the portion of generated power actually used to run the station's pumps and fans has to be allowed for.

To evaluate the total cost of production of electricity, the streams of costs are converted to a net present value using the time value of money. These costs are all brought together using discounted cash flow.[2][3]

Levelized cost of electricity

The levelized cost of electricity (LCOE), also known as Levelized Energy Cost (LEC), is the net present value of the unit-cost of electricity over the lifetime of a generating asset. It is often taken as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime. It is a first-order economic assessment of the cost competitiveness of an electricity-generating system that incorporates all costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital.

The levelized cost is that value for which an equal-valued fixed revenue delivered over the life of the asset's generating profile would cause the project to break even. This can be roughly calculated as the net present value of all costs over the lifetime of the asset divided by the total electrical energy output of the asset.[4]

The levelized cost of electricity (LCOE) is given by:

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t	: investment expenditures in the year t
M_t	: operations and maintenance expenditures in the year t
F_t	: fuel expenditures in the year t
E_t	: electrical energy generated in the year t
r	: discount rate
n	: expected lifetime of system or power station

Note: Some caution must be taken when using formulas for the levelized cost, as they often embody unseen assumptions, neglect effects like taxes, and may be specified in real or nominal levelized cost. For example, other versions of the above formula do not discount the electricity stream.

Typically the LCOE is calculated over the design lifetime of a plant, which is usually 20 to 40 years, and given in the units of currency per kilowatt-hour or megawatt-day, for example AUD/kWh or EUR/kWh or per megawatt-hour, for example AUD/MWh (as tabulated below).[5] However, care should be taken in comparing different LCOE studies and the sources of the information as the LCOE for a given energy source is highly dependent on the assumptions, financing terms and technological deployment analyzed.[6] In particular, assumption of capacity factor has significant impact on the calculation of LCOE. Thus, a key requirement for the analysis is a clear statement of the applicability of the analysis based on justified assumptions.[6]

Many scholars, such as Paul Joskow, have described limits to the "levelized cost of electricity" metric for comparing new generating sources. In particular, LCOE ignores time effects associated with matching production to demand. This happens at two levels:

- Dispatchability, the ability of a generating system to come online, go offline, or ramp up or down, quickly as demand swings.

- The extent to which the availability profile matches or conflicts with the market demand profile.

Thermally lethargic technologies like coal and nuclear are physically incapable of fast ramping. Capital intensive technologies such as wind, solar, and nuclear are economically disadvantaged unless generating at maximum availability since the LCOE is nearly all sunk-cost capital investment. Intermittent power sources, such as wind and solar, may incur extra costs associated with needing to have storage or backup generation available.[7] At the same time, intermittent sources can be competitive if they are available to produce when demand and prices are highest, such as solar during summertime mid-day peaks seen in hot countries where air conditioning is a major consumer.[6] Despite these time limitations, leveling costs is often a necessary prerequisite for making comparisons on an equal footing before demand profiles are considered, and the levelized-cost metric is widely used for comparing technologies at the margin, where grid implications of new generation can be neglected.

Another limitation of the LCOE metric is the influence of energy efficiency and conservation (EEC).[8] EEC has caused the electricity demand of many countries to remain flat or decline. Considering only the LCOE for utility scale plants will tend to maximise generation and risks overestimating required generation due to efficiency, thus "lowballing" their LCOE. For solar systems installed at the point of end use, it is more economical to invest in EEC first, then solar (resulting in a smaller required solar system than what would be needed without the EEC measures). However, designing a solar system on the basis of LCOE would cause the smaller system LCOE to increase (as the energy generation [measured in kWh] drops faster than the system cost [$]). The whole of system life cycle cost should be considered, not just the LCOE of the energy source.[8] LCOE is not as relevant to end-users than other financial considerations such as income, cashflow, mortgage, leases, rent, and electricity bills.[8] Comparing solar investments in relation to these can make it easier for end-users to make a decision, or using cost-benefit calculations "and/or an asset's capacity value or contribution to peak on a system or circuit level".[8]

Avoided cost

The US Energy Information Administration has recommended that levelized costs of non-dispatchable sources such as wind or solar may be better compared to the avoided energy cost rather than to the LCOE of dispatchable sources such as fossil fuels or geothermal. This is because introduction of fluctuating power sources may or may not avoid capital and maintenance costs of backup dispatchable sources. Levelized Avoided Cost of Energy (LACE) is the avoided costs from other sources divided by the annual yearly output of the non-dispatchable source. However, the avoided cost is much harder to calculate accurately.[9][10]

Marginal cost of electricity

A more accurate economic assessment might be the marginal cost of electricity. This value works by comparing the added system cost of increasing electricity generation from one source versus that from other sources of electricity generation (see Merit Order).

External costs of energy sources

Typically pricing of electricity from various energy sources may not include all external costs - that is, the costs indirectly borne by society as a whole as a consequence of using that energy source.[11] These may include enabling costs, environmental impacts, usage lifespans, energy storage, recycling costs, or beyond-insurance accident effects.

The US Energy Information Administration predicts that coal and gas are set to be continually used to deliver the majority of the world's electricity,[12] this is expected to result in the evacuation of millions of homes in low-lying areas, and an annual cost of hundreds of billions of dollars' worth of property damage.[13][14][15][16][17][18][19]

Furthermore, with a number of island nations becoming slowly submerged underwater due to rising sea levels,[20] massive international climate litigation lawsuits against fossil fuel users are currently beginning in the International Court of Justice.[21][22]

An EU funded research study known as ExternE, or Externalities of Energy, undertaken over the period of 1995 to 2005 found that the cost of producing electricity from coal or oil would double over its present value, and the cost of electricity production from gas would increase by 30% if external costs such as damage to the environment and to human health, from the particulate matter, nitrogen oxides, chromium VI, river water alkalinity, mercury poisoning and arsenic emissions produced by these sources, were taken into account. It was estimated in the study that these external, downstream, fossil fuel costs amount up to

1%-2% of the EU's entire Gross Domestic Product (GDP), and this was before the external cost of global warming from these sources was even included.[23][24] Coal has the highest external cost in the EU, and global warming is the largest part of that cost.[11]

A means to address a part of the external costs of fossil fuel generation is carbon pricing — the method most favored by economics for reducing global-warming emissions. Carbon pricing charges those who emit carbon dioxide (CO_2) for their emissions. That charge, called a 'carbon price', is the amount that must be paid for the right to emit one tonne of CO_2 into the atmosphere.[25] Carbon pricing usually takes the form of a carbon tax or a requirement to purchase permits to emit (also called "allowances").

