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The End of Big Iron: How Wind and Solar Became Cheaper than Hydro, Coal, and Nuclear

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Since the electrification of North America commenced at the start of the last century, the industry has focused on "big iron." Larger projects offered efficiency in location and economies of scale. The end of this era is rapidly approaching as smaller, more maneuverable, and less expensive options take the center stage in electric utility planning. Until recently the competition between renewables and traditional thermal generation was easy. Renewables were expensive and traditional thermal was cost-effective with serious negative externalities.

That traditional trade-off makes less sense today as the Levelized Cost of Energy (LCOE) from wind and solar generation has now dropped below the LCOE of hydro and most thermal energy resources. Moving forward, wind and solar investments offer electric utilities the benefits of clean production at lower prices than existing choices. For aging nuclear and coal units, renewables actually cost less than operating costs.[1] Wind and solar's weaknesses are their intermittency, but they can be backed up by cheap natural gas peaker plants, and perhaps someday soon, batteries. Overall, in spite of claims by the owners of older fossil fuel units, the nation's capacity surplus is enormous.

History

The history of the electric industry often revolves around the conflict between J.P. Morgan and Samuel Insull to build North America's electric and gas infrastructure. The cost of early central stations was high – phenomenally high by our standards. The costs were so high that the utility franchise model was adopted across the U.S. and Canada. Under this

[1] Generating facilities have fixed costs – capital costs – and operating costs – fuel and O&M. The total cost of a new renewable plant is gradually falling below the cost of fuel and O&M for older thermal power plants.

structure, utilities were able to finance expensive central stations based on their monopoly rights in urban areas.

The system worked well – so well that the U.S. and Canada achieved a world leading adoption of electricity and natural gas. In the 1930s, the holding companies based on the franchise model were overextended. The restructuring of the industry that followed their collapse also brought about today's regulatory agencies – the SEC, FERC, and the CFTC, among others.

The basic investment problem was solved and fortified by a regulatory process that prevented the flagrant abuses of its early years. Much of it remains in place today.

Technological advances and economies of scale drove down the price of coal and natural gas fueled plants until recently.[2] Nuclear units showed a dramatic reduction in costs over time until the 1980s when safety concerns added considerably to their costs.

In the 1980s, a technological shift to natural-gas-based generation reduced costs significantly. In 1991, the west coast of the U.S. and Canada adopted open wholesale markets that enabled economies beyond the traditional franchise area.

[2] While technology has continued to improve, environmental concerns have added to the cost of thermal units over time, leading to a parabola effect on their costs.

