Renewable vs. Traditional Power Generation: The State of the Race

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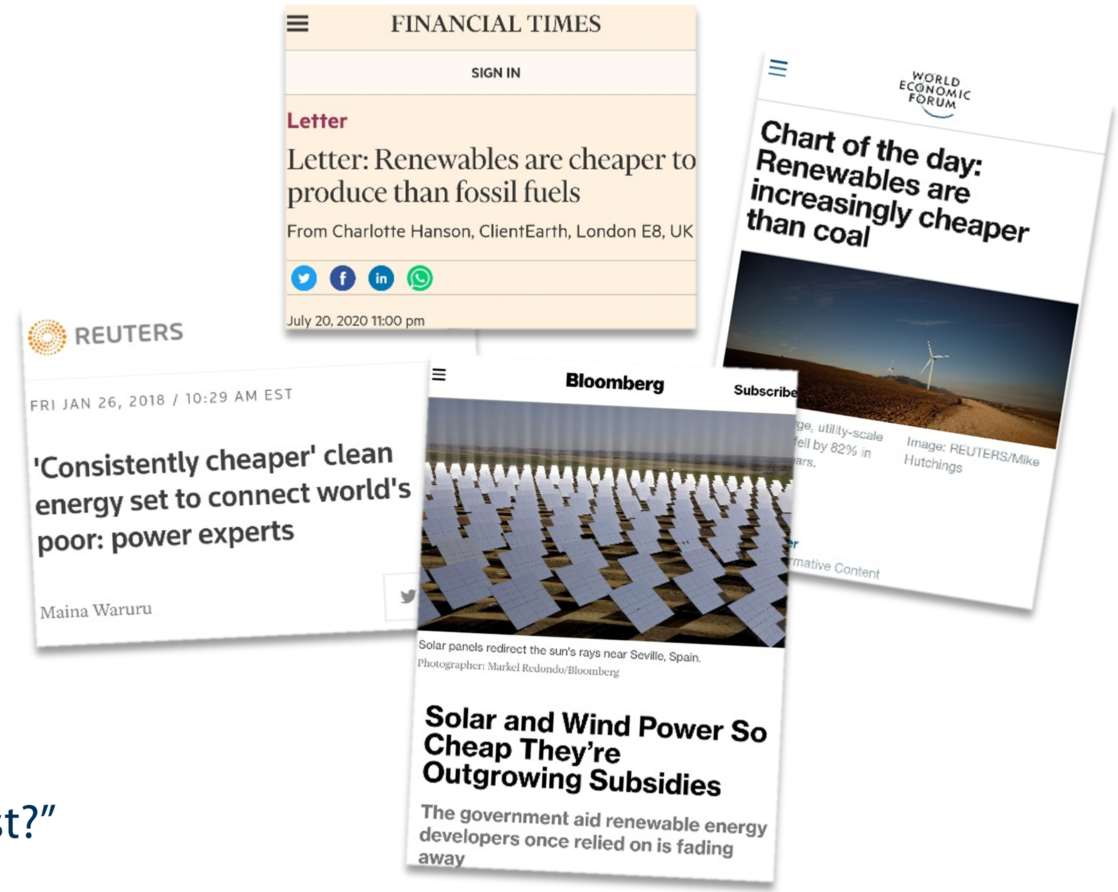
Common Observations

- “Wind and solar power are now the cheapest source of energy,”
- “…but they don’t always produce power when we need it,”
- “…and when they produce, they all produce at the same time!”



Immediate Questions

- “What use has it that wind and solar power are now the cheapest?”
- “Won’t we still need traditional energy sources even if they are more expensive?”

"Cost Competitiveness" of Alternative Energy Technologies

The Common Measure: a life-cycle cost figure that gives the break-even price per unit of output

"... the levelized cost of electricity (LCOE) is the constant dollar electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors." [1]

Conceptual Criticism: the LCOE metric is insufficient to measure cost competitiveness, as it ignores

- the **timing of production** and the corresponding level of electricity prices[2]
- **system cost** incurred for meeting electricity demand at any point in time

Empirical Debate: economics are **changing rapidly over time** and, in that, differently across jurisdictions