Depending on the assumptions of possible accidents and their probabilites external costs for nuclear power vary significantly and can reach between 0.2 to 200 ct/kWh.[26] Furthermore, nuclear power is working under an insurance framework that limits or structures accident liabilities in accordance with the Paris convention on nuclear third-party liability, the Brussels supplementary convention, and the Vienna convention on civil liability for nuclear damage[27] and in the U.S. the Price-Anderson Act. It is often argued that this potential shortfall in liability represents an external cost not included in the cost of nuclear electricity; but the cost is small, amounting to about 0.1% of the levelized cost of electricity, according to a CBO study.[28]

These beyond-insurance costs for worst-case scenarios are not unique to nuclear power, as hydroelectric power plants are similarly not fully insured against a catastrophic event such as the Banqiao Dam disaster, where 11 million people lost their homes and from 30,000 to 200,000 people died, or large dam failures in general. As private insurers base dam insurance premiums on limited scenarios, major disaster insurance in this sector is likewise provided by the state.[29]

Because externalities are diffuse in their effect, external costs can not be measured directly, but must be estimated. One approach estimate external costs of environmental impact of electricity is the Methodological Convention of Federal Environment Agency of Germany. That method arrives at external costs of electricity from lignite at 10.75 Eurocent/kWh, from hard coal 8.94 Eurocent/kWh, from natural gas 4.91 Eurocent/kWh, from photovoltaic 1.18 Eurocent/kWh, from wind 0.26 Eurocent/kWh and from hydro 0.18 Eurocent/kWh.[30] For nuclear the Federal Environment Agency indicates no value, as different studies have results that vary by a factor of 1,000. It recommends the nuclear given the huge uncertainty, with the cost of the next inferior energy source to evaluate.[31] Based on this recommendation the Federal Environment Agency, and with their own method, the Forum Ecological-social market economy, arrive at external environmental costs of nuclear energy at 10.7 to 34 ct/kWh.[32]

Additional cost factors

Calculations often do not include wider system costs associated with each type of plant, such as long distance transmission connections to grids, or balancing and reserve costs. Calculations do not include externalities such as health damage by coal plants, nor the effect of CO_2 emissions on the climate change, ocean acidification and eutrophication, ocean current shifts. Decommissioning costs of nuclear plants are usually not included (The USA is an exception, because the cost of decommissioning is included in the price of electricity, per the Nuclear Waste Policy Act), is therefore not full cost accounting. These types of items can be explicitly added as necessary depending on the purpose of the calculation. It has little relation to actual price of power, but assists policy makers and others to guide discussions and decision making.

These are not minor factors but very significantly affect all responsible power decisions:

- Comparisons of life-cycle greenhouse gas emissions show coal, for instance, to be radically higher in terms of GHGs than any alternative. *Accordingly, in the analysis below, carbon captured coal is generally treated as a separate source rather than being averaged in with other coal.*
- Other environmental concerns with electricity generation include acid rain, ocean acidification and effect of coal extraction on watersheds.
- Various human health concerns with electricity generation, including asthma and smog, now dominate decisions in developed nations that incur health care costs publicly. A Harvard University Medical School study estimates the US health costs of coal alone at between 300 and 500 billion US dollars annually.[33]
- While cost per kWh of transmission varies drastically with distance, the long complex projects required to clear or even upgrade transmission routes make even attractive new supplies often uncompetitive with conservation measures (see below), because the timing of payoff must take the transmission upgrade into account.

Studies

Australia

Renewables advocates assert that the cost for wind and solar has dramatically reduced since 2006, for example, the climate council claims over the 5 years between 2009-2014 solar costs fell by 75% making them comparable to coal, and are expected to continue dropping over the next 5 years by another 45% from 2014 prices, however supporting data is unclear.[34] Another claim is that wind has been cheaper than coal since 2013, and that coal and gas will become less viable as subsidies are withdrawn and there is the expectation that they will eventually have to pay the costs of pollution.[34]