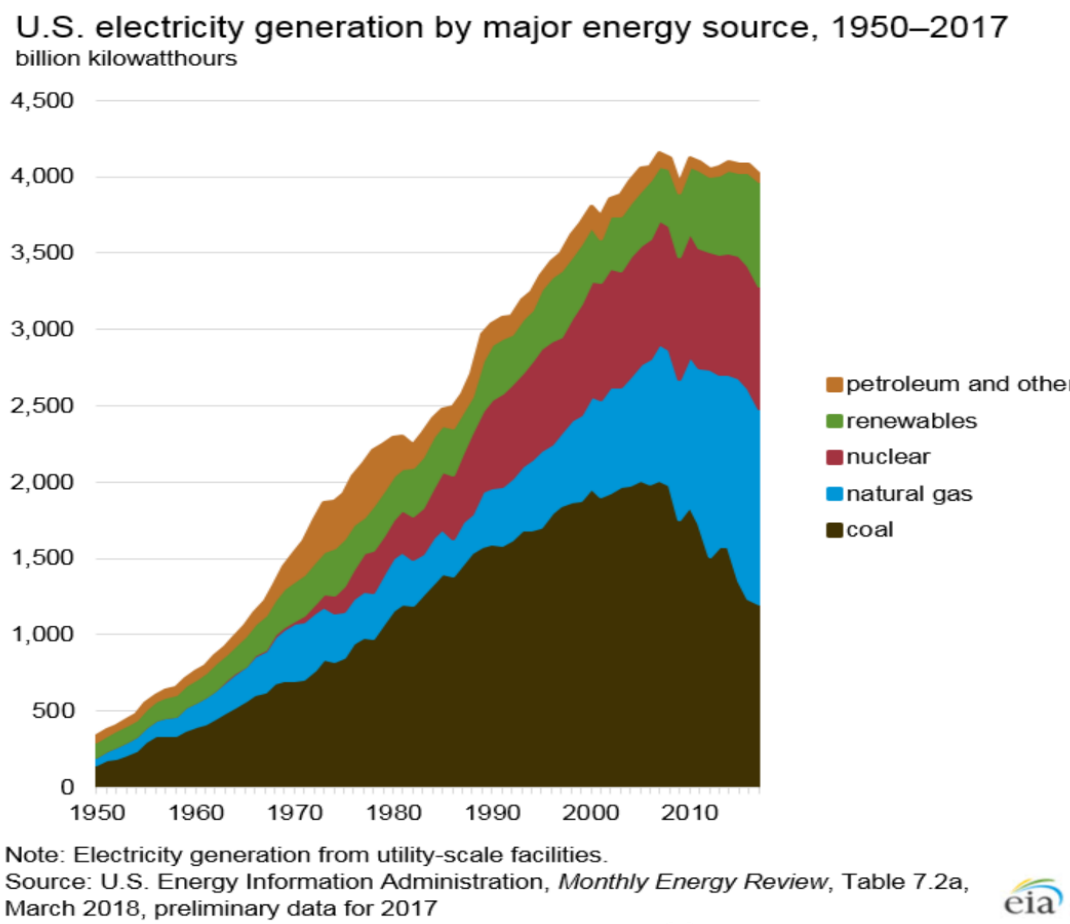


Figure 1:U.S. Electricity Generation by Source

The emerging cost advantages of renewables are changing the playing field yet again. As natural gas has gradually replaced coal and nuclear generation, wind and solar are exploiting their cost advantage – as well as a number of other advantages – over traditional thermal units.

Renewables can include a number of sources including hydroelectricity, solar, wind, geothermal, and biomass. As the price of solar and wind has plummeted, these sources are dominating new renewable generation:

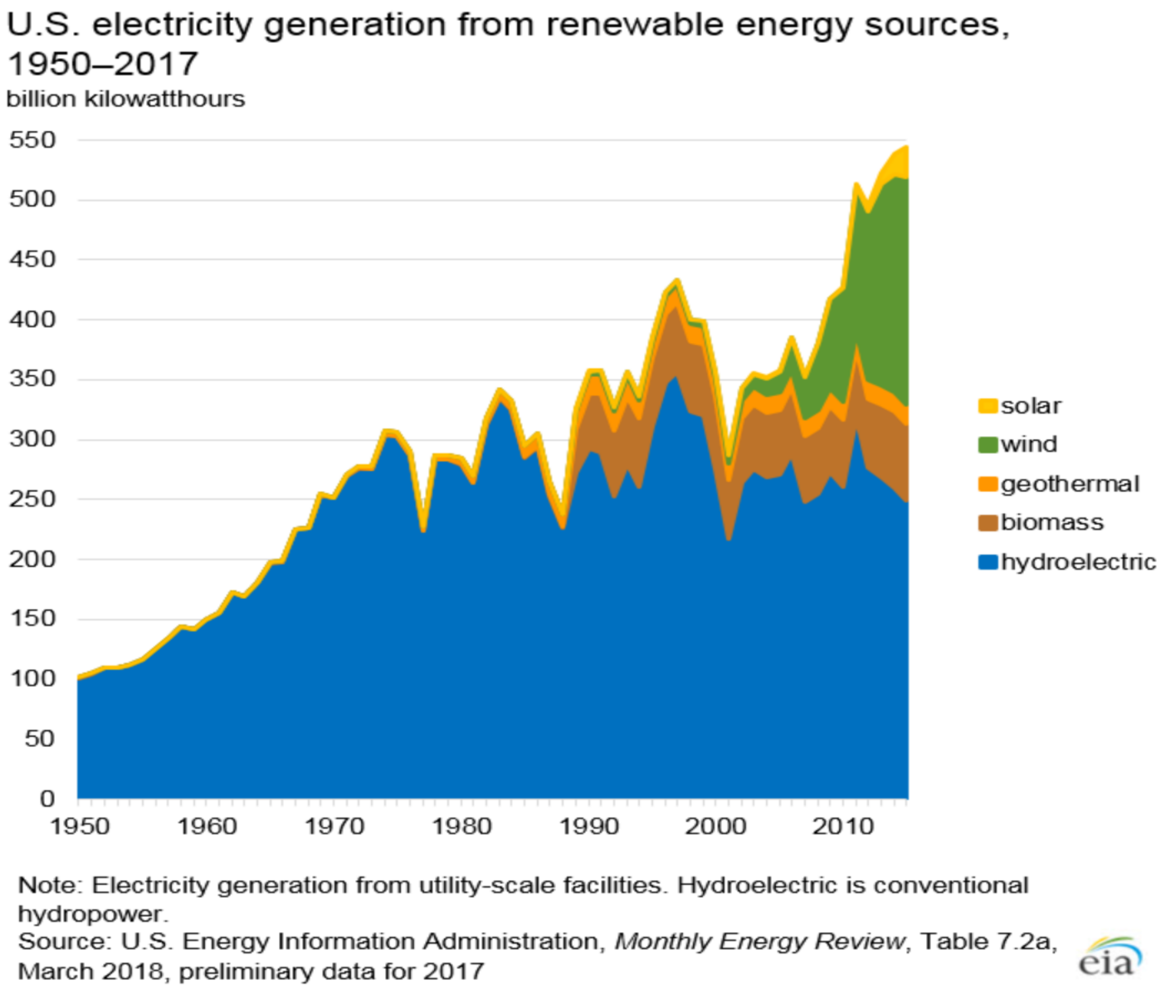


Figure 2: U.S. Electricity Generation from Renewables

A variety of data sources exist that allow the evaluation of the cost of different generation options over the past one hundred years. One of these, the Federal Energy Regulatory Commission's Form 1 contains the capital cost and data in service for every investor-owned unit.[3] This was one of the many regulatory innovations that followed the collapse of the Insull utility holding company during the 1930s. The majority of power plants in the United States are owned by investor owned utilities.

[3] FERC Form 1s are available in scanned image format at <https://elibrary.ferc.gov/>. In recent years FERC has also released the Form 1 data in database format at <https://www.ferc.gov/docs-filing/forms/form-1/data.asp>.

The following chart summarizes the thousands of plants and their per kilowatt capital costs using second degree polynomial curves.[4]

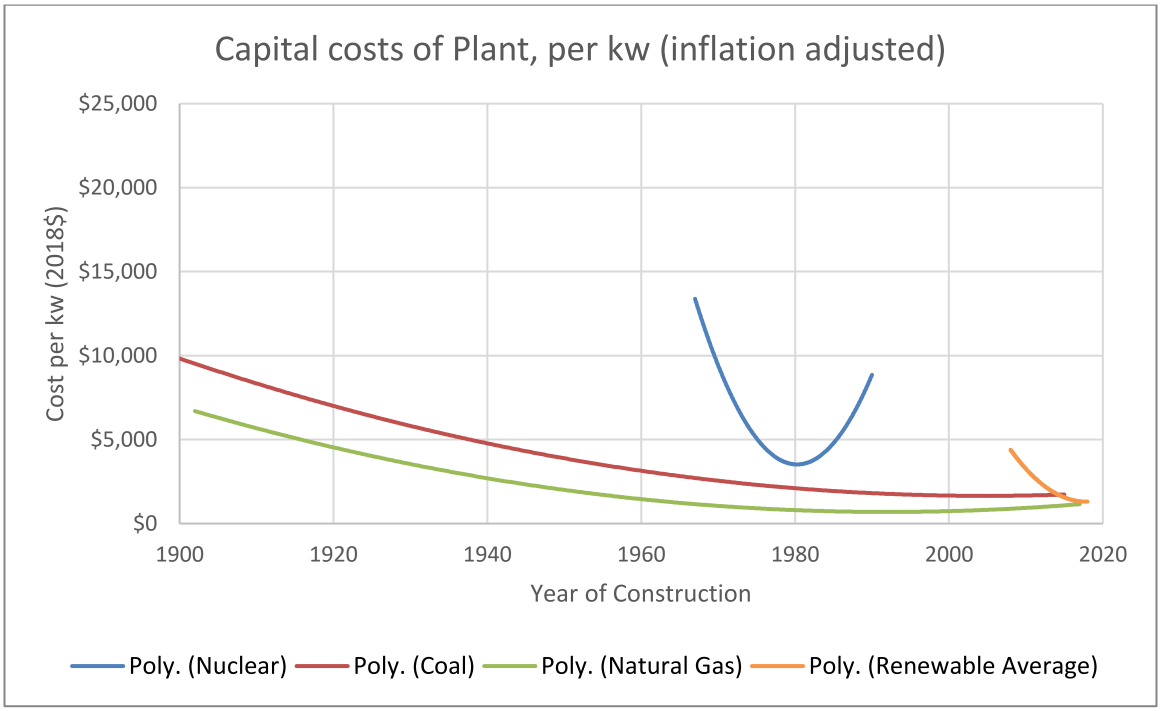


Figure 3: FERC Form 1 and Lazard capital cost data[5]

The green line shows the rapidly declining capital cost of wind and solar over the past decade.[6] The chart is unnecessarily unfair to renewables since it does not include the cost of fuel, but the recent convergence of capital costs is worth observing. When all costs are taken into consideration, the situation indicates that most traditional generating stations are no longer competitive. Moreover, recent studies indicate that thermal station operating cost competitiveness is falling behind the LCOE of renewables.[7]

[4] The second-degree polynomial fits the data well. However, it is an overly simplistic approach when attempting to capture technology, economies of scale, environmental costs, and nuclear safety costs. In addition, although FERC accounting rules apply to all U.S. utilities, our review indicated that many of the FERC Form 1s used inconsistent reporting standards.
[5] Lazard's Levelized Cost of Energy Analysis, Versions 1-12; FERC Form 1 Databases for years 1994, 2000, 2010, 2017; and EIA Form 412, Schedule 9, 2002.
[6] Lazard's Levelized Cost of Energy Analysis, Versions 1-12, 2008-2018.
[7] Lazard's Levelized Cost of Energy Analysis, Version 12, November 2018.

