PESD STANFORD | PROGRAM ON ENERGY AND SUSTAINABLE DEVELOPMENT

Long-Term Resource Adequacy with Significant Intermittent Renewables

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Future Electricity Supply Industry

Electricity supply industry in a low-carbon world will have a significant amount of intermittent renewables

- Intermittent renewable energy shares in excess of 50 percent
- Significant amount of distributed solar generation capacity

Large intermittent renewables share will require

- Investments in both grid-scale and distributed storage
- Active demand-side participation by customers with interval meters using dynamic retail electricity prices
- Automated distribution network monitoring and on-site load-shifting technologies

Market design should support business models that lead to efficient levels of investment in these technologies

Future Electricity Supply Industry

Policy Question: What long-term resource adequacy mechanism will facilitate a least-cost transition to this future electricity supply industry with these pricing policies and technologies?

- Capacity payment mechanism--Increasingly expensive approach to long-term resource adequacy, particularly for regions with a large share of intermittent renewables
  - Limits economic benefits from dynamic pricing and storage and load flexibility investments
- Standardized long-term energy contracting--Least cost approach to long-term resource adequacy for future electricity supply industry
  - Supports storage investments and investments in flexibility technologies on supply and demand side of market

Need for Resource Adequacy Mechanism

In former vertically-integrated geographic monopoly regime, monopoly is responsible for ensuring there are sufficient resources to meet demand

- Regulator penalizes monopoly for supply shortfalls

In wholesale market regime no single entity is responsible for ensuring sufficient resources to meet system demand

- Independent System Operator (ISO) can only operate market with resources it has
- Generation unit owners can only supply energy from the generation units they control
- Retailers can only purchase the energy that generation unit owners supply to wholesale market

Conclusion—Unless regulator treats electricity like any other product (see next slide), wholesale market regime requires a long-term resource adequacy mechanism

Need for Resource Adequacy Mechanism

A long-term resource adequacy mechanism is necessary because of "reliability externality"

- Unwillingness of regulator to commit to use real-time price of energy to clear market under all possible system conditions creates a "reliability externality"
- Lack of interval meters often used to justify this unwillingness of regulator "to treat electricity like any other product"

All consumers know that random curtailment will occur if aggregate supply is less than aggregate demand, so no customer faces full expected cost of failing to procure adequate energy in forward market

Because of existence of "reliability externality," in markets with a finite offer cap regulator must mandate a long-term resource adequacy mechanism

- *Ensure adequate supply to meet system demand under all future system conditions and allowed short-term prices*
- *Make most efficient use of all resources available to ISO*

Historical Long-Term Resource Adequacy Challenge

- Initial Conditions: Electricity supply industry with dispatchable (typically, thermal) generation resources, mechanical meters, and offer cap on short-term wholesale market
- Major concern: Sufficient installed capacity to meet system demand peak
- Mechanical meters: Only allow measurement of total electricity consumption between consecutive meter reads
  - Typically done on monthly or bi-monthly basis
  - Precludes use of dynamic prices to reduce system peaks
- Offer cap on short-term market: Can prevent units that run infrequently to recover their total cost

Capacity Payments: Historical Solution to Problem

- Assign all retailers firm capacity obligations equal to a multiple of their annual peak demand
  - Between 110 to 120 percent, depending on region
- All generation units assigned firm capacity quantity equal to amount of energy unit can produce under stressed system conditions
  - For thermal resource this is typically equal to nameplate capacity times the availability factor of the unit
  - For hydro units, typically based on historically worst hydrological conditions
    - For example from Colombia, see McRae and Wolak (2016) "Diagnosing the Causes of the Recent El Nino Event and Recommendations" available from web-site.
  - For solar and wind resources, it is extremely difficult to determine firm capacity of generation units
    - 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 correlation in output across locations
      - For case of California, "Wolak, Frank A. "Level versus Variability Trade-offs in Wind and Solar Generation Investments: The Case of California." *The Energy Journal* 37, (2016).