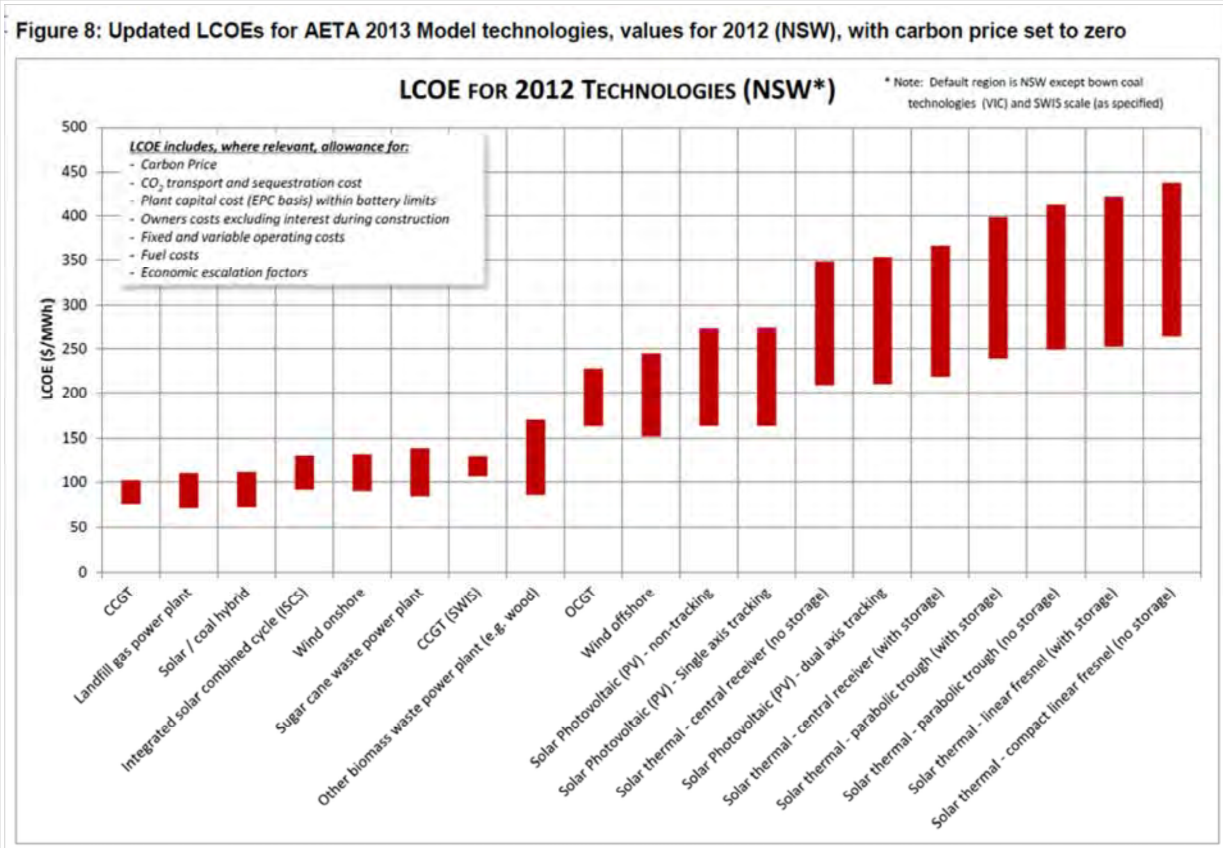
Most energy industry reports will counter that solar and wind cannot replace base load electricity sources due to the intermittent nature of production and that the necessity to maintain unused base load power generation increases the cost of any substantial shift to renewables.[35]

The table gives a selection of LCOE with and without a carbon price for coal (brown and black, with and without CCS) and wind from the Australian Technology Assessment (2012), Table 5.2.1.[36]

The chart below, from the Australian Energy Technology Assessment 2013 Model Update (Figure 8) also shows more current levelised costs of energy.[37] The second table and chart (in a modified form) were included in an article on The Conversation in 2015.[38]

LCOE in AUD per MWh for some coal and wind technologies (2012)

Technology	Cost with CO2 price	Cost without CO2 price
Supercritical brown coal	\$162	\$95
Supercritical brown coal with CCS	\$205	\$192
Supercritical black coal	\$135 - \$145	\$84 - \$94
Supercritical black coal with CCS	\$162 - \$205	\$153 - \$196
Wind	\$111 - \$122	\$111 - \$122



LCOEs by source in Australia in 2012.

France

The International Agency for the Energy and EDF have estimated for 2011 the following costs. For the nuclear power they include the costs due to new safety investments to upgrade the French nuclear plant after the Fukushima Daiichi nuclear disaster; the cost for those investments is estimated at 4 €/MWh. Concerning the solar power the estimate at 293 €/MWh is for a large plant capable to produce in the range of 50–100 GWh/year located in a favorable location (such as in Southern Europe). For a small household plant capable to produce typically around 3 MWh/year the cost is according to the location between 400 and 700 €/MWh. Currently solar power is by far the most expensive renewable source to produce electricity among the technologies studied, although increasing efficiency and longer lifespan of photovoltaic panels together with reduced production costs could make this source of energy more competitive.

French LCOE in €/MWh (2011)

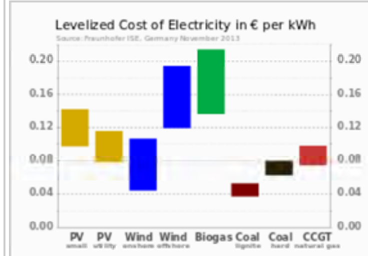
Technology	Cost in 2011
Hydro power	20
Nuclear (with State-covered insurance costs)	50
Natural gas turbines without CO_2 capture	61
Onshore wind	69
Solar farms	293

Germany

In November 2013, the Fraunhofer Institute for Solar Energy Systems ISE assessed the levelised generation costs for newly built power plants in the German electricity sector.[39] PV systems reached LCOE between 0.078 and 0.142 Euro/kWh in the third quarter of 2013, depending on the type of power plant (ground-mounted utility-scale or small rooftop solar PV) and average German insolation of 1000 to 1200 kWh/m² per year (GHI). There are no LCOE-figures available for electricity generated by recently built German nuclear power plants as none have been constructed since the late 1980s.

German LCOE in €/MWh (2013)

Technology		Low cost	High cost
Coal-fired power plants	brown coal	38	53
	hard coal	63	80
CCGT power plants		75	98
Wind Power	Onshore wind farms	45	107
	Offshore wind farms	119	194
Solar	PV systems	78	142
Biogas power plant		135	250
Source: Fraunhofer ISE - Levelized cost of electricity renewable energy technologies[39]			



Comparison of the levelized cost of electricity for some newly built renewable and fossil-fuel based power stations in euro per kWh (Germany, 2013)
Note: employed technologies and LCOE differ by country and change over time.

Japan

A 2010 study by the Japanese government (pre-Fukushima disaster), called the Energy White Paper, concluded the cost for kilowatt hour was ¥49 for solar, ¥10 to ¥14 for wind, and ¥5 or ¥6 for nuclear power. Masayoshi Son, an advocate for renewable energy, however, has pointed out that the government estimates for nuclear power did not include the costs for reprocessing the fuel or disaster insurance liability. Son estimated that if these costs were included, the cost of nuclear power was about the same as wind power.[40][41][42]

United Kingdom

The Institution of Engineers and Shipbuilders in Scotland commissioned a former Director of Operations of the British National Grid, Colin Gibson, to produce a report on generation levelised costs that for the first time would include some of the transmission costs as well as the generation costs. This was published in December 2011.[43] The institution seeks to encourage debate of the issue, and has taken the unusual step among compilers of such studies of publishing a spreadsheet.[44]

On 27 February 2015 Vattenfall Vindkraft AS agreed to build the Horns Rev 3 offshore wind farm at a price of 10.31 Eurocent per kWh (http://www.ens.dk/en/supply/renewable-energy/wind-power/offshore-wind-power/large-scale-offshore-wind-tenders). This has been quoted as below 100 UK pounds (http://blogs.dnvgl.com/utilityofthefuture/100mwh-and-falling-dawn-breaks-on-a-cheaper-stronger-offshore-wind-industry) per MWh.