Levelized Cost of Energy

The LCOE measures the overall competitiveness of different generating technologies to compare the per-megawatt-hour cost of building and operating a plant over its assumed financial life. Onshore wind now has a lower LCOE than even hydro. Solar has become on par with hydro, and their momentum for decline continues. The U.S. Energy Information Administration predicts that for new projects entering service in 2040, solar power will be significantly cheaper than hydro as shown in Figure 4.

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmission cost	Total system LCOE	Levelized tax credit[2]	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS[3]	NB	NB	NB	NB	NB	NB	NA	NB
Coal with 90% CCS[3]	NB	NB	NB	NB	NB	NB	NA	NB
Conventional CC	87	13.0	1.5	32.8	1.0	48.3	NA	48.3
Advanced CC	87	15.5	1.3	30.3	1.1	48.1	NA	48.1
Advanced CC with CCS	NB	NB	NB	NB	NB	NB	NA	NB
Conventional CT	NB	NB	NB	NB	NB	NB	NA	NB
Advanced CT	30	22.7	2.6	51.3	2.9	79.5	NA	79.5
Advanced nuclear	90	67.0	12.9	9.3	0.9	90.1	NA	90.1
Geothermal	91	28.3	13.5	0.0	1.3	43.1	-2.8	40.3
Biomass	83	40.3	15.4	45.0	1.5	102.2	NA	102.2
Non-dispatchable technologies								
Wind, onshore	43	33.0	12.7	0.0	2.4	48.0	-11.1	37.0
Wind, offshore	45	102.6	20.0	0.0	2.0	124.6	-18.5	106.2
Solar PV[4]	33	48.2	7.5	0.0	3.3	59.1	-12.5	46.5
Solar thermal	NB	NB	NB	NB	NB	NB	NB	NB
Hydroelectric[5]	65	56.7	14.0	1.3	1.8	73.9	NA	73.9

[1]The capacity-weighted average is the average levelized cost per technology, weighted by the new capacity coming online in each region. The capacity additions for each region are based on additions in 2020–2022. Technologies for which capacity additions are not expected do not have a capacity-weighted average and are marked as *NB* or not built.

[2]The tax credit component is based on targeted federal tax credits such as the PTC or ITC available for some technologies. It reflects tax credits available only for plants entering service in 2022 and the substantial phase out of both the PTC and ITC as scheduled under current law. Technologies not eligible for PTC or ITC are indicated as *NA* or not available. The results are based on a regional model, and state or local incentives are not included in LCOE calculations. See text box on page 2 for details on how the tax credits are represented in the model.

[3]Because Section 111(b) of the Clean Air Act requires conventional coal plants to be built with CCS to meet specific CO2 emission standards, two levels of CCS removal are modeled: 30%, which meets the NSPS, and 90%, which exceeds the NSPS but may be seen as a build option in some scenarios. The coal plant with 30% CCS is assumed to incur a 3 percentage-point increase to its cost of capital to represent the risk associated with higher emissions.

[4]Costs are expressed in terms of net AC power available to the grid for the installed capacity.

[5]As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.

CCS=carbon capture and sequestration. CC=combined-cycle (natural gas). CT=combustion turbine. PV=photovoltaic.

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2018*.

Figure 4: Capacity-weighted average LCOE for new generation resources in 2022 (2017 $/MWh) [8]

[8] Lazard. Levelized Cost of Energy Analysis, Version 12, November 2018.

These latest Energy Information Administration numbers are significant because their LCOE estimates of wind and solar power have been conservative compared to investment advisory services like Lazard's annual LCOE estimates, which come out every November. Last November Lazard found solar LCOEs under $46 per MWh.[9]

