The Engineering Economics of Low Carbon Electricity Market Design

Frank A. Wolak

Department of Economics
Program on Energy and Sustainable Development (PESD)
Stanford University
wolak@zia.stanford.edu
Note: All papers cited are at http://web.stanford.edu/group/fwolak

Architecture of Green Energy Systems: Underlying Problem and Its Challenges
Institute for Mathematical and Statistical Innovation (IMSI)
University of Chicago
June 18, 2024

Reliability Challenges in Wholesale Electricity Markets

California ISO

- Firm Load Curtailed on August 14 and 15, 2020
- Barely Avoided Firm Load Curtailment in September 2022

Electricity Reliability Council of Texas (ERCOT)

- Massive Amount of Firm Load Curtailed in February 14-18, 2021
- Barely Avoided Firm Load Curtailment in Early July 2022

Australia National Electricity Market (NEM)

- Market Operations Suspended from June 15-22, 2022
- Barely Avoided Firm Load Curtailment in Early June 2022

Note: **Interruptible** load different from **Firm** load

What Do These Regions Have in Common?

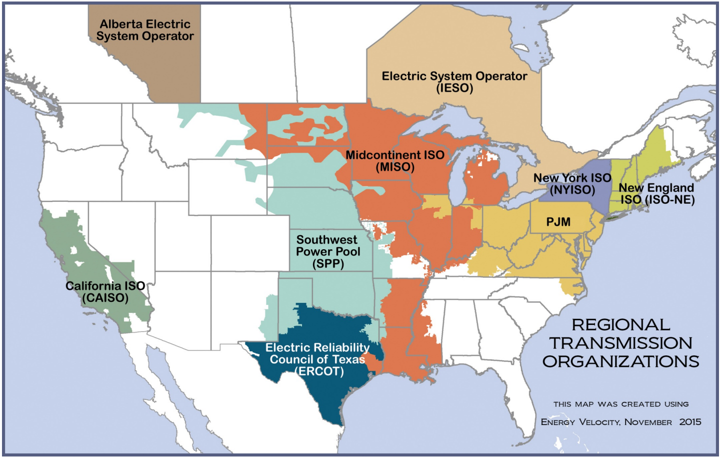
California–Approximately 25% of annual instate generation from grid scale wind and solar in 2021 and 2022

Electricity Reliability Council of Texas (ERCOT)–Approximately 25% of annual instate generation from grid scale wind and solar in 2021 and 2022

Australia National Electricity Market (NEM)–More than 25% of annual in-region generation from grid scale wind and solar and distributed solar in 2021 and 2022

California and ERCOT wholesale markets have, by far, the largest intermittent wind and solar generation shares in North America

Formal Wholesale Electricity Markets in the North America



Renewable versus Thermal Generation Dominated Regions

Electricity supplied only where and when wind, solar, and hydroelectric resource is available

- Substantial degree of contemporaneous correlation in renewable output across locations for the same generation technology
  - "Level versus variability trade-offs in wind and solar generation investments: The case of California."
  - Precipitation highly correlated across locations in hydro-dominated regions–El Nino/La Nina weather events in Latin America

Electricity from thermal resources supplied where and when input fuel can be delivered to generation unit

- Availability of individual thermal resource largely uncorrelated with availability of other thermal resources
- Electricity can be produced either where input fuel is produced or close to load center

Hourly Wind and Solar Output in ERCOT for 2022

Are Supply Shortfalls Only Due to Intermittent Renewables?

Electric system operation with a significant amount of intermittent renewables is significantly more challenging than operating a purely thermal generation dominated system

All of the regions that have experienced supply shortfalls are served by offer-based wholesale electricity markets rather than vertically-integrated price-regulated monopolies

Two possible explanations for increasing supply shortfalls

- Technology–Large share of intermittent renewables energy
- Market Design–Offer-based market versus regulated vertically integrated monopoly

Why Does Market Design Matter?

Economic incentives determine how technology is used, which technologies are built, and direction and speed of technological change

Negative Implication: For the same set of technologies poorly designed incentives can lead to costly market outcomes

- "Accidents" happen but economic incentives can make them more likely and more harmful

Positive Implication: Design mechanism for compensating each market participant that makes it in their unilateral interest to achieve market designer's goals

- Market designer must understand technology employed by each market participant and the economic incentives that they face
- Requires intimate knowledge of power systems engineering, economics, and legal framework governing electricity supply industry

All Wholesale Electricity Markets Face a “Reliability Externality”

Different from *vertically-integrated geographic monopoly regime*, in wholesale market regime no single entity is responsible for ensuring system demand is met under all possible system conditions

- Independent System Operator (ISO) can only operate market with resources offered into market
- Generation unit owners can only supply energy from the generation units they control
- Retailers can only withdraw energy supplied to wholesale market

Unique feature of grid-supplied electricity-—Currently a customer only gets a reliable supply with desired voltage and frequency if other nearby customers do too

Engineering Economics of Electricity Market Design

Electricity Market Design is Different

- Typical market design process not possible for electricity because of single grid and high level of reliability of supply demanded
- Consumers vote with their feet in typical market design process
  - Coffee market–Starbucks, Peets, Philz (in Silicon Valley and Hyde Park)
- Electricity market design takes place through regulatory process guided by stakeholder input at Federal and State level in United States and similar regulatory process in other parts of the world
- How electricity market is designed can have an enormous impact on market outcomes
  - Poor market designs can cost consumers billions of dollars annually