In 2013 in the United Kingdom for a new-to-build nuclear power plant (Hinkley Point C: completion 2023), a feed-in tariff of 92.50 pounds/MWh (around 142 USD/MWh) plus compensation for inflation with a running time of 35 years was agreed.[45][46]

BEIS

The Department for Business, Energy and Industrial Strategy (BEIS) publishes regular estimates of the costs of different electricity generation sources, following on the estimates of the merged Department of Energy and Climate Change (DECC). Levelised cost estimates for new generation projects begun in 2015 are listed in the table below.[47]

Estimated UK LCE for projects starting in 2015, £/MWh

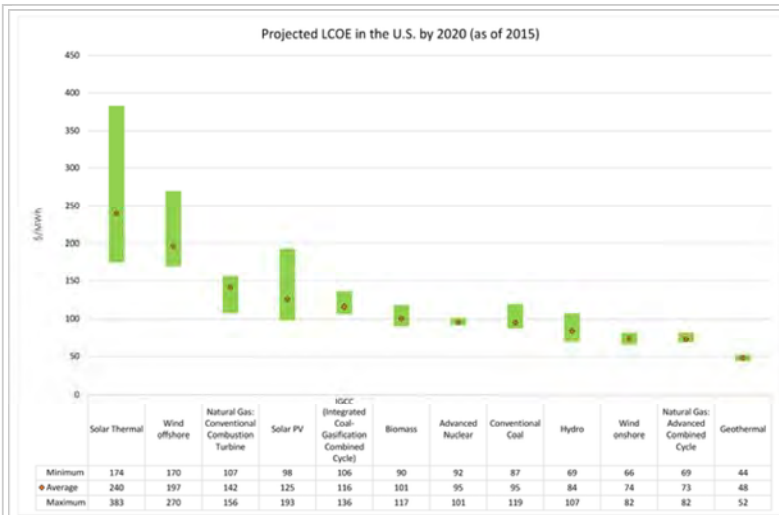
Power generating technology		Low	Central	High
Nuclear PWR (Pressurized Water Reactor)[a]		82	**93**	121
Solar Large-scale PV (Photovoltaic)		71	**80**	94
Wind	Onshore	47	**62**	76
	Offshore	90	**102**	115
Biomass		85	**87**	88
Natural Gas	Combined Cycle Gas Turbine	65	**66**	68
	CCGT with CCS (Carbon capture and storage)	102	**110**	123
	Open-Cycle Gas Turbine	157	**162**	170
Coal	Advanced Supercritical Coal with Oxy-comb. CCS	124	**134**	153
	IGCC (Integrated Gasification Combined Cycle) with CCS	137	**148**	171

[a] new nuclear power: guaranteed strike price of £92.50/MWh for Hinkley Point C in 2023[48][49])

United States

Energy Information Administration

The following data are from the Energy Information Administration's (EIA) Annual Energy Outlook released in 2015 (AEO2015). They are in dollars per megawatt-hour (2013 USD/MWh). These figures are estimates for plants going into service in 2020.[10] The LCOE below is calculated based off a 30-year recovery period using a real after tax weighted average cost of capital (WACC) of 6.1%. For carbon intensive technologies 3 percentage points are added to the WACC. (This is approximately equivalent fee of \$15 per metric ton of carbon dioxide CO_2)



Projected LCOE in the U.S. by 2020 (as of 2015) in dollars per MWh[50]

Since 2010, the US Energy Information Administration (EIA) has published the Annual Energy Outlook (AEO), with yearly LCOE-projections for future utility-scale facilities to be commissioned in about five years' time. In 2015, EIA has been criticized by the Advanced Energy Economy (AEE) Institute after its release of the AEO 2015-report to "consistently underestimate the growth rate of renewable energy, leading to 'misperceptions' about the performance of these resources in the marketplace". AEE points out that the average power purchase agreement (PPA) for wind power was already at \$24/MWh in 2013. Likewise, PPA for utility-scale solar PV are seen at current levels of \$50–\$75/MWh.[51] These figures contrast strongly with EIA's estimated LCOE of \$125/MWh (or \$114/MWh including subsidies) for solar PV in 2020.[52]

Projected LCOE in the U.S. by 2020 (as of 2015) $/MWh

Power generating technology		Minimum	Average	Maximum
Geothermal		43.8	**47.8**	52.1
Wind	Onshore	65.6	**73.6**	81.6
	Offshore	169.5	**196.9**	269.8
Natural Gas-fired	Conventional Combined Cycle	70.4	**75.2**	85.5
	Advanced Combined Cycle	68.6	**72.6**	81.7
	Advanced CC with CCS	93.3	**100.2**	110.8
	Conventional Combustion Turbine	107.3	**141.5**	156.4
	Advanced Combustion Turbine	94.6	**113.5**	126.8
Hydro		69.3	**83.5**	107.2
Coal	Conventional Coal	87.1	**95.1**	119.0
	IGCC (Integrated Coal-Gasification Combined Cycle)	106.1	**115.7**	136.1
	IGCC with CCS	132.9	**144.4**	160.4
Advanced Nuclear		91.8	**95.2**	101.0
Biomass		90.0	**100.5**	117.4
Solar	Photovoltaic	97.8	**125.3**	193.3
	Concentrated Solar Power	174.4	**239.7**	382.5

The electricity sources which had the most decrease in estimated costs over the period 2010 to 2016 were solar photovoltaic (down 79%), onshore wind (down 57%) and conventional natural gas combined cycle (down 30%).