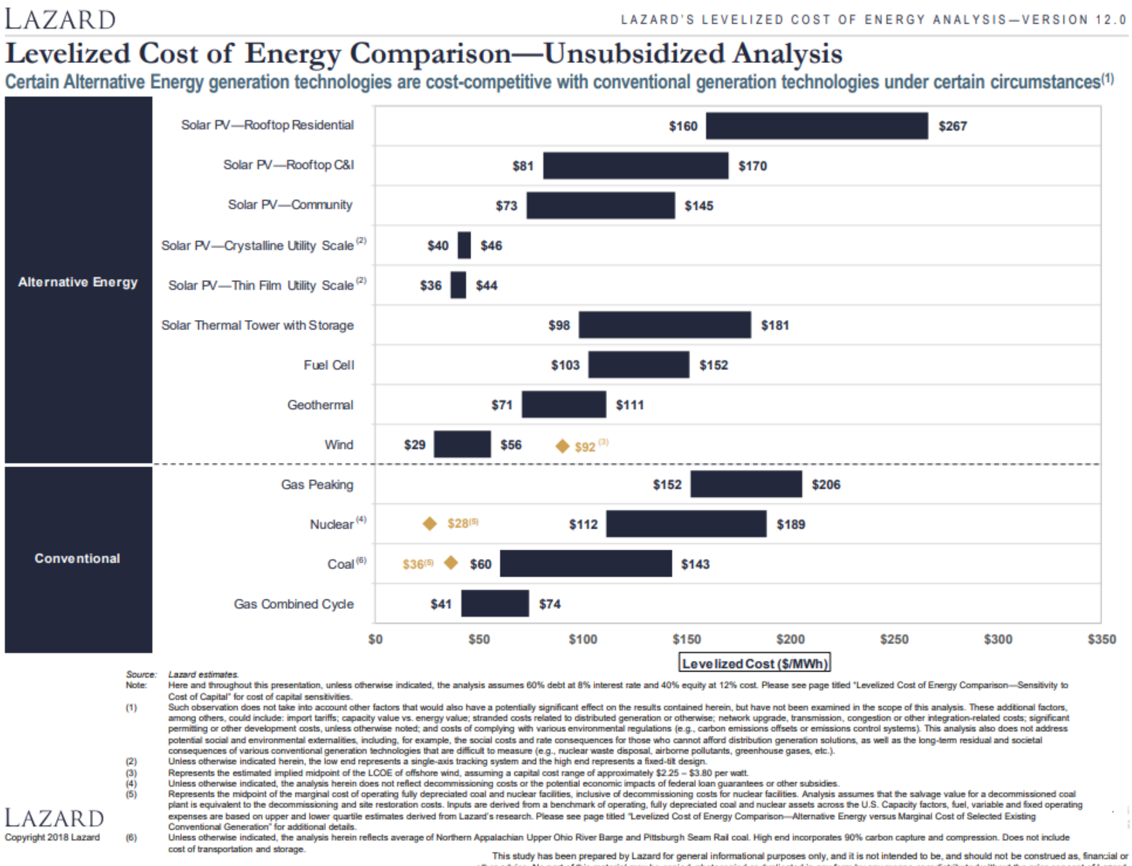


Figure 5 Lazard LCOE estimates 2018[10]

Interestingly, even Lazard's estimates have been overtaken by the market. Xcel Energy conducted an RFP (Request for Proposals) for their operations in Colorado last year. The bids they received rocked the industry:

[9] Lazard. *Lazard's Levelized Cost of Energy Analysis* November 2018, page 2.
[10] *Ibid.*

RFP Responses by Technology

Generation Technology	# of Bids	Bid MW	# of Projects	Project MW	Median Bid Price or Equivalent	Pricing Units
Combustion Turbine/IC Engines	30	7,141	13	2,466	$ 4.80	$/kW-mo
Combustion Turbine with Battery Storage	7	804	3	476	6.20	$/kW-mo
Gas-Fired Combined Cycles	2	451	2	451	6.70	$/kW-mo
Stand-alone Battery Storage	28	2,143	21	1,614	11.30	$/kW-mo
Compressed Air Energy Storage	1	317	1	317	14.60	$/kW-mo
Wind	96	42,278	42	17,380	$ 18.10	$/MWh
Wind and Solar	5	2,612	4	2,162	19.90	$/MWh
Wind with Battery Storage	11	5,700	8	5,097	21.00	$/MWh
Solar (PV)	152	29,710	75	13,435	29.50	$/MWh
Wind and Solar and Battery Storage	7	4,048	7	4,048	30.60	$/MWh
Solar (PV) with Battery Storage	87	16,725	59	10,813	36.00	$/MWh
IC Engine with Solar	1	5	1	5	50.00	$/MWh
Waste Heat	2	21	1	11	55.40	$/MWh
Biomass	1	9	1	9	387.50	$/MWh
Total	430	111,963	238	58,283		

Figure 6: Xcel 2017 All Source Solicitation 30-Day Report[11]

Overall, Xcel received over 52,000 MW of renewables with a weighted average price of $20.1/MWh. Unlike the forecasts from the U.S. Energy Information Administration and Lazard's, these are actual market prices.