- Intermittent renewable energy sources: costs (↓↓)[3], but subsidies also (↓), and cannibalization (↑?)[4]
- Traditional power generators: costs (↑↓?), utilization (↑↓?), and volatility of power prices (↑)[5]

Selection of recent publications
[1] MIT (2007), Reichelstein/Bastian-Rohlfing (*TAR*, 2015), [2] Joskow (*AER*, 2011), Borenstein (*NBER*, 2008), Gautam et al. (*JPE*, 2016), Hirth (2013, *Energy Economics*)
[3] Wiser et al. (*Nature Energy*, 2016), Reichelstein/Sahoo (*CAR*, 2017), [4] Prol et al. (*Energy Economics*, 2020), Zhou et al. (*Mgmt Science*, 2015)
[5] Harrison/Kaffine (*AEJ*, 2018), Olauson et al. (*Nature Energy*, 2016), Kök et al. (*MSOM*, 2020)

Scope of this Talk

Central Questions

- Under what condition is a power generation facility "**cost competitive**"?
- How have recent **market dynamics** affected the cost competitiveness?

Analysis in this Study (joint work with S. Reichelstein)

- Necessary and sufficient conditions for the **cost competitiveness** of a generic power generation facility
- Application to **natural gas turbines, solar PV and wind energy** in California and Texas
- Numerical measurements for rapidly changing economics over the past decade

Model Framework: Unit Economics

Market Environment

- Suppliers are price-takers in a market for electricity where prices are set hourly by supply and demand
- Generation capacity is constraint in the short-run but can be idled if market price falls below marginal cost
- Market includes alternative generation technologies that differ in terms of (i) their cost structure and (ii) their capability of providing power at certain hours of the years
- A technology is 'cost competitive' if the investment in 1 additional kW of capacity achieves a non-negative net present value, provided the facility is operated so as to maximize subsequent contribution margins

Levelized Cost of Electricity (LCOE)

- LCOE identifies the constant revenue per kWh of power generation required over lifetime to break-even
- Metric aggregates a share of upfront capacity investment with periodic cash outflows after taxes
- Central variable is the anticipated capacity utilization, i.e., number of hours of power generation

Optimized Real-time Capacity Utilization

Time-variant contribution margin

- $p_i(t)$: time-variant selling price per kWh of electricity at time t in year i
- PTC_i: production tax credit, federal after-tax subsidy for wind power in the U.S.
- w_i: variable operating cost per kWh of power generation of a generation facility in year i

Capacity utilization is freely chosen at each point in time

- $CF_i(t) \in [0, b(t)]$: share of capacity utilization at time t in year i, with b(t) as exogenous upper bound
- for intermittent renewable source: b(t) is determined by the availability of local natural resources
- for dispatchable generation: b(t) = 1 for all t

The optimized capacity factor of a power generation facility at time t in year i is chosen to maximize:

$$[p_i(t) + PTC_i - w_i] \cdot CF_i(t), \quad \text{subject to } CF_i(t) \in [0, b(t)]$$

Thus, $CF_i^*(t) = b(t)$ if $p_i(t) + PTC_i \geq w_i$, while $CF_i^*(t) = 0$ otherwise.

Co-Variation between Power Generation and Prices

Co-variation coefficient that captures any synergies between time-variant power generation and prices:

$$\mathbf{\Gamma_i^* = \frac{1}{8760}\int_1^{8760} \varepsilon_i^*(t)\cdot \mu_i(t)dt}$$

with

- $\varepsilon_i^*(t)$: multiplicative deviation of hourly $CF_i^*(t)$ from the annual average value CF_i^*
- $\mu_i(t)$: multiplicative deviation of hourly $p_i(t)$ from the annual average price p_i

Intuition for $\mathbf{\Gamma_i^*}$:

- above (below) 1.0 if most of the energy is produced during above-average (below-average) prices
- equal to 1.0 if either electricity prices are time-invariant or the plant produces during all hours (baseload)

Cost Competitiveness: Levelized Profit Margin

Proposition. Given a trajectory of future annual electricity prices distributions, $(p_1(\cdot), \dots, p_T(\cdot))$, and the corresponding optimized annual capacity factors, $\overrightarrow{CF}^* = (CF_1^*, \dots, CF_T^*)$, a power generation facility is cost competitive if and only if:

$$\sum_{i=1}^{T} \boldsymbol{\beta_i^* \cdot \Gamma_i^* \cdot p_i + ptc \geq LCOE\left(\overrightarrow{CF}^*\right)}$$

with $\beta_i^* \equiv \frac{CF_i^* \cdot x^{i-1} \cdot \gamma^i}{\sum_{j=1}^{T} CF_j^* \cdot x^{j-1} \cdot \gamma^j}$ and $ptc \equiv \sum_{i=1}^{T} \beta_i^* \cdot PTC_i$.