Combining Power Systems Engineering and Economic Analysis

- **Economics Incentives faced by market participants drive market outcomes in vertically-integrated monopoly regime and wholesale market regime**
  - When market rules change, incentives faced by market participants change, which causes their behavior to change
  - Technology is the same in both regimes, but how it is used changes because market participants face different economic incentives
  - Market design is choice between **imperfect competition** and **imperfect regulation**–For more on this point see Wolak (2015)"Regulating Competition in Wholesale Electricity Supply"
- **Proposed Market Design Objective:** Electricity consumers benefit from energy transition in wholesale market regime
  - Lower average retail prices consistent with long-term financial viability of industry and achieving region's environmental policy goals

Four Areas of Power Systems-Based Economic Analysis

- Match Between Market Mechanism that Sets Prices and Generation Unit Output Levels and Physics Governing Operation of Grid
  - The INC/DEC game in zonal markets and the benefits of multisettlement Locational Marginal Pricing (LMP) markets
- Least Cost Transmission Network Configuration Depends Market Structure
  - Transmission upgrades improve performance of imperfectly regulated vertically-integrated monopoly or imperfectly competitive wholesale market
- Long-Term Resource Adequacy with Significant Intermittent Renewables
  - Origin of *Reliability Externality* in the wholesale market regime and how to internalize it
- Efficient Network Pricing with Distributed Generation
  - Inefficient network pricing leads to inefficient bypass of grid-supplied electricity

The Future of Power Systems-Based Economic Analysis

- Access to Confidential Market Input and Market Output Data for Research Purposes
  - United States markets are unique in providing this data to its market monitors–"Data Analysis Beats an Anecdote"
  - Data-based measures of market performance that are comparable across markets–Measures vital signs of market
    - "Measuring market inefficiencies in California's restructured wholesale electricity market," *American Economic Review*, 2002.
  - Help market designers understand implications of their design choices
- Confidential Access to Transmission Network Data
  - Transmission upgrades can reduce market performance, particularly with significant intermittent renewables, so accurate network data is crucial to finding cost effective upgrades
- Regulator training and policy prototyping
  - Energy Market Game (`http://www.energymarketgame.org`)
  - With a common understanding of market mechanisms regulators can make better informed decisions

Match Market Model with Physics of Grid Operation

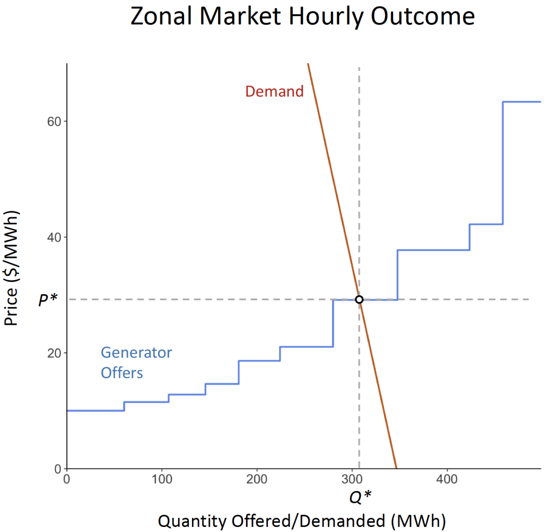
Market Model versus Physics of Grid Operation

- Initial US wholesale markets ignored physics of grid operation
    - Single-price or zonal-pricing financial markets to settle day-ahead and intra-day transactions, while secure system operation could be left to engineering models and real-time re-dispatch instructions
- Designers argued that transmission congestion would be infrequent and costs associated with real-time re-dispatch would be small
- However, once simplified markets were implemented, costs of re-dispatch rapidly exceeded expectations
- Experience from all simplified day-ahead markets showed that in "real-time physics always wins"
    - All generation unit owners understand this and use this knowledge to earn additional profits
- Competition between suppliers takes place subject to *actual transmission network* and *actual generation operating constraints*, regardless of market model employed to set prices and operating levels

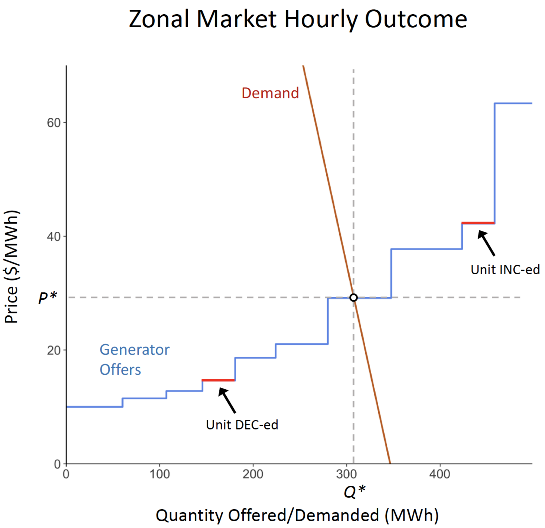
INCs and DECs in Simplified Market Design