For utility-scale generation put into service in 2040, the EIA estimated in 2015 that there would be further reductions in the constant-dollar cost of concentrated solar power (CSP) (down 18%), solar photovoltaic (down 15%), offshore wind (down 11%), and advanced nuclear (down 7%). The cost of onshore wind was expected to rise slightly (up 2%) by 2040, while natural gas combined cycle electricity was expected to increase 9% to 10% over the period.[52]

http://www.eia.gov/forecasts/aeo/electricity_generation.cfm

Historical summary of EIA's LCOE projections (2010–2016)

Estimate in $/MWh			Coal	NG combined cycle		Nuclear	Wind		Solar	
of year	ref	for year	convent'l	convent'l	advanced	advanced	onshore	offshore	PV	CSP
2010	[53]	2016	100.4	83.1	79.3	119.0	149.3	191.1	396.1	256.6
2011	[54]	2016	95.1	65.1	62.2	114.0	96.1	243.7	211.0	312.2
2012	[55]	2017	97.7	66.1	63.1	111.4	96.0	N/A	152.4	242.0
2013	[56]	2018	100.1	67.1	65.6	108.4	86.6	221.5	144.3	261.5
2014	[57]	2019	95.6	66.3	64.4	96.1	80.3	204.1	130.0	243.1
2015	[52]	2020	95.1	75.2	72.6	95.2	73.6	196.9	125.3	239.7
2016	[58]	2022	NA	58.1	57.2	102.8	64.5	158.1	84.7	235.9
Nominal change 2010-2016			**NA**	**-30%**	**-28%**	**-14%**	**-57%**	**-17%**	**-79%**	**-8%**

Note: Projected LCOE are adjusted for inflation and calculated on constant dollars based on two years prior to the release year of the estimate. Estimates given without any subsidies. Transmission cost for non-dispatchable sources are on average much higher.

NREL OpenEI (2015)

OpenEI, sponsored jointly by the US DOE and the National Renewable Energy Laboratory (NREL), has compiled a historical cost-of-generation database[59] covering a wide variety of generation sources. Because the data is open source it may be subject to frequent revision.

LCOE from OpenEI DB as of June, 2015

Plant Type (USD/MWh)		Min	Median	Max	Data Source Year
Distributed Generation		10	70	130	2014
Hydropower	Conventional	30	70	100	2011
	Small Hydropower		140		2011
Wind	Onshore	40		80	2014
	Offshore	100		200	2014
Natural Gas	Combined Cycle	50		80	2014
	Combustion Turbine	140		200	2014
Coal	Pulverized, scrubbed	60		150	2014
	Pulverized, unscrubbed		40		2008
	Integrated gasification, combined cycle	100		170	2014
Solar	Photovoltaic	60	110	250	2014
	CSP	100		220	2014
Geothermal	Hydrothermal	50		100	2011
	Blind		100		2011
	Enhanced	80		130	2014
Biopower		90		110	2014
Fuel Cell		100		160	2014
Nuclear		90		130	2014
Ocean		230	240	250	2011

Note:
Only Median value = only one data point.
Only Max + Min value = Only two data points

California Energy Commission (2014)

LCOE data from the California Energy Commission report titled "Estimated Cost of New Renewable and Fossil Generation in California".[60] The model data was calculated for all three classes of developers: merchant, investor-owned utility (IOU), and publicly owned utility (POU).

Type	Year 2013 (Nominal $$) ($/MWh)			Year 2024(Nominal $$) ($/MWh)		
Name	**Merchant**	**IOU**	**POU**	**Merchant**	**IOU**	**POU**
Generation Turbine 49.9MW	662.81	2215.54	311.27	884.24	2895.90	428.20
Generation Turbine 100MW	660.52	2202.75	309.78	881.62	2880.53	426.48
Generation Turbine - Advanced 200MW	403.83	1266.91	215.53	533.17	1615.68	299.06
Combined Cycle 2CTs No Duct Firing 500MW	116.51	104.54	102.32	167.46	151.88	150.07
Combined Cycle 2CTs With Duct Firing 500MW	115.81	104.05	102.04	166.97	151.54	149.88
Biomass Fluidized Bed Boiler 50MW	122.04	141.53	123.51	153.89	178.06	156.23
Geothermal Binary 30MW	90.63	120.21	84.98	109.68	145.31	103.00
Geothermal Flash 30MW	112.48	146.72	109.47	144.03	185.85	142.43
Solar Parabolic Trough W/O Storage 250MW	168.18	228.73	167.93	156.10	209.72	156.69
Solar Parabolic Trough With Storage 250MW	127.40	189.12	134.81	116.90	171.34	123.92
Solar Power Tower W/O Storage 100MW	152.58	210.04	151.53	133.63	184.24	132.69
Solar Power Tower With Storage 100MW 6HR	145.52	217.79	153.81	132.78	196.47	140.58
Solar Power Tower With Storage 100MW 11HR	114.06	171.72	120.45	103.56	154.26	109.55
Solar Photovoltaic (Thin Film) 100MW	111.07	170.00	121.30	81.07	119.10	88.91
Solar Photovoltaic (Single-Axis) 100MW	109.00	165.22	116.57	98.49	146.20	105.56
Solar Photovoltaic (Thin Film) 20MW	121.31	186.51	132.42	93.11	138.54	101.99
Solar Photovoltaic (Single-Axis) 20MW	117.74	179.16	125.86	108.81	162.68	116.56
Wind Class 3 100MW	85.12	104.74	75.8	75.01	91.90	68.17
Wind Class 4 100MW	84.31	103.99	75.29	75.77	92.88	68.83

Lazard (2015)

In November 2015, the investment bank Lazard headquartered in New York, published a study on the current electricity production costs of photovoltaics in the US compared to conventional power generators. The best large-scale photovoltaic power plants can produce electricity at 50 USD per MWh. The upper limit at 60 USD per MWh. In comparison, coal-fired plants are between 65 USD and $150 per MWh, nuclear power at 97 USD per MWh. Small photovoltaic power plants on roofs of houses are still at 184-300 USD per MWh, but which can do without electricity transport costs. Onshore wind turbines are 32-77 USD per MWh. One drawback is the intermittency of solar and wind power. The study suggests a solution in batteries as a storage, but these are still expensive so far.[61][62]

Below is the complete list of LCOEs by source from the investment bank Lazard.[61]

Plant Type (USD/MWh)	Low	High
Solar PV-Rooftop Residential	184	300
Solar PV-Rooftop C&I	109	193
Solar PV-Crystalline Utility Scale	58	70
Solar PV-Thin Film Utility Scale	50	60
Solar Thermal with Storage	119	181
Fuel Cell	106	167
Microturbine	79	89
Geothermal	82	117
Biomass Direct	82	110
Wind	32	77
Energy Efficiency	0	50
Battery Storage	**	**
Diesel Reciprocating Engine	212	281
Natural Gas Reciprocating Engine	68	101
Gas Peaking	165	218
IGCC	96	183
Nuclear	97	136
Coal	65	150
Gas Combined Cycle	52	78

NOTE: ** Battery Storage is no longer include in this report (2015). It has been rolled into its own separate report (See charts below).