Firm Capacity of Intermittent Resources

- Firm capacity of solar or wind resource typically determined by effective load carrying capacity (ELCC)
  - If stressed system conditions occur when it is dark, firm capacity of solar generation unit should be zero
  - If stressed system conditions occur when wind is not blowing, firm capacity of wind generation unit should be zero
- Assignment of firm capacity to intermittent renewable resources has a significant political component
  - Values used for August 2020 were 27% for solar PV and solar thermal and 21% for wind
    - Rolling blackouts occurred in late evening on August 14 and 15
  - Recent study by three CA investor-owned utilities estimated effective load carrying capability (ELCC) of solar PV at ~5 percent of nameplate capacity
    - *2020 Joint IOU ELCC Study*, prepared by Astrape Consulting
- Conclusion: Firm capacity approach to long-term resource adequacy poorly suited to regions with high shares of intermittent renewable energy

Summary Comments on Capacity Mechanisms

Capacity payments are a expensive mechanism for attempting to achieve long-term resource adequacy in regions with significant intermittent generation resources

- Does not address primary reliability challenge in intermittent-renewable-dominated wholesale markets
  - Energy shortfalls
- No guarantee that adequate capacity will be built
  - Depends on level of capacity payment
- Little success with capacity payments in international markets outside of Latin America countries with cost-based energy markets, e.g., Chile
  - See Galetovic, Munoz, and Wolak, "Capacity Payments in a Cost-Based Wholesale Electricity Market: The Case of Chile" (available on web-site)
- Market-based pricing of capacity extremely challenging, particularly locationally
- Little evidence that markets with capacity payments in the US have achieved higher levels of short-term or long-term reliability

Long-Term Resource Adequacy for Markets Dominated by Intermittent Renewables

Question is not an energy-only market versus capacity market

- Key Point: A long-term resource adequacy mechanism is necessary in any energy market with a finite offer cap because of the reliability externality
- Higher offer caps on short-term market only reduce magnitude of reliability externality, but do not eliminate it

How to maximize benefits of market mechanisms while still providing regulator with assurance that demand will equal supply under all possible future system conditions

- Long-term resource adequacy mechanism that provide consumers with what they want
- Requires consumers pay for what they want
  - Some long-term resource adequacy mechanisms involve many "small" charges that sum up to higher costs for consumers
- Allow market participants maximum flexibility to determine least cost way to provide consumers with what they want

Consumers want system demand for electricity to be met under all possible future system conditions

- Long-term resource adequacy mechanism should focus on having sufficient resources to meet system demand, not demand for each individual retailer
- Electricity supplied to a load comes from grid, not from specific generation units
- Recall that in wholesale market regime, no market participant responsible for meeting system demand all hours of the year

Energy-Contracting Resource Adequacy Process

Mandate standardized forward contract holdings by retailers for pre-specified fractions of system demand at various horizons to delivery

- 100% of demand one year in advance
- 97% of demand two years in advance
- 95% of demand three years in advance
- 92% of demand four years in advance
- Percentages are not set in stone, nor is length of contracting mandate

Contracts are shaped to actual hourly system demand within delivery period

- QD_h = actual system demand in hour h of delivery period of contract for h=1,2…,H
- QC_{total} = amount of energy sold in standardized contract for delivery period
- $QC_{jh} = \left(\frac{QD_h}{\sum_{h=1}^{H} QD_h}\right) QC_{j,total}$ for h=1,2,…H is forward contract obligation of seller j for hour h
- Note that $QD_h = \sum_{j=1}^{N} QC_{jh}$ for all h, where N = total number of sellers of contracts