- Infinite network capacity is implicitly assumed in simplified market, as well as absence of system security constraints, generation unit ramping constraints, and costs associated with generation unit starts and stops
- All generators and loads in the region settle at same price in simplified market
- After simplified market settlement, a re-dispatch of generation resources takes place to ensure the is physically feasible
- Because of real-time operating constraints certain generation units are given instructions to provide incremental energy (INC-ed) or to buy back decremental energy (DEC-ed) to resolve constraints
    - Paid as-offered for INCs and purchased as-bid for DECs
- Cost of redispatched INCs and DECs paid by final consumers

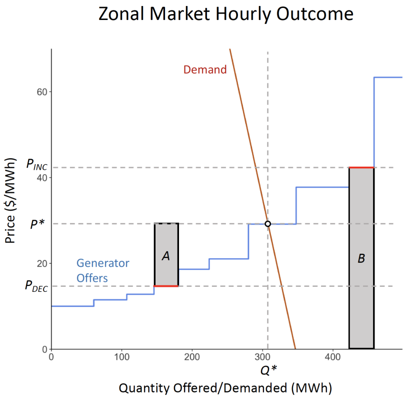
Simplified Market-Clearing



Simplified Market Infeasibilty



Simplified Market Before Real-Time Operation



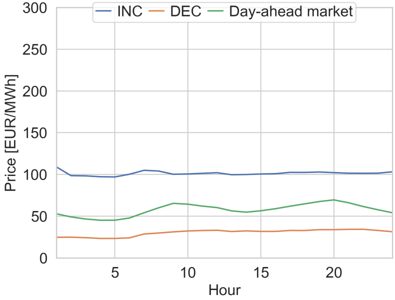
- The generator that was DEC-ed earns $P^* - P_{DEC}$ times the amount of decremental energy (Box A)
- The generator that was INC-ed receives P_{INC} times the amount of incremental energy (Box B)
- Generators that have a high probability of being DEC-ed have an incentive to submit lower offer price
- Generators that have a high probability of being INC-ed have an incentive to submit higher offer price

The "INC/DEC" Game

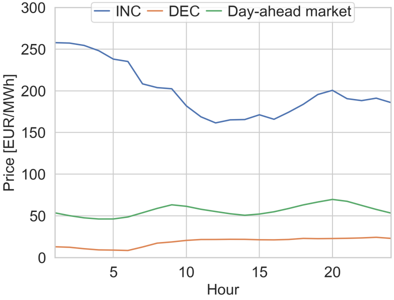
- Rapid growth in re-dispatch costs in simplified markets in United States due in large part to these incentives
  - Commonly referred to as the "INC/DEC Game"
- All European markets–United Kingdom, Italy, Germany, the Netherlands, and Spain currently have simplified market with redispatch process
  - Increase in intermittent renewables significantly increases uncertainty in patterns of transmission congestion and number of operating constraints
  - Re-dispatch costs increasing rapidly in all European markets driven in part by increasing share of intermittent renewables
- Empirical analysis of frequency and cost of INC/DEC game in Italian market
  - Graf, Quaglia, and Wolak (2021) "Simplified Electricity Market Models with Significant Intermittent Renewable Capacity: Evidence from Italy."

Incentives to Buy/Sell in Italian Re-Dispatch Market

North Bidding Zone



Center-South Zone



Key Takeaway

Price received [paid] for INCremental [DECremental] energy significantly above [below] the day-ahead market price

Generator Offer Price Strategy in Zonal or Single Zone Market

- A rich set of constraints (e.g., transmission, voltage, frequency, reserves) necessary for a *secure* real-time operation of the grid. These are not accounted for in simplified market
- Market participants are aware of these physical constraints and have incentive to earn higher price from INC in re-dispatch market or buy back energy sold at day-ahead price at offer price as a DEC in re-dispatch market
- **Caveat:** Market participants must be able to *predict* if and when these constraints will be binding in order to from profit INCs and DECs in re-dispatch market

Empirical Analysis—Step 1

Estimate generation unit-level models of hourly probability of INC or DEC instruction in re-dispatch market

- Use hourly unit-level offer curves for the day-ahead market and real-time re-dispatch market between 2017 and 2018
- Select most important combined cycle gas turbine units (provided by Italian Grid Operator) that are used to for re-dispatching
- Estimate random forest model for probability that a unit will be INCed/DECed using forecasts of system conditions known by generation unit owners before the day-ahead market closes
  - National zone-level day-ahead forecasts for demand and renewables
  - Neighboring countries' (+ Germany) day-ahead forecasts for demand and renewables
  - Day-ahead market cross-border transmission limits with adjacent countries and the national zonal transmission limits
  - Month-of-year, hour-of-day, and workday indicator variables

Empirical Analysis—Step 2

Calculating day-ahead offer markups (P(offer) - MC)

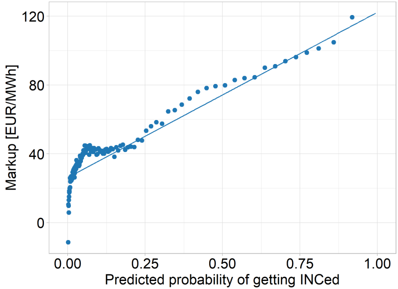
- Defined as the day-ahead market offer-price minus short-run marginal cost estimate
- Unit-level short-run marginal cost estimates are based on heat-rates estimates, fuel-cost, environmental cost such as CO_2 emissions allowances, and variable operations and maintenance cost
- Use offer-quantity weighted average offer-price to have a single day-ahead market offer price number for each unit and hour
- For each unit and hour of the sample match day-ahead market offer markup to predicted probability of that unit getting INCed or DECed in the real-time re-dispatch market