Intuition for the Proposition:

- weighted average of adjusted annual revenues per kWh must at least cover the LCOE
- both Γ_i^* and $LCOE\left(\overrightarrow{CF}^*\right)$ vary across alternative power generation technologies
- we refer to the margin $\sum_{i=1}^{T} \beta_i^* \cdot \Gamma_i^* \cdot p_i + ptc - LCOE\left(\overrightarrow{CF}^*\right)$ as the Levelized Profit Margin

Market Dynamics in California and Texas

Application of the model framework

- Utility-scale natural gas combined-cycle (NGCC) turbines, solar photovoltaic (PV), and onshore wind power
- Located in day-ahead wholesale market environments of California and Texas
- California and Texas have traditionally relied on natural gas for power generation
- Both jurisdictions also deregulated their electricity market and deployed vast amounts of renewables

Cost and price parameters

- Required data available in full since 2012
- System prices of either technology: average of plants built in the U.S., adjusted for price level in either state
- Variable operating costs of NGCC turbines: calculated per year and state from plants in operation
- Capacity factors: calculated per year, technology and state from hourly capacity factors of plants in operation in either state in that year → reported values indicate to be optimized
- Annual co-variation coefficients: calculated per year, technology and state from hourly day-ahead wholesale market electricity prices and the hourly capacity factors of plants operating in that year

Dynamics of Key Cost Parameters

NGCC facilities

- w_i in Texas ↓ due to cheap gas from **fracking**
- w_i in California → due to **rising CO_2 price**[1]
- CF_i^* in Texas slightly ↑ due to replacement of **coal**[2]
- CF_i^* in Texas ↓ due to rising share of renewables[3]

Renewable Energy Sources

- v ↓↓ and CF_i^* ↑ for both solar PV and wind in both California and Texas due to **learning effects**[4]
- Increase in CF_i^* attributed for solar PV to rising deployment of axis trackers and for wind energy to growing sizes of towers and rotors[4]