While administered markets in U.S. eastern states routinely report prices significantly higher than the more competitive markets in the west, few industry participants have proposed eliminating the cumbersome administered market structures of MISO, PJM, NYISO, and their companions. They often claim that western markets simply respect past investment in hydroelectricity. This is ironic since the marginal resources on both sides of the continental divide is fueled by natural gas. A more realistic explanation for the west's relatively lower wholesale prices is the existence of larger, more mature, and more competitive wholesale markets.[12]

The industrial advantage of wind and solar

[11] Xcel Energy. *2016 Electric Resource Plan: 2017 All Source Solicitation 30-Day Report* December 28, 2017, page 9.

[12] Wholesale market in the west date to the early 1980s. FERC approval of wholesale pricing took place in 1987. The last major hydroelectric price in the west dates from 1971. Since that date, resources have been primarily natural gas fueled.

We are used to thinking of alternative energy as a high-cost source primarily because of its novelty. The cost of wind and solar power generation have come way down in the same way most new technologies eventually enjoy economy of scale benefits and the diffusion of knowledge. Pocket calculators were once an expensive luxury; now they are just another free app on our phones.

Because wind and solar components are built in factories, the slope of their long-run price decline will remain steeper than other energy generating technologies that have to be custom built on location. Like the building of homes, there is some element of standardization in building power plants, but ultimately each project will be somewhat unique.

Utility-scale wind and solar are different. The bulk of the capital expenditure is on manufactured goods that do not need to be built on site. Thus, wind and solar are to traditional generating stations what manufactured homes are to custom-built homes. By cutting out the intensive need for itinerant construction labor at the site, wind and solar will continue to enjoy cost savings that traditional generation choices may not.

Wind and solar also possess another significant industrial advantage over hydropower: Just in Time (JIT) delivery. This transformative concept, pioneered in the 1950s by the Toyota industrial engineer Taiichi Ohno, is a foundational principle of what we today call Lean Production. JIT reduces input inventories to the minimum necessary to meet real time production needs. This reduces lead times in production, saves capital costs, and reduces waste.

So, in a Toyota plant, they would only want a hood when the assembly line needed a hood. Before the widespread adoption of Lean Production processes, a stamping plant would try to produce as many hoods as possible to reduce unit costs. These components would then be shipped all at once to the final assembly plant and stored. As vehicles were built, the assembly plant would tap into its large inventory of hoods. At some point, as the hoods' supply reached some minimal level, the stamping plant would then get another mass order.

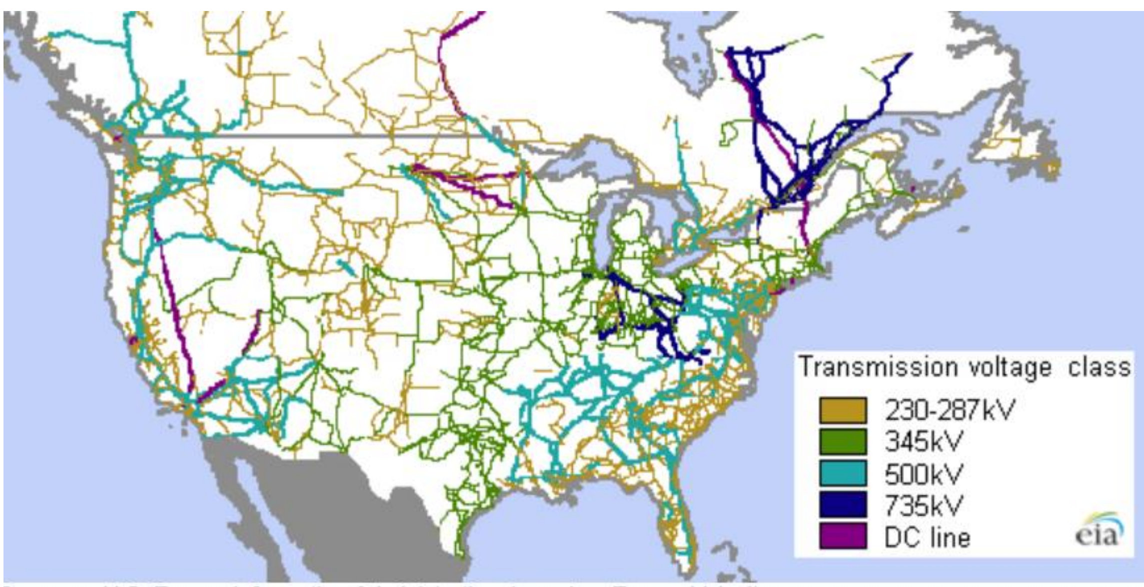
Ohno figured out that the costs associated with the capital expenditures, storage, and waste from making so many hoods in advance were higher than the savings from lower unit costs from manufacturing the components all at once. Instead, he accepted higher unit costs by supplying his assembly plants with hoods only as they were needed. There was thus no need to stockpile steel at the stamping plant and no need to stockpile hoods at the assembly plant. This reduced the cash needed for operations, and whenever the design of a vehicle model was changed, there was no longer a pile of unusable hoods.