Graphical Results

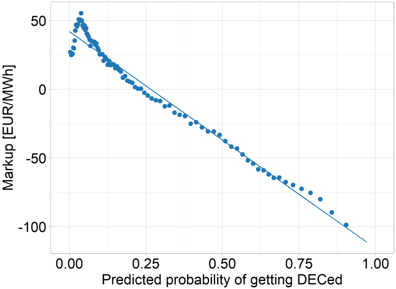
Binscatter of unit-level day-ahead offer markup and unit-level estimated probability of getting INCed/DECed

Note: Control for unit, hour-of-day, day-of-week, month-of-year fixed effects using nonparametric binscatter

INC



DEC



Empirical Results

- A 0.1 increase in probability of being INC-ed predicts €5/MWh increase in day-ahead offer price
- A 0.1 increase in probability of being DEC-ed predicts €6/MWh decrease in day-ahead offer price
- Average day ahead market price was €61.3/MWh during sample period
- Total re-dispatch costsl estimated to be approximately 10% of total day-ahead wholesale energy costs for sample period
    - Italian market likely have lowest re-dispatch costs of all European markets because it has multiple pricing zones, not just one for country as is the case in many other European countries

Solution: Price All Relevant Operating Constraints

- Generators submit unit-level start-up and minimum load offers and energy offer curve along with ramp rates to day-ahead (DA) market
- Market model accounts for transmission network configuration, ramp rates of generation units, capacity constraints of units, minimum operating level, voltage constraints
  - Thousands of operating constraints modeled in DA and real-time (RT) market
- These markets are called multi-settlement Locational Marginal Price (LMP) markets
- LMP is the change in the optimized as-offered cost of serving an additional unit of load (MWh) at the associated electrical node in the corresponding settlement interval
  - Day-ahead market simultaneously solves for day-ahead market outcomes for all 24 hours of following day
  - Real-time market solves for real-time operating levels respecting same underlying physical constraints of the electrical system in market mechanism

Benefits of a Nodal Market Design

- Physically infeasible schedules unlikely to emerge from the day ahead solution because all relevant real-time operating constraints modeled in day-ahead market and real-time market
- Generators have incentive to operate as they have cleared in the day ahead
  - Generators that under supply in real-time will have to buy the difference at real-time LMP at their location
  - Generators that over supply in real-time will get paid real-time LMP at their location
- **Key Economic Insight:** Make match between market *model* used to set prices and dispatch levels for all resources as close as possible to how actual network operates
  - Balance this goal against computational complexity of solving mixed integer programming problem used to obtain day-ahead schedules and LMPs
- Match is never perfect, but it is a moving target
  - All US LMP markets assume a Direct Current (DC) power flow when reality is Alternating Current (AC)
  - As more intermittent renewables are added to region more operating constraints must respected in system operation

Restructured Markets and Nodal Market Design

- There are now seven LMP markets in the United States: CAISO, MISO, ISO-NE, NYISO, PJM, SPP, and ERCOT, but only MISO, NYISO and SPP started that way
- Significant market efficiency benefits to transitioning from simplified day-ahead market to multisettlement LMP market
  - Wolak (2011) "Measuring the Benefits of Greater Spatial Granularity in Short-Term Pricing in Wholesale Electricity Markets," finds a 2.1% reduction in variable costs and 2.5% decrease in heat input for same total generation as a result of nodal market implementation for estimated total annual operating cost savings of approximately $100 million
  - Triolo and and Wolak (2022) "Quantifying the Benefits of Nodal Market Design in the Texas Electricity Market," finds daily costs savings for same generation level of 4 percent for annual estimated cost savings of approximately $300 million
- Many simplified markets outside of the US are struggling with high level of re-dispatch costs due in large part to a growing share of intermittent renewables

Measuring the Benefits of Transmission Network Expansions in Wholesale Market Regime

Benefits of Transmission Network Expansions in Wholesale Market

- Transmission network improves performance of imperfectly regulated vertically-integrated monopoly
  - Increases ability of vertically integrated utility to substitute **high cost** supply near load center with **low cost** supply from distant resources
- Transmission network improves performance of imperfectly competitive wholesale market
  - Transmission expansions in wholesale market regime increases number of firms able to compete to supply electricity at each location in transmission network
  - Increases amount of **low-priced** energy that can displace **high-priced** energy at load centers
- **Conclusion:** Least-delivered-to-consumers-cost transmission network configuration different for vertically-integrated regime versus wholesale market regime

Engineering Economics of Transmission Expansions

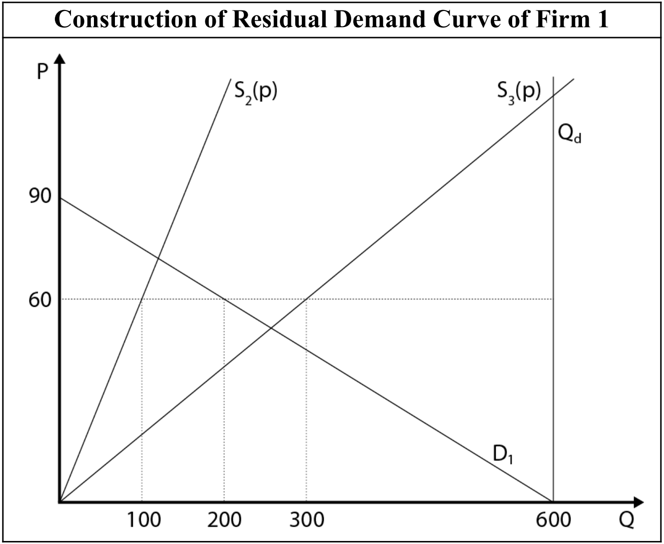
- Transmission planning is optimal second-best problem that is regime specific
  - Transmission network configuration impacts ability of supplier to exercise unilateral market power
  - Suppliers have economic incentive to take transmission network configuration into account in formulating offer curves
  - For more on this point see Graf and Wolak, "Measuring the Ability to Exercise Unilateral Market Power in Locational-Pricing Markets: An Application to the Italian Electricity Market" (2022)
- Additional transmission capacity can increase number of hours per year that supplier faces competition from more suppliers in market
  - Causes more competitive behavior by supplier (submit offer curve closer to marginal cost curve)
- For more details on this point, see "Transmission Planning and Operation in the Wholesale Market Regime" (2022)

How Do Firms Exercise Unilateral Market Power

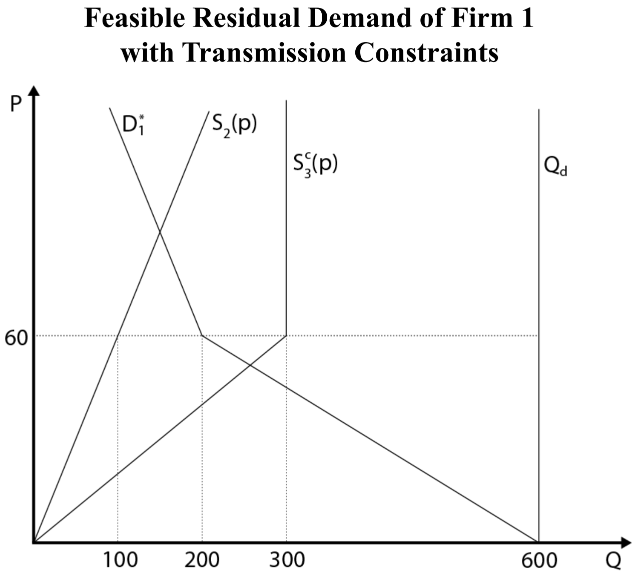
An unilateral profit-maximizing supplier acts as a monopolist against *residual demand* curve left by competitors

- Cournot competitor faces residual demand equal to market demand less output choice of all competitor
- Bertrand competitor faces residual demand equal to market demand below price of competitor and zero above this price
- Suppliers in wholesale electricity market submit non-decreasing willingness to supply functions, $S(p)$
- $DR(p) = D(p) - SO(p)$, market demand $D(p)$ less aggregate willingness to supply of all other firms, $SO(p)$
- Supplier submits offer curve, $S(p)$ to achieve p that attempts to maximize ex post variable profit, $\pi(p) = DR(p)(p - c)$ where c marginal cost of production
  - For more on this point see "An Empirical Analysis of the Impact of Hedge Contracts on Bidding Behavior in a Competitive Electricity Market"

Residual Demand in "Copper Plate" Transmission Network



Residual Demand with Finite Capacity into Load Center



Measuring Competitiveness of Transmission Investment

- Change in wholesale energy and ancillary services costs to electricity consumers associated with transmission expansions (due to more competitive offer behavior by suppliers)
  - If wholesale energy cost savings to consumers is more than cost of network expansion consumers should be willing to pay for it
  - "Measuring the competitiveness benefits of a transmission investment policy: The case of the Alberta electricity market," finds many transmission upgrades in Alberta can be justified based on competitiveness benefits
  - "Using Market Simulations for Economic Assessment of Transmission Upgrades: Application of the California ISO Approach," demonstrates that competitiveness benefits are a major source of consumer benefits for a proposed transmission upgrade in California
- Many regions recognize existence of competitiveness benefits from transmission expansions, but limited progress has been made in rigorously including them in planning process
- Growing share of intermittent renewables implies competitiveness benefits of many transmission expansions likely to become even larger

Ensuring Long-Term Resource Adequacy

Long-Term Resource Adequacy Mechanism

- In vertically-integrated geographic monopoly regime, utility is responsible for ensuring that demand is met under all possible future system conditions
  - Regulatory bargain–Utility to agrees to serve all demand at regulated price if regulator sets price that allow utility the oppportunity to recover prudently incurred costs
  - Regulator can penalize monopoly utility for supply shortfalls
- In wholesale market regime no single entity is responsible for ensuring system demand is met under all possible system conditions
  - Because of forward financial market purchases of energy by large consumers and retailers, it is often be lower cost to some retailers and customers to source energy and operating reserves from short-term market
  - When generators are net long on energy this can lead to extremely high short term wholesale prices for those customers

Conclusion–All wholesale electricity markets, particularly those with significant intermittent renewables, requires a long-term resource adequacy mechanism

Reliability Externality in Wholesale Market Regime

- **All consumers know that random curtailment will occur if aggregate supply is less than aggregate demand**
  - This implies that no customer faces full expected cost of failing to procure adequate energy in forward market
  - Cannot curtail specific customers during rolling blackouts, only all customers in a specific region of grid
- **Conclusion: Because of existence of "reliability externality" regulator must mandate a long-term resource adequacy mechanism**
  - Ensure adequate supply of *energy* to meet system demand under all possible future system conditions and allowed short-term wholesale prices
- Because of the increasing share of intermittent renewables in many electricity markets energy shortfalls can occur despite installed generation capacity much larger than annual system demand peak
  - Not surprising that energy supply shortfalls occurred in Texas (February 2021) and California (August 2020) where annual shares of intermittent renewable energy are by far the largest in US

Historical Approach to Long-Term Resource Adequacy

- Industry with dispatchable (typically, thermal) resources, mechanical meters
- Major concern is sufficient installed capacity to meet system demand peak
- Assign all retailers firm capacity obligations equal to multiple of annual peak demand
  - Between 110 and 120 percent of peak demand, depending on region
- Firm capacity is the amount of **energy** generation unit can produce under stressed system conditions
  - For thermal resource this is typically equal to nameplate capacity times the availability factor of unit
  - Availability factor is percent of hours of the year unit is available to produce energy

What is Firm Capacity of an Intermittent Resource?

- Firm capacity of hydroelectric resources is typically based on historical worst hydrological conditions, but this does not always prevent energy supply shortfalls
  - For an example from Colombia, see, “Diagnosing the Causes of the Recent El Nino Event and Recommendations”
- For wind and solar resources, it is extremely difficult to determine firm capacity
  - Firm capacity of a MW of wind or solar capacity declines with share of wind or solar energy in system demand because of high degree of contemporaneous correlation in output across locations
  - For example from California, see “Level versus Variability Trade-offs in Wind and Solar Generation Investments: The Case of California” (2016)
- Assignment of firm capacity to intermittent wind and solar resources involves ”engineering alchemy” and “political compromise”
  - If stressed system conditions occur when it is dark or when there is no wind, then firm capacity of solar and wind unit should be zero
  - Supply shortfalls in August 2020 in California and February 2021 in Texas are cases for this point

Reliability of Firm Capacity of Thermal Resource

- Firm capacity construct with thermal resource based on assumption that availability of individual thermal resources are independent random events
  - Suppose region has peak demand of 1,000 MW and market composed of equal size thermal units with availability factor of 0.9 and outages are independent across units
  - With 100 MW units, then each unit has firm capacity of 90 MW and a 1.17 times peak demand requirement ensures system peak is met with 0.96 probability with 13 units
  - With 20 MW units, then each unit has firm capacity of 18 MW and 1.17 times peak demand requirement ensures system demand peak is met with 0.999 probability with 65 units
- Key assumption for this reliability outcome with thermal resources is independence of availability of individual generation units
- This is a terrible assumption for intermittent hydro, wind and solar resources that have extremely high degree of contemporaneous correlation across units

Firm Capacity and Import Dependent Regions

- Capacity-based approaches poorly suited to import-dependent regions
- Generation source of an electricity import to a region is a financial construct
  - Two connected bathtubs view of electricity imports–If more electricity poured into tub A than is draining from tub and less electricity is poured into tub B than is draining from tub, electricity flows from tub A to B
  - Impossible to know which generation unit in region A is producing energy flowing into region B
- **Conclusion:** Capacity-based construct for long-term resource adequacy poorly to intermittent renewables and import-dependent regions
  - Note that because renewables must be produced where water, wind or solar resource exists, import share in most regions likely to increase

Standardized Energy Contracts for Resource Adequacy

- Energy-only market versus capacity market is false dichotomy
  - A long-term resource adequancy mechanism is necessary in any electricity market with finite offer cap because of reliability externality
  - As experience of Texas in February 2022 demonstrates, higher offer cap on short-term market reduces probability of supply shortfall but increases its realized cost
- **Important Fact: There has never been a supply shortfall in wholesale market caused by inadequate generation capacity**
  - All supply shortfalls in California, Texas, New Zealand, Colombia, Brazil, etc., caused by inadequate energy
- Standardized Fixed-Price Forward Contracts (SFPFC) approach to Long-Term Resource Adequacy
  - "Market Design in a Intermittent Renewable Future: Cost Recovery with Zero Marginal Cost Resources"
  - "Long-Term Resource Adequacy in an Intermittent Renewable and Import Dependent Future in California, Submission to Track 3B.2 Proceedings R.19-11-009 at California Public Utilities Commission," on web-site

Develop Forward Market for Energy at Long Horizons to Delivery

Long-term resource adequacy with significant intermittent renewables requires deep forward financial market for energy at long horizons (multiple years) to "delivery" at multiple locations

- Massive amount of volatility of short-term prices of electricity prices greater than any other product
- Order of magnitude greater volatility than even spot price of oil

Key Implication: Development of wide-range of financial products and increase depth of financial participants to manage this price risk essential to least cost energy transition

- "Measuring the Impact of Purely Financial Participants on Wholesale and Retail Market Performance: The Case of Singapore"
- Jha and Wolak "Can Forward Commodity Markets Improve Spot Market Performance? Evidence from Wholesale Electricity."

Daily Financial versus Physical Volume of Oil Traded

Global Oil Consumption is $\approx$ 100 million barrels per day

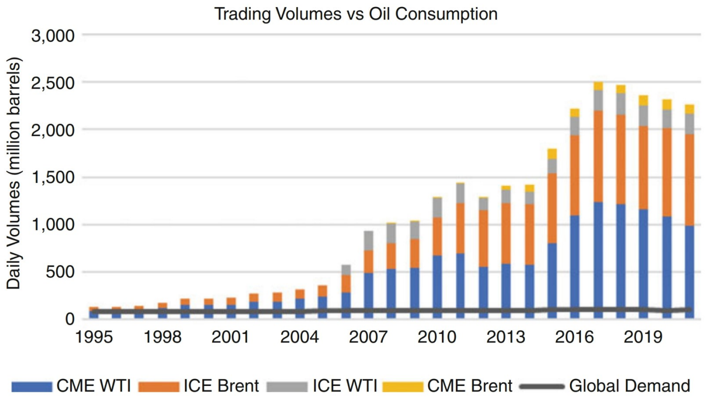


Fig. 1.1 Daily trading volume of two benchmark oil futures contracts, WTI and Brent, is at least twenty times larger than daily global oil consumption. Source: CME, ICE, EIA

Inefficient Network Pricing and the Energy Transition

The Cost of Inefficient Network Pricing

- Historically sunk network costs recovered through a cents per kilowatt-hour (KWh) charge to final consumer
  - Did not lead to inefficient decision to consume electricity (not the amount consumed), because household had no alternative to grid-supplied electricity
- Distributed (rooftop) solar provides household with ability to avoid purchases from grid
  - Pay cents/KWh charge only for electricity withdrawn from grid
  - Retail price is avoided cost of energy from installing solar panels "behind the meter"
  - P(retail) = P(Energy) + P(Trans+Dist) + P(Other)
  - Other = retailing margin and fixed cost of state policies
  - State policies include energy efficiency, renewables, storage, and low income consumers programs
- Marginal cost of grid supplied electricity is P(Energy) + Distribution Losses, which are less than 10% of P(Energy) in industrialized countries

Distribution Network Cost Increases–The Denominator

- Fixed cost of distribution grid does not depend on how many kWh are withdrawn from grid
  - Very small marginal cost of delivering 1 KWh (primarily losses)
- As more customers install distributed (rooftop) solar, the same fixed cost must recovered from fewer total KWh which implies an increase in cents/KWh charge
- Higher cents/KWh charge increases incentive to install distributed solar
  - Consumer avoids paying higher distribution charge
- More spending on "Other" factors also increases per unit retail price

Distribution Network Cost Increases–The Numerator

- As more distributed solar is installed in a given distribution grid, upgrades may be necesary
  - Manage large surges of energy injections to grid (even power flows back to transmission network) during periods of day with significant solar energy
  - Solar system sized to produce close to customer's monthly consumption produces more electricity than customer durimg consumes daylight hours
  - Annual capacity factor of rooftop solar system in California is approximately 15 percent
  - Annual capacity factor is total energy produced annually divided by nameplate capacity times number of hours in the year
- Grid upgrades to accommodate solar increases fixed cost of grid, which further increases cents/KWh charge to all customers

Upgrades of Distribution Grid Where Rooftop Solar Installations Occur

Following lengthy power outages in Los Altos that have gone from several hours to several days, PG&E officials announced this week a major infrastructure project that will involve power pole and transformer replacements, and new wiring.

The Los Altos work will include replacing 74 power poles, 134 transformers and trenching 650 feet to install underground cable and more than 5,000 feet of overhead wires along North El Monte Avenue between Jay Street in Mountain View and South El Monte Avenue and Cuesta Drive in Los Altos. Work will continue throughout the year.

Inefficient Network Pricing Leads to Inefficient Bypass

- Current average residential price in California is approximately 23 cents/KWh
  - All three investor-owned utilities employ increasing block prices that can be as high as 40 cents/KWh
- At $3.00/Watt installed, rooftop solar photovoltaic (PV) system has a levelized cost of energy equal to 15 cents/KWH (3 percent real discount rate)
  - Levelized cost equals discounted present value of lifetime costs divided by discounted present value of lifetime energy production
  - Going solar requires no subsidies to be privately profitable for "typical" California household
- Average annual wholesale cost of energy and ancillary services in California is about 4 cents/KWh
  - **Conclusion:** Socially unprofitable to invest in rooftop solar, because it is much cheaper for customer to consume electricity from wholesale market

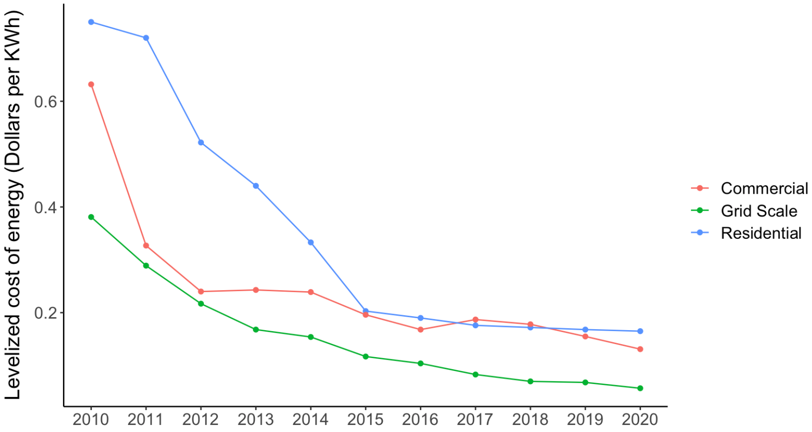
Inefficient Bypass of Grid Supplied Electricity

- Divergence between privately optimal decision for household and socially optimal decision due to inefficient distribution network pricing
    - Household willingly substitutes 15 cents/KWh electricity for 4 cents/KWh electricity because this avoids 19 cents/KWh = (23 cents/KWh - 4 cents/KWh) charge for network and "Other" *fixed costs*
- Marginal incentive to install rooftop solar even larger for high consumption households because of increasing block retail prices
- Even with high California gasoline rices, electric vehicles do not make economic sense because of high marginal price of electricity
    - Cost per mile higher for EV versus comparable ICE vehicle

Reforming Distribution Network Pricing

- Reform distribution network pricing to eliminate incentive for inefficient bypass of grid supplied electricity and investment in ICE versus electric vehicles
  - "Evidence from California on the Economic Impact of Inefficient Distribution Network Pricing"
  - McRae and Wolak " Retail Pricing in Colombia to Support the Efficient Deployment of Distributed Generation and Electric Stoves"
- According to International Renewable Energy Agency (IRENA), levelized cost of energy of grid scale solar is roughly one-third of the levelized cost of energy from rooftop solar
- Similar issues exist in other regions with significant amounts of distributed solar, such as Australia and Germany
- Alternative pricing proposal is income-based monthly fixed charge for residential consumers
  - California recently raised monthly fixed charge to $24 and $12 for low-income customers to substantial political resistance

LCOE of Distributed versus Grid Scale Solar from IRENA



Overcoming Challenges to Achieving Energy Transition

Access to Market Input and Output Data

- Access to confidential market input and output data for analysis is crucial
- US Bureau of Census and Social Security Administration provide confidential access to data to academic researchers
  - This data allow researchers to construct a consistent set of measures measures of health of the market that are comparable across markets
  - Allows construction of an data-based estimate of cost of a market design flaw and perform empirical analysis of impact of proposed changes
  - Federal Energy Regulatory Commission (FERC) could manage this confidential data access process
- Analyses by independent market monitors have played a major role in market design process in United States
  - `http://www.caiso.com/meetings-events/topics/market-surveillance-committee`
  - All US Wholesale Markets have Independent Market Monitor that prepares detailed periodic reports on market performance using market input and output data

Empirically-Based Transmission Network Models

- Transmission facilitates trade and competitiveness of wholesale electricity market
  - Different from vertically-integrated monopoly regime
- Realistic transmission network models for specific regions of US can increase likelihood of beneficial transmission network upgrades for wholesale market regime
- National security and computational complexity concerns make this task more challenging
- Confidential access to network models by researchers is key to designing cost effective national transmission plan

Key Takeaway: More realistic transmission network models to limit potential for negative net benefits from upgrades

Regulation and Policy Prototyping

- Regulator staff and other participants in the market design processes face significant challenges with understanding the implications of their decisions
- “Simulated market” training teaches important concepts using own behavior of market participants
- Examine performance of different market rules real-world market participants
- PESD has taught over twenty-five regulator short courses globally, recent examples include
  - CRE –France
  - PUCT–ERCOT
  - CPUC–CAISO
  - ANEEL–Brazil

PESD/Stanford Energy Market Game

http://www.energymarketgame.org

Energy Market Game for Regulation and Policy Prototyping

Game Creators | Publications | Using the game | About

About the Game

Welcome to the website for the Energy Market Game—a tool developed at the Program and Energy and Sustainable Development (PESD) at Stanford University to help policymakers, regulators, market participants, and students improve their understanding of how energy and environmental markets work. On this site, you will find documentation about how the game works, interesting results from past runs of the game, information about customized educational workshops using the game, and, soon, simple games that you can be played in “solo mode” against computer-simulated agents.

Each player in the Energy Market Game takes on the role of an electricity generating company ("genco") or of a company selling electricity to retail customers ("retailer"). In each hour of each simulated electricity market day, gencos offer in the capacities of their various generating units at whatever prices they choose. Retailers may enter into fixed-price forward contracts for electricity with gencos or simply buy electricity on the spot market. They may also call “critical peak pricing rebates,” in which they pay their simulated retail customers to reduce demand in a given period.

The Energy Market Game can incorporate environmental policies that are found in real markets, such as a cap and trade system for greenhouse gas emissions and a renewable portfolio standard (RPS) to incentivize the development of wind and solar facilities. When these additional elements are added to the basic features described above, the game becomes a sophisticated simulation of an electricity market subject to overlapping environmental regulations.

These kinds of complex markets have significant scope for strategic behavior and can be difficult to analyze theoretically. Our hope is that the game—and this website—will help policymakers, regulators, market participants, and students gain a higher level of comfort with these markets, as well as an improved sense of how markets may respond to different policies.

For further details about the Energy Market Game please read Features of the Energy Market Game.

Concluding Remarks

- Market design process is a engineer and economist intensive collaborative process
  - Incentives market participants face as a result of physics of electricity network operation and market design determines market outcomes
  - Failure to account for all physical operating constraints in market mechanism typically creates private incentives to degrade market efficiency and system reliability
- **Engineering-Based Economic Analysis of Market Input and Output Data (Including Physical Network Characteristics and Resource Operating Constraints) is Crucial to Success of Energy Transition**