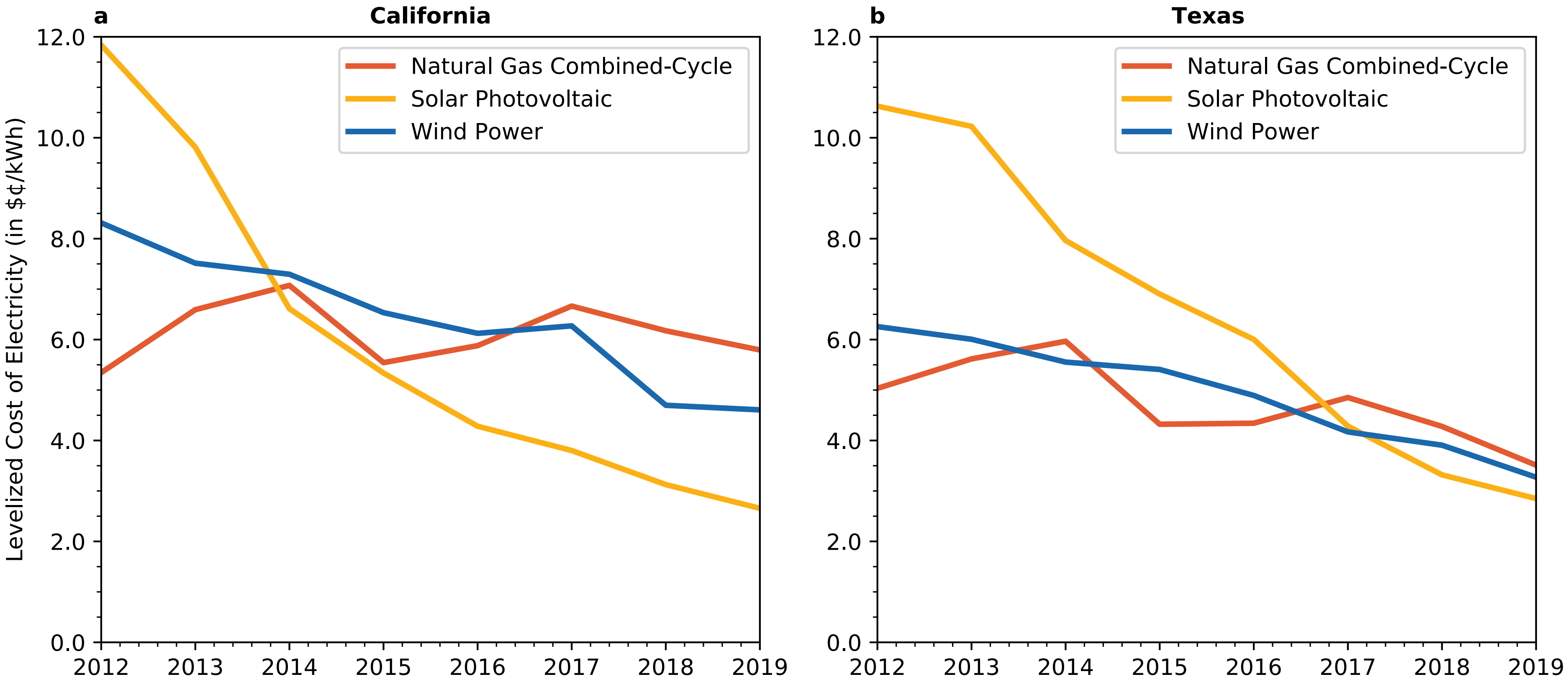
	NGCC		Solar PV		Wind	
Year	w_i	CF_i^*	v	CF_i^*	v	CF_i^*
California						
2012	2.87	58.75	4,088	20.83	2,532	32.13
2013	4.06	55.59	3,504	21.78	2,382	34.25
2014	4.56	54.40	2,967	26.75	2,198	31.62
2015	3.11	53.80	2,593	27.67	2,000	30.99
2016	2.93	44.83	2,161	27.67	2,044	33.69
2017	3.41	39.94	1,986	29.23	1,959	32.44
2018	3.54	43.45	1,565	29.59	1,747	37.74
2019	3.39	42.61	1,343	28.69	1,678	34.70
Texas						
2012	2.54	52.77	3,838	21.78	2,377	39.76
2013	3.10	50.48	3,289	19.25	2,236	39.11
2014	3.50	50.11	2,785	20.82	2,063	37.72
2015	2.23	56.73	2,434	20.02	1,877	33.93
2016	2.05	52.35	2,028	18.66	1,918	38.47
2017	2.39	47.71	1,864	24.39	1,839	44.37
2018	2.34	53.85	1,469	26.38	1,640	41.99
2019	1.87	57.04	1,261	25.48	1,575	44.78

w_i: variable operating cost in year i ($c/kWh), CF_i^*: capacity factor in year i (%), v: system price ($/kW), $-values in 2019 $US.

[1] C2ES (2020); [2] Fell and Kaffine (*AMJ: Ec Pol*, 2018); [3] Bushnell and Novan (*JAERE*, 2021);
[4] Berkeley Lab (2020a, 2020b), Glenk et al. (2012)

Trajectory of Levelized Cost of Electricity

- Assumption of a *stationary environment*, where cost and price distributions remain the same as in the investment year



- LCOE of NGCC in Texas ↓, while LCOE of NGCC in California → due to CF_i^* ↓ buffered by cost of capital ↓
- LCOE of both renewables ↓↓ and now the lowest in both states, which confirms the widespread observation[1]
- Texas appears to be a tight race among the three technologies, while, in California, solar PV appears clearly ahead

[1] see, for instance, IEA (2020), BNEF (2020)

Dynamics of Key Price Parameters

NGCC facilities

- Γ_i^* in California ↑ from about 1.0 to 1.2
  → NGCC move away from providing baseload power to complementing intermittent renewables[1]
- Γ_i^* in Texas slightly ↑ but remained well above 1.0
  → NGCC and wind turbines together replaced baseload power generation from coal[2]