Below are the LCOEs for different battery technologies. This category has traditionally been filled by Diesel Engines. These are "Behind the meter" applications.[63]

Purpose	Type	Low ($/MWh)	High ($/MWh)
MicroGrid	Flow Battery	429	1046
MicroGrid	Lead-Acid	433	946
MicroGrid	Lithium-Ion	369	562
MicroGrid	Sodium	411	835
MicroGrid	Zinc	319	416
Island	Flow Battery	593	1231
Island	Lead-Acid	700	1533
Island	Lithium-Ion	581	870
Island	Sodium	663	1259
Island	Zinc	523	677
Commercial and Industrial	Flow Battery	349	1083
Commercial and Industrial	Lead-Acid	529	1511
Commercial and Industrial	Lithium-Ion	351	838
Commercial and Industrial	Sodium	444	1092
Commercial and Industrial	Zinc	310	452
Commercial Appliance	Flow Battery	974	1504
Commercial Appliance	Lead-Acid	928	2291
Commercial Appliance	Lithium-Ion	784	1363
Commercial Appliance	Zinc	661	833
Residential	Flow Battery	721	1657
Residential	Lead-Acid	1101	2238
Residential	Lithium-Ion	1034	1596
All of the above Traditional Method	Diesel Reciprocating Engine	212	281

Below are the LCOEs for different battery technologies. This category has traditionally been filled by Natural Gas Engines. These are "In front of the meter" applications.[63]

Purpose	Type	Low ($/MWh)	High ($/MWh)
Transmission System	Compressed Air	192	192
Transmission System	Flow Battery	290	892
Transmission System	Lead-Acid	461	1429
Transmission System	Lithium-Ion	347	739
Transmission System	Pumped Hydro	188	274
Transmission System	Sodium	396	1079
Transmission System	Zinc	230	376
Peaker Replacement	Flow Battery	248	927
Peaker Replacement	Lead-Acid	419	1247
Peaker Replacement	Lithium-Ion	321	658
Peaker Replacement	Sodium	365	948
Peaker Replacement	Zinc	221	347
Frequency Regulation	Flywheel	276	989
Frequency Regulation	Lithium-Ion	211	275
Distribution Services	Flow Battery	288	923
Distribution Services	Lead-Acid	516	1692
Distribution Services	Lithium-Ion	400	789
Distribution Services	Sodium	426	1129
Distribution Services	Zinc	285	426
PV Integration	Flow Battery	373	950
PV Integration	Lead-Acid	402	1068
PV Integration	Lithium-Ion	355	686
PV Integration	Sodium	379	957
PV Integration	Zinc	245	345
All of the above Traditional Method	Gas Peaker	165	218

Global

IEA and NEA (2015)

The International Energy Agency and the Nuclear Energy Agency published a joint study in 2015 on LCOE data internationally.[64][65]

Other studies and analysis

Buffett Contract (2015)

In a power purchase agreement in the United States in July 2015 for a period of 20 years of solar power will be paid 3.87 UScent per kilowatt hour (38.7 USD/MWh). The solar system, which produces this solar power, is in Nevada (USA) and has 100 MW capacity.[66]

Sheikh Mohammed Bin Rashid solar farm (2016)

For a construction phase of Sheikh Mohammed Bin Rashid solar farms over 800 MW photovoltaic a bid of 2,99 UScent per kilowatt hour of solar energy was in the spring of 2016 at a tender achieved.[67]

Nuclear Energy Agency (2012)

In November 2012, the OECD Nuclear Energy Agency published a report with the title *System effects in low carbon energy systems*.[68] In this report NEA looks at the interactions of dispatchable energy technologies (fossil and nuclear) and variable renewables (solar and wind) in terms of their effects on electricity systems. These *grid-level systems costs* differ from the levelized cost of electricity metric that scholars like Paul Joskow have criticised as incomplete, as they also include costs related to the electricity grid, such as extending and reinforcing transport and distribution grids, connecting new capacity to the grid, and the additional costs of providing back-up capacity for balancing the grid. NEA calculated these costs for a number of OECD countries with different levels of penetration for each energy source.[68] This report has been criticized for its adequacy and used methodology.[69][70] Swedish KTH in Stockholm published a report in response, finding "several question marks concerning the calculation methods".[71]:5 While the grid-level systems costs in the 2012 OECD-NEA report is calculated to be $17.70 per MWh for 10% onshore wind in Finland, the Swedish Royal Institute of Technology concludes in their analysis, that these costs are rather $0 to $3.70 per MWh (or 79% to 100% less than NEA's calculations), as they are either much smaller or already included in the market.[71]:23–24