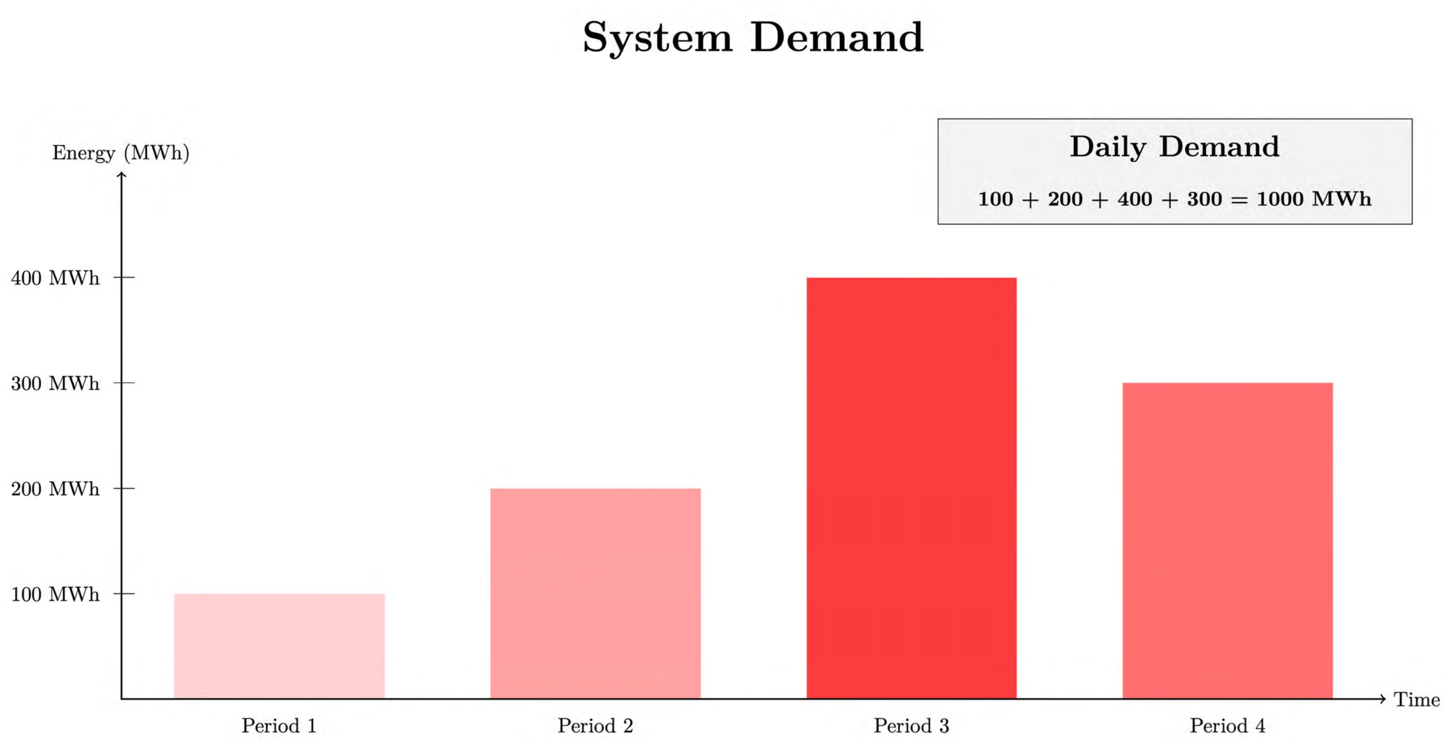
Total energy shaped to realized pattern of system demand sold in standardized contract

- Note that during any hour of the year, there is a value of $QC(h)_{total}$, the remaining amount of system-wide eligible standardized contract energy that can be delivered in hour h
  - $QC(h)_{total}$ satisfies the following difference equation
  - $QC(h+1)_{total} = QC(h)_{total} – QC_h + \Delta QC(h)_{total}$
  - $\Delta QC(h)_{total}$ = purchases of additional QC_{total} that is eligible to deliver during hour h and h+1

Note that QC_h varies with realized values of QD_h

- Sellers of contracts have ability to manage this quantity risk through use of own generation units or through their hedging arrangements
- Sellers charge price for standardized contract that incorporates cost of managing quantity risk

Energy-Contracting Resource Adequacy Process



Realized Total System Demand ($\sum_{h=1}^{4} QD_h$) is equal 1,000 MWh and Has the Above Hourly Values, QD_h, h=1,2,3, and 4