Renewable Energy Sources

- Γ_i^* of solar PV in California and wind in Texas ↓↓
  → cannibalization effects have begun to materialize[3]
- Γ_i^* of solar PV in Texas remained well above 1.0, peaks in 2012, 2018 and 2019 due to heat waves[4]

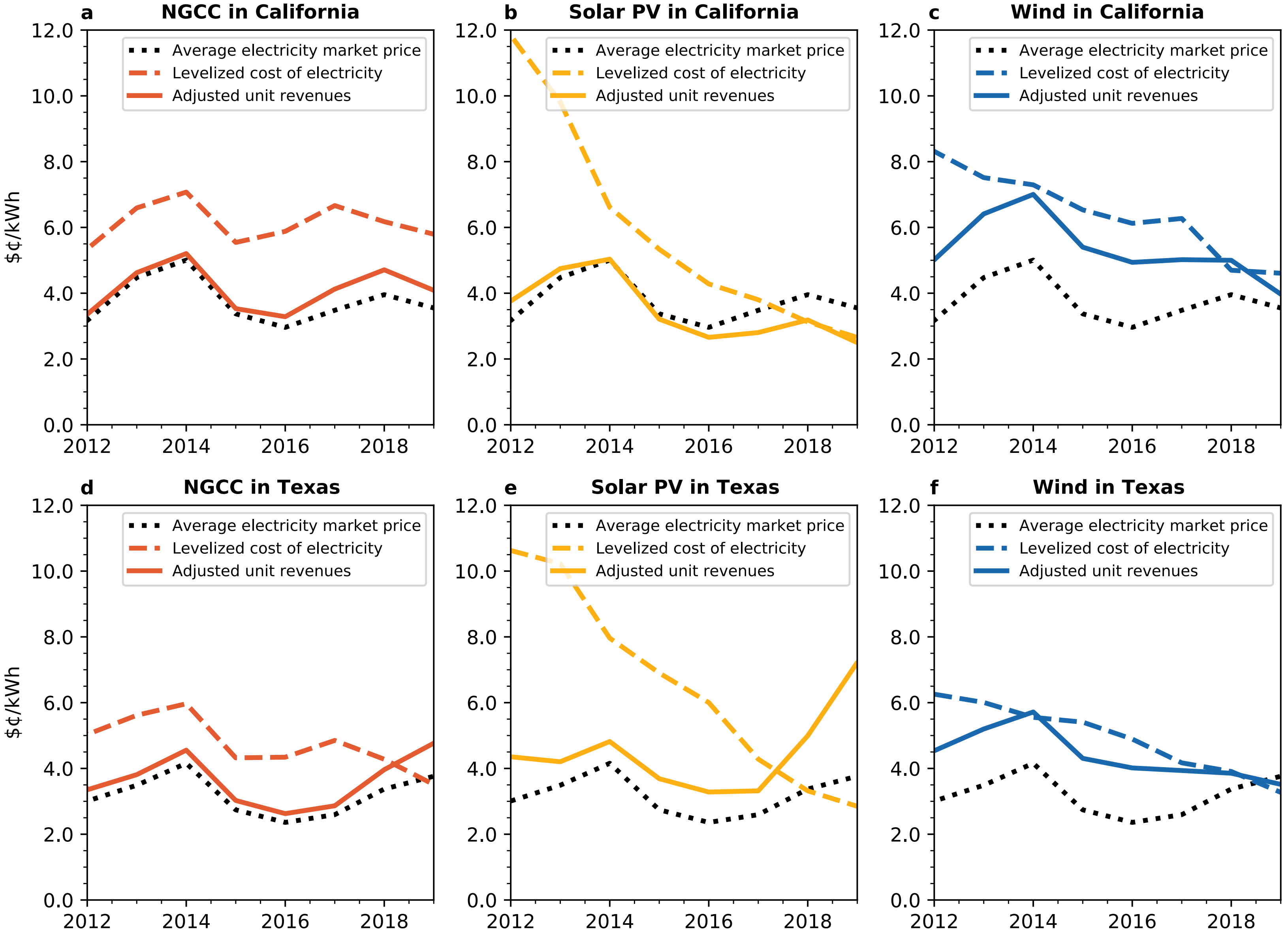
		NGCC	Solar PV	Wind	
Year	p_i	Γ_i^*	Γ_i^*	Γ_i^*	ptc
California					
2012	3.17	1.06	1.19	0.94	2.04
2013	4.48	1.03	1.06	0.97	2.08
2014	5.01	1.04	1.01	0.99	2.05
2015	3.37	1.05	0.95	0.99	2.05
2016	2.96	1.11	0.90	0.98	2.05
2017	3.48	1.19	0.81	0.96	1.67
2018	3.96	1.19	0.81	0.99	1.07
2019	3.55	1.15	0.70	0.92	0.70
Texas					
2012	3.01	1.11	1.45	0.89	1.86
2013	3.49	1.09	1.20	0.95	1.89
2014	4.16	1.10	1.16	0.92	1.87
2015	2.74	1.10	1.35	0.89	1.87
2016	2.36	1.11	1.39	0.91	1.86
2017	2.59	1.10	1.28	0.93	1.53
2018	3.37	1.17	1.48	0.85	0.98
2019	3.76	1.27	1.92	0.76	0.64