Estimated Grid-Level Systems Cost, 2012 (USD/MWh)[68]:8

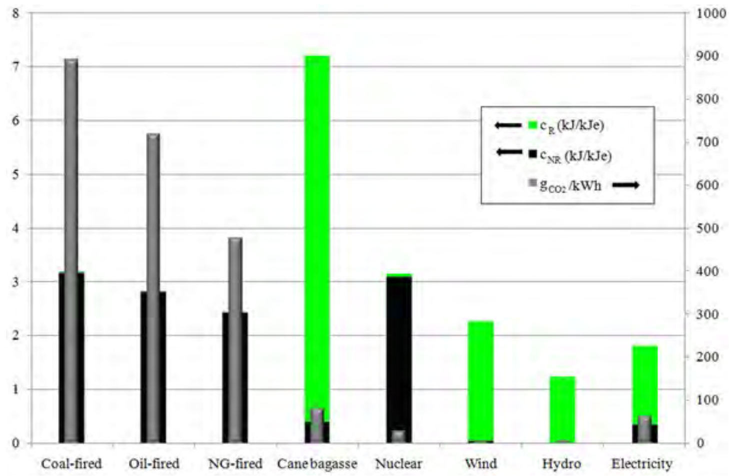
Technology	Nuclear		Coal		Gas		Onshore Wind		Offshore Wind		Solar	
Penetration Level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Backup costs (adequacy)	0.00	0.00	0.04	0.04	0.00	0.00	5.61	6.14	2.10	6.85	0.00	10.45
Balancing costs	0.16	0.10	0.00	0.00	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	10.05
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 Grid-level System Costs	**1.72**	**1.67**	**1.07**	**1.07**	**0.51**	**0.51**	**16.30**	**19.84**	**20.51**	**28.26**	**14.82**	**28.27**

Brookings Institution (2014)

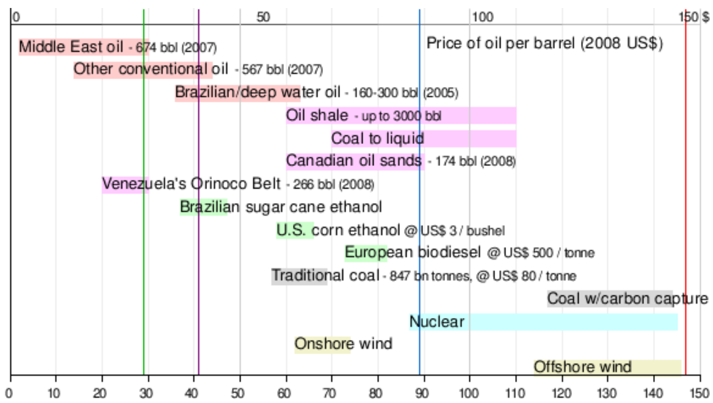
In 2014, the Brookings Institution published *The Net Benefits of Low and No-Carbon Electricity Technologies* which states, after performing an energy and emissions cost analysis, that "The net benefits of new nuclear, hydro, and natural gas combined cycle plants far outweigh the net benefits of new wind or solar plants", with the most cost effective low carbon power technology being determined to be nuclear power.[72][73]

Brazilian electricity mix: the Renewable and Non-renewable Exergetic Cost (2014)

As long as exergy stands for the useful energy required for an economic activity to be accomplished, it is reasonable to evaluate the cost of the energy on the basis of its exergy content. Besides, as exergy can be considered as measure of the departure of the environmental conditions, it also serves as an indicator of environmental impact, taking into account both the efficiency of supply chain (from primary exergy inputs) and the efficiency of the production processes. In this way, exergoeconomy can be used to rationally distribute the exergy costs and CO2 emission cost among the products and by-products of a highly integrated Brazilian electricity mix. Based on the thermoeconomy methodologies, some authors[74] have shown that exergoeconomy provides an opportunity to quantify the renewable and non-renewable specific exergy consumption; to properly allocate the associated CO2 emissions among the streams of a given production route; as well as to determine the overall exergy conversion efficiency of the production processes. Accordingly, the non-renewable unit exergy cost (cNR) [kJ/kJ] is defined as the rate of non-renewable exergy necessary to produce one unit of exergy rate/flow rate of a substance, fuel, electricity, work or heat flow, whereas the Total Unit Exergy Cost (cT) includes the Renewable (cR) and Non-Renewable Unit Exergy Costs. Analogously, the CO2 emission cost (cCO2) [gCO2/kJ] is defined as the rate of CO2 emitted to obtain one unit of exergy rate/flow rate.[74]



Analysis from different sources (2009)



Conventional oil Unconventional oil Biofuels Coal Nuclear Wind

Colored vertical lines indicate various historical oil prices. From left to right:

— 1990s average — January 2009 — 1979 peak — 2008 peak

Price of oil per barrel (bbl) at which energy sources are competitive.

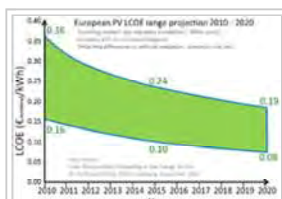
- **Right end of bar** is viability without subsidy.
- **Left end of bar** requires regulation or government subsidies.
- **Wider bars** indicate uncertainty.

Source: *Financial Times* (edit)

Renewables

Photovoltaics

Photovoltaic prices have fallen from $76.67 per watt in 1977 to an estimated $0.30 per watt in 2015, for crystalline silicon solar cells.[76][77] This is seen as evidence supporting Swanson's law, which states that solar cell prices fall 20% for every doubling of cumulative shipments. The famous Moore's law calls for a doubling of transistor count every two years.



European PV LCOE range projection 2010–2020 (in €-cts/kWh)[75]

By 2011, the price of PV modules per MW had fallen by 60% since 2008, according to Bloomberg New Energy Finance estimates, putting solar power for the first time on a competitive footing with the retail price of electricity in some sunny countries; an alternative and consistent price decline figure of 75% from 2007 to 2012 has also been published,[78] though it is unclear whether these figures are specific to the United States or generally global. The levelised cost of electricity (LCOE) from PV is competitive with conventional electricity sources in an expanding list of geographic regions,[6] particularly when the time of generation is included, as electricity is worth more during the day than at night.[79] There has been fierce competition in the supply chain, and further improvements in the levelised cost of energy for solar lie ahead, posing a growing threat to the dominance of fossil fuel generation sources in the next few years.[80] As time progresses, renewable energy technologies generally get cheaper,[81][82] while fossil fuels generally get more expensive:

Price history of silicon PV cells since 1977

> The less solar power costs, the more favorably it compares to conventional power, and the more attractive it becomes to utilities and energy users around the globe. Utility-scale solar power [could in 2011] be delivered in California at prices well below $100/MWh ($0.10/kWh) less than most other peak generators, even those running on low-cost natural gas. Lower solar module costs also stimulate demand from consumer markets where the cost of solar compares very favourably to retail electric rates.[83]