Energy-Contracting Resource Adequacy Process

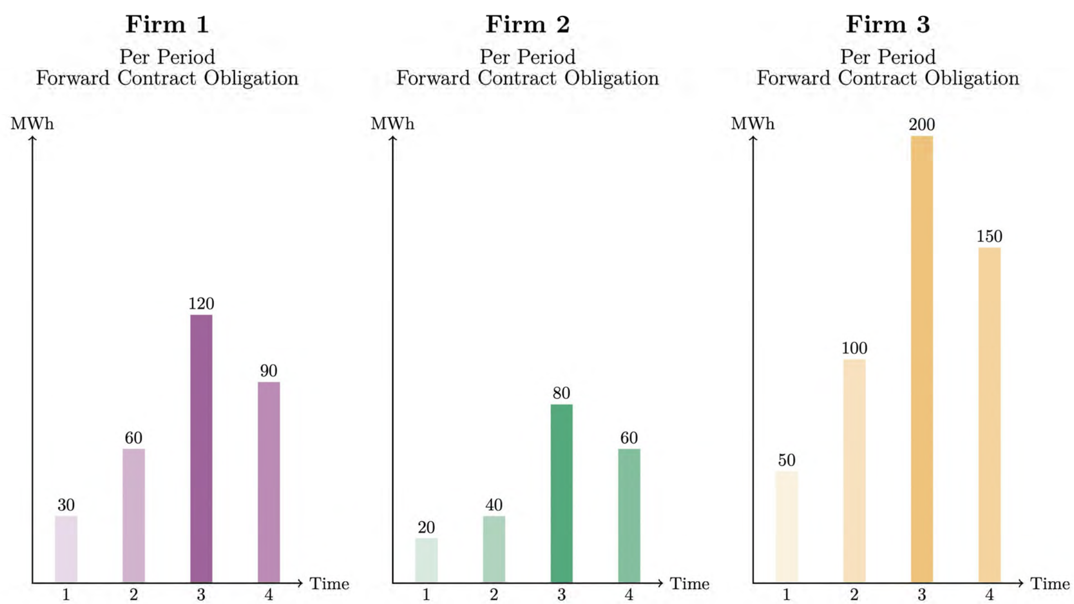
There are Three Firms:

Firm 1 sells 300 MWh

Firm 2 sells 200 MWh

Firm 3 sells 500 MWh

Total Amount Sold by Three Firms = 1000 MWh



Period-Level Values of QC_{hk} for Total Sales $Q_{total,k}$ of Each Firm k=1,2,3

$$\sum_{k=1}^{3} QC_{Total,k} = 1000 \text{ MWh} = \sum_{k=1}^{4} QD_h$$

Energy-Contracting Resource Adequacy Process

Standardized contracts can run for different delivery horizons

- Multi-year, single year, quarterly or monthly

Delivery on initial multi-year contracts should begin far enough in advance of delivery that new sources of supply can compete to provide energy

- At least three years between close of auction and delivery of energy
- Time horizon necessary for new entry to compete with existing generation unit owners to supply standardized forward contract

Contracts can be procured to meet actual system demand on behalf of retailers and large consumers through periodic standardized auctions

- Annually, Quarterly, Monthly

Simple auction mechanism can be used to procure energy because single product is being purchased—energy shaped to hourly system demand

- Can run simple declining clock auction to purchase standardized contract for energy

Energy-Contracting Resource Adequacy Process

Contracting mandates (percentages) are regulator's security blanket to ensure adequate supply of energy under all possible system conditions in future

- Allows offer cap on short-term energy market
- Can increase offer caps over time because system demand is hedged

No capacity requirement

- Lets suppliers figure out least cost way to meet system demand for energy and ancillary services
  - By allocating quantity risk associated with hourly variation in QC(h) among suppliers creates supply of operating reserves that can sell ancillary services
- Creates level playing field for demand-side and supply-side solutions
- Focuses on primary reliability problem in markets with significant amounts of renewables—adequate energy to serve demand
  - There has never been a shortage of generation capacity in California and other high renewables regions--New Zealand, Colombia, Brazil, and Chile--in wholesale market regime

Energy-Contracting Resource Adequacy Process

Periodic standardized auctions run by Market Operator overseen by State PUCs

- Purchases of standardized contracts are made and allocated to all loads based on their monthly (quarterly or annual) share of system load
- QD_k = system demand in MWh during interval k
- C_{ik} = consumption in MWh of retailer or large consumer i during interval k
- QC_{ik} = forward contract coverage of retailer or large customer i during interval k
  - Note that QC_{ik} shaped to system load shape, which may not match hourly load obligation of retailer

If allocation interval is a monthly, then retailers and large consumers have hourly value of QC_{ik} equal to their monthly share of system demand

- Can assign forward contract quantity to retailers and large consumers at lower or higher degree of temporal aggregation than monthly
- Only have to ensure that aggregate hourly difference payments between buyers and sellers of standardized contracts balance