p_i: average electricity market price in year i ($c/kWh), Γ_i^*: co-variation coefficient in year i (-), ptc: levelized production tax credit ($c/kWh), $-values in 2019 $US.

[1] Bushnell and Novan (*JAERE*, 2021), Henbest (2018); [2] Fell and Kaffine (*AMJ: Ec Pol*, 2018);
[3] López Prol et al. (Energy Econ, 2020); [4] Reuters (2019)

Estimates of Annual Levelized Profit Margins (LPM)

- Assumption of a *stationary market environment*
- LPM of NGCC in Texas ↑ up to slightly positive values in last years
- LPM of NGCC in California negative but slightly ↑ due to Γ_i^* ↑
- LPMs of both renewables in both states ↑ ↑ up to ≈ 0 in last years, except for solar PV in Texas where LPM >> 0 due to recent heat waves
- Change in LPMs of renewables **dominated by** cost declines from **learning-by-doing**
- Overall, **renewables** in both states, respectively, have obtained the **highest LPMs** in recent years
- Tight race among renewables in California, while, in Texas, solar PV clearly leads



Discussion

- In estimating LPMs of new power plants built in the past, a central question is what expectation about future electricity prices and variable cost of NGCC plants investors had at various points in time?

- Since that is difficult to recapitulate, we consider two additional forecasting scenarios:
  1) Cost and price distributions may vary across years. Investors are assumed to have known these distributions with perfect foresight until 2019. Beyond that, they assumed variable operating costs of NGCC plants, average electricity prices, and co-variation coefficients to remain at terminal values set as the average across the last three years 2017-2019.
  2) Like scenario 1 until 2019, but, beyond that, investors they rely on forecasts by the U.S. EIA and on own extrapolations of the ongoing dynamics in the distribution of electricity prices. That accounts for potential of cannibalization ↑, and utilization of NGCC plants ↓ while their time-of-use value ↑.

- Resulting trajectories of LPMs in both scenarios, respectively, are consistent with the main insights from the previous calculation under the assumption of a *stationary market environment*
- Scenario 2 entails two differences: (i) solar PV in California has not yet obtained a LPM ≥ 0 due to expected cannibalization ↑, (ii) NGCC in Texas has not yet obtained a LPM ≥ 0 due to expected utilization ↓.

Concluding Remarks

Decarbonization Imperative

- Cost competitiveness of clean energy technologies is the central aspect for the speed of decarbonization
- Definition of the Levelized Profit Margin as the relevant measure of competitiveness of a generic power plant
- Solar PV and wind have become the most competitive power generation technologies in California and Texas, as cost declines from learning-by-doing have outpaced revenue declines from cannibalization

Managerial and Policy Implications

- Widely used LCOE analysis remains valid if adjusted with technology-specific co-variation coefficients
- Practitioners must keep in mind complementary dynamics, for renewables learning vs cannibalization, for traditional generators utilization vs time-of-use value
- Magnitude of such complementary dynamics and hence the overall effect depends on regional market specifics

Avenues for Future Research

- Extend model framework to a comprehensive competitive market equilibrium analysis
- Extend analysis to (a combination of renewables with) energy conversion and storage technologies
- Transfer empirical analysis of market dynamics over time to dynamics over cumulative capacity deployments (i.e., global learning effects vs local cannibalization effects)

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