The principle of JIT could also be applied to electric utilities' resource development. Wind and solar capacity can be delivered as needed, but major thermal and hydroelectric projects have to be built long before the load demand exists. We see this problem with B.C. Hydro's development of the Site C dam. British Columbia does not need 1,100 MW of new installed capacity, but it may need more capacity decades from now. Their plan is to build the dam and export the excess capacity to the United States until their own province eventually needs this energy. To get the project approved, B.C. Hydro has had to both overestimate its customers' future demand and overestimate the wholesale prices they will get selling this power in the Mid-Columbia market. The losses that will follow will have to be absorbed by either ratepayers or the government of British Columbia.

The JIT approach would be to only build capacity as it's needed. Since traditional plants cannot be partially built over time. You either have no generation, or you have a generation producing energy substantially in advance of need. Wind and solar farms, in contrast, can be built small and expanded as actually needed by consumers. By delaying the procurement of capacity until it's needed, the electric utility will lower its financing costs, lower its depreciation costs, and the JIT procurement of wind and solar will avoid the losses incurred from overestimated load growth.

Transmission

The U.S. and Canada operate three grids – the east and midwest, Texas, and the west. As the map below illustrated the major transmission lines have tended to be oriented north to south. This reflects seasonal diversity between northern loads and southern loads. Traditionally system in the north are winter peaking since their consumers need energy for heating.



Sources: U.S. Energy Information Administration, based on Energy Velocity.

Figure 7: Major U.S. and Canadian Transmission Lines

Southern systems tend to have summer peaks since a major energy use is for cooling. The massive transmission projects from the Canadian Rockies all the way to Los Angeles reflects this seasonal diversity. The north to south transmission also serves hydroelectric projects since the spring thaw releases a major portion of the flows to hydroelectric projects. Northern systems reduce their needs during this period while southern systems are just beginning to experience warm weather.

Solar and wind generation turns this picture by ninety degrees. Both solar and wind have diurnal diversity. Wind tends to peak just before dawn. Solar, of course, peaks during peak hours. The transmission system should reflect the diurnal benefits of renewables east to west. This will have a major impact on portfolio effects of renewables discussed below.

Capacity

A frequent challenge to the growth of renewables is that the generation is intermittent. Both wind and solar are highly intermittent – with generation averaging approximately 30% of nameplate rating.[13] Hydroelectric projects are also intermittent, although usually less than solar and wind. Even major thermal projects have a degree of intermittency with availability rates as low as 80%.[14]

The industry's solution to the need for high degrees of reliability based on only partially reliable resources has been to assemble portfolios of resources. The presence of inefficient capacity markets – especially in the eastern administered market sates has driven the U.S. and Canadian capacity margin – the margin above the nameplate capacity of individual resources to higher and higher levels. The American and Canadian average in the most recent North American Reliability Corporation report has increased the capacity margin to 23.6% -- almost twice the level required in traditional utility requirements.[15] Certain sub regions, PJM, for example, are expected to reach a reserve margin of 34.53% by 2023.[16]

The concern over intermittency is real, but currently of secondary importance given the very high reserve margins currently in place in the U.S. and Canada. In the long term, there are three very viable solutions available: portfolio strategies, batteries, and simple cycle natural gas turbines.

Portfolio Strategies

Traditionally renewables were so expensive that only the very best sites were suitable for development. The following chart shows the cluster of wind resources surround the Tri-Cities area of southeastern Washington:

Figure 8: Oregon and Washington Wind Projects[17]

As mentioned above, this is a very inefficient portfolio. Any competent investment advisor would recommend diversifying the renewable resource by either adding resources further

[13] The actual plate affixed to an electric generator contains its "name-plate" rating. This is generally regarded as the capacity of a thermal power plant. A wind farm might have a very high name-plate capacity, but capacity factors for wind farms are generally lower than those of traditional generators.
[14] See, for example, https://www.nerc.com/pa/RAPA/gads/Pages/Reports.aspx
[15] 2018 Long-Term Reliability Assessment, North American Electric Reliability Corporation, December 2018, page 56.
[16] *Ibid*., page 56.
[17] https://renewablenw.org/project_map?field_project_state_value%5B%5D=OR&field_project_state_value%5B%5D=WA&tid%5B%5D=7

to the east – thus realizing the diurnal diversity of earlier daybreak or seeking renewables with a negative correlation to the resources in the Tri-Cities area.

As the price of renewables falls, the freedom to diversify the renewable portfolio has expanded significantly. Sites with less average generation that were not cost effective at high prices are now available for development to create a more balanced portfolio.