Energy-Contracting Resource Adequacy Process

Overarching goal of standardized energy contracting approach to long-term resource adequacy

- All suppliers and load-serving entities know that actual system demand is fully hedged for all hours of the year
- Hourly output of individual suppliers is not fully hedged
- Hourly demand of individual load serving entities is not fully hedged

All suppliers and load serving entities are free to sign hedging arrangements to manage this residual short-term quantity and price risk

Wholesale energy markets typically start from zero hedging of system demand and market participants engage in hedging arrangements

- Inadequate amounts of hedging because of reliability externality

Standardized long-term contracting approach to resource adequacy starts from position that 100% of actual system load is hedged

- Suppliers and load-serving entities can take on short-term prices through additional hedging arrangements

Energy Contract Allocation Process

There are Four Retailers:

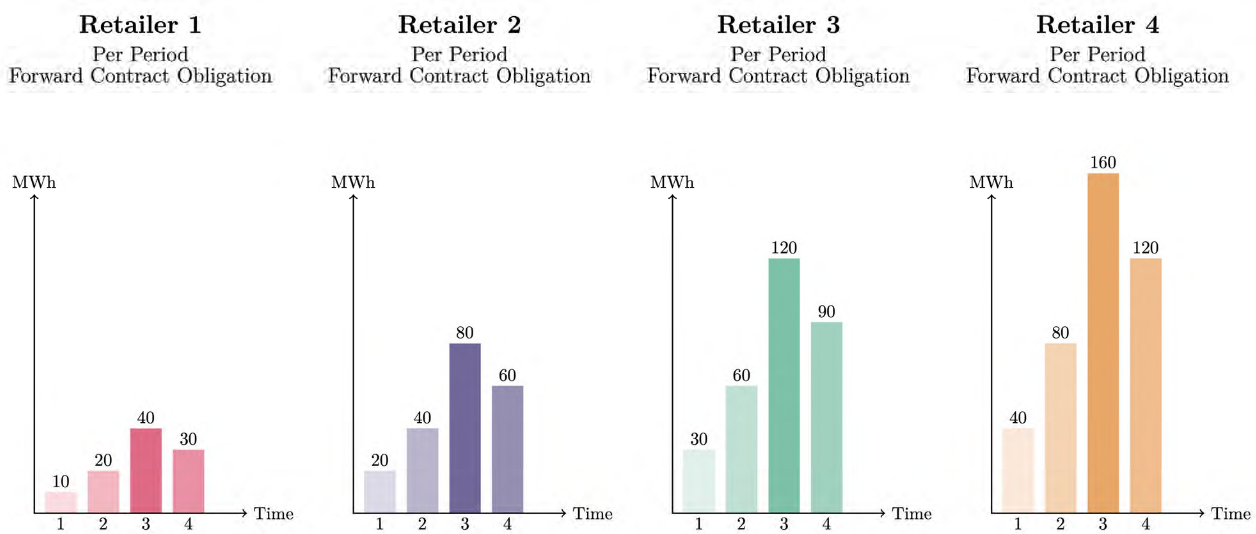
Retailer 1 sells 100 MWh

Retailer 2 sells 200 MWh

Retailer 3 sells 300 MWh

Retailer 4 sells 400 MWh

Total Amount Sold by Four Retailers = 1000 MWh



Sum of Hourly Forward Contract Obligations (QR_{hr}) Assigned to r=1,2,3,4 Retailers is equal to Hourly System Demand (QD_h) and Aggregate Forward Contract Obligations of Generation Unit Owners (QC_{hk})

$$\sum_{r=1}^{4} QR_{hr} = QD_h = \sum_{k=1}^{3} QC_{hk} \ \ for\ h = 1,2,3,4$$

Ex Post True-Up Process for 100% Coverage

There will be a need for true-up auctions to buy or sell standardized contracts for energy after the actual hourly output levels for the year have been determined

- Sales or purchases of incremental standardized fixed-price forward contracts occur and these contracts are allocated to loads using same monthly (quarterly or annual) load fractions

No suppliers and load-serving entities are disadvantaged by over-procurement or under-procurement of standardized fixed-price forward contracts

- Allocation of purchases and sales known before they occur

Ex Post Purchase for 100% Coverage