In the year 2015, First Solar agreed to supply solar power at 3.87 cents/kWh levelised price from its 100 MW Playa Solar 2 project which is far cheaper than the electricity sale price from conventional electricity generation plants.[84] From January 2015 through May 2016, records have continued to fall quickly, and solar electricity prices, which have reached levels below 3 cents/kWh, continue to fall.[85] In August 2016, Chile announced a new record low contract price to provide solar power for $29.10 per megawatt-hour (MWh).[86] In September 2016, Abu Dhabi announced a new record breaking bid price, promising to provide solar power for $24.2 per megawatt-hour (MWh) [87]

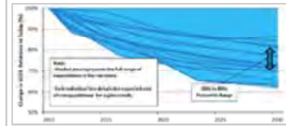
It is now evident that, given a carbon price of $50/ton, which would raise the price of coal-fired power by 5c/kWh, solar PV, Wind, and Nuclear will be cost-competitive in most locations. The declining price of PV has been reflected in rapidly growing installations, totaling about 23 GW in 2011. Although some consolidation is likely in 2012, due to support cuts in the large markets of Germany and Italy, strong growth seems likely to continue for the rest of the decade. Already, by one estimate, total investment in renewables for 2011 exceeded investment in carbon-based electricity generation.[88]

In the case of self consumption, payback time is calculated based on how much electricity is not brought from the grid. Additionally, using PV solar power to charge DC batteries, as used in Plug-in Hybrid Electric Vehicles and Electric Vehicles, leads to greater efficiencies, but higher costs. Traditionally, DC generated electricity from solar PV must be converted to AC for buildings, at an average 10% loss during the conversion. Inverter technology is rapidly improving and current equipment has reached 99% efficiency for small scale residential,[89] while commercial scale three-phase equipment can reach well above 98% efficiency. However, an additional efficiency loss occurs in the transition back to DC for battery driven devices and vehicles, and using various interest rates and energy price changes were calculated to find present values that range from $2,057.13 to $8,213.64 (analysis from 2009).[90]

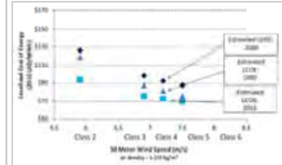
It is also possible to combine solar PV with other technologies to make hybrid systems, which enable more stand alone systems. The calculation of LCOEs becomes more complex, but can be done by aggregating the costs and the energy produced by each component. As for example, PV and cogen and batteries [91] while reducing energy- and electricity-related greenhouse gas emissions as compared to conventional sources.[92]

Wind power

In 2004, wind energy cost a fifth of what it did in the 1980s, and some expected that downward trend to continue as larger multi-megawatt turbines were mass-produced.[94] As of 2012 capital costs for wind turbines are substantially lower than 2008–2010 but are still above 2002 levels.[95] A 2011 report from the American Wind Energy Association stated, "Wind's costs have dropped over the past two years, in the range of 5 to 6 cents per kilowatt-hour recently.... about 2 cents cheaper than coal-fired electricity, and more projects were financed through debt arrangements than tax equity structures last year.... winning more mainstream acceptance from Wall Street's banks.... Equipment makers can also deliver products in the same year that they are ordered instead of waiting up to three years as was the case in previous cycles.... 5,600 MW of new installed capacity is under construction in the United States, more than double the number at this point in 2010. 35% of all new power generation built in the United States since 2005 has come from wind, more than new gas and coal plants combined, as power providers are increasingly enticed to wind as a convenient hedge against unpredictable commodity price moves."[96]



NREL projection: the LCOE of U.S. wind power will decline by 25% from 2012 to 2030.[93]



Estimated cost per MWh for wind power in Denmark as of 2012

This cost has additionally reduced as wind turbine technology has improved. There are now longer and lighter wind turbine blades, improvements in turbine performance and increased power generation efficiency. Also, wind project capital and maintenance costs have continued to decline.[97] For example, the wind industry in the USA in 2014 was able to produce more power at lower cost by using taller wind turbines with longer blades, capturing the faster winds at higher elevations. This has opened up new opportunities in Indiana, Michigan, and Ohio. The price of power from wind turbines built 300 to 400 ft (91 to 122 m) above the ground can now compete with conventional fossil fuels like coal. Prices have fallen to about 4 cents per kilowatt-hour in some cases and utilities have been increasing the amount of wind energy in their portfolio, saying it is their cheapest option.[98]

In 2016 the Norwegian Wind Energy Association (NORWEA) estimated the LCoE of a typical Norwegian wind farm at 44 €/MWh, assuming a weighted average cost of capital of 8% and an annual 3,500 full load hours, i.e. a capacity factor of 40%. NORWEA went on to estimate the LCoE of the 1 GW Fosen Vind onshore wind farm which is expected to be operational by 2020 to be as low as 35 €/MWh to 40 €/MWh.[99] In November 2016, Vattenfall won a tender to develop the Kriegers Flak windpark in the Baltic Sea for 49,9 €/MWh.[100] As of 2016, this is the lowest price for wind energy.

See also

- Electricity pricing
- Comparisons of life-cycle greenhouse gas emissions
- Distributed generation
- Economics of new nuclear power plants
- Demand response
- Intermittent energy source
- National Grid Reserve Service
- Nuclear power in France
- List of thermal power station failures
- Calculating the cost of the UK Transmission network: Estimating cost per kWh of transmission
- List of countries by electricity production from renewable sources
- List of U.S. states by electricity production from renewable sources
- Environmental concerns with electricity generation
- Grid parity

Further reading

- Economic Value of U.S. Fossil Fuel Electricity Health Impacts (http://www.ncbi.nlm.nih.gov/pubmed/23246069). United States Environmental Protection Agency.
- The Hidden Costs of Electricity: Comparing the Hidden Costs of Power Generation Fuels (http://www.civilsocietyinstitute.org/media/pdfs/091912%20Hidden%20Costs%20of%20Electricity%20report%20FINAL2.pdf). Civil Society Institute (http://www.civilsocietyinstitute.org/).

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