Batteries

One of the surprises in the responses to the Xcel RFP discussed above was the number of proposals that came with battery to provide more stable generation. Xcel received 13,435 MW of wind proposals with batteries – enough to supply the energy needs of three large cities. The key to the battery solution is economics. Lazard has recently introduced a series of annual studies on the levelized cost of storage as a companion to the resource cost analyses mentioned above. Last fall's report showed the steep decline in costs continues apace.[18]

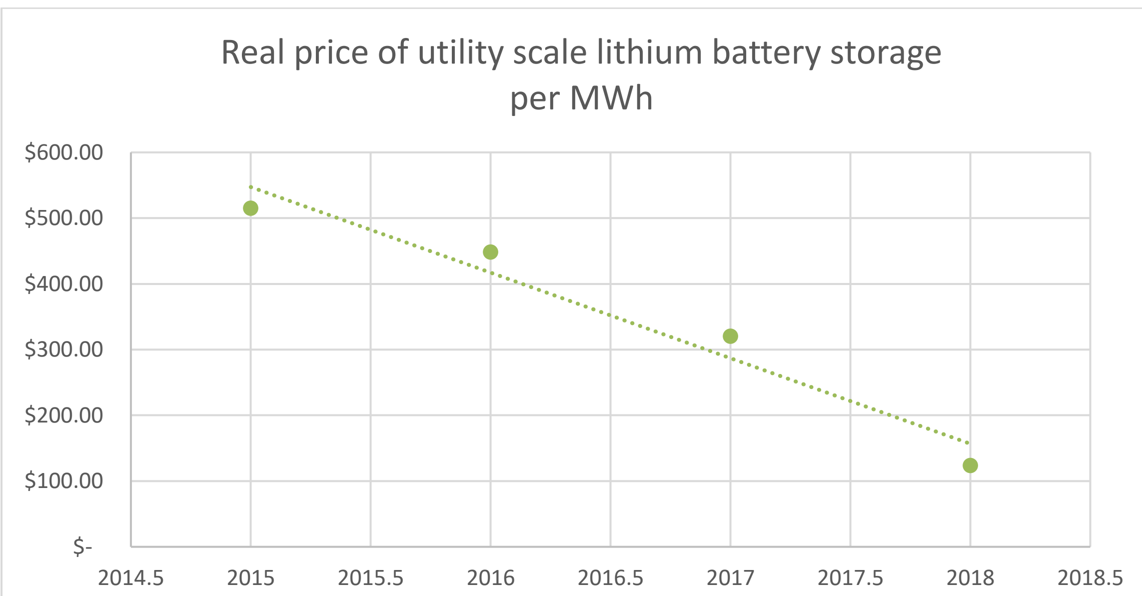


Figure 9: Levelized Cost of Storage research from Lazard

As with wind and solar, there is evidence that technology has outpaced Lazard's calculations. Hawaiian Electric released the results of their solar plus battery storage RFP this week:

[18] Lazard. *Levelized Cost of Storage Analysis* version 4, November 2018, page 10.

Project name	Island	Developer	Size	Storage	Total Cost	Implicit Storage Cost
			(MW)	(MWh)	($/MWh)	($/MWh)
Waikoloa Solar	Hawaiʻi	AES	30	120	$80.00	$100.00
Hale Kuawehi	Hawaiʻi	Innergex	30	120	$90.00	$116.67
Kuihelani Solar	Maui	AES	60	240	$80.00	$100.00
Paeahu Solar	Maui	Innergex	15	60	$120.00	$166.67
Hoohana	Oʻahu	174 Power Global	52	208	$100.00	$133.33
Mililani I Solar	Oʻahu	Clearway	39	156	$90.00	$116.67
Waiawa Solar	Oʻahu	Clearway	36	144	$100.00	$133.33
Lazard Estimate						$124.00

Figure 10: Hawaiian Electric Solar RFP[19]

Four of the seven winning bids at Hawaiian Electric were less than Lazard's most recent storage estimates.

Batteries are now being introduced into utility systems across the United States. The cost trajectory is encouraging enough to expect a greatly increased use in the near future.

Simple Cycle Gas Turbines

The most cost-effective option right now remains simply cycle turbines. They are relatively inexpensive, can be installed quickly, and will be used to operate only when the collective renewables portfolio is unable to meet the minimum operating level. Their role will be comparable to local backup generators – available for need, but dispatched rarely.

Conclusion

There was a day when coal and hydropower offered some of the lowest levelized costs of energy. Those days are over. Research from both Lazard and the Energy Information Administration shows wind and solar have become just as cheap, and in the case of land-based wind, cheaper than hydro. Xcel's recent RFP confirms their estimates.

The end of big iron has come.

[19] California Energy Markets, January 11, 2019, page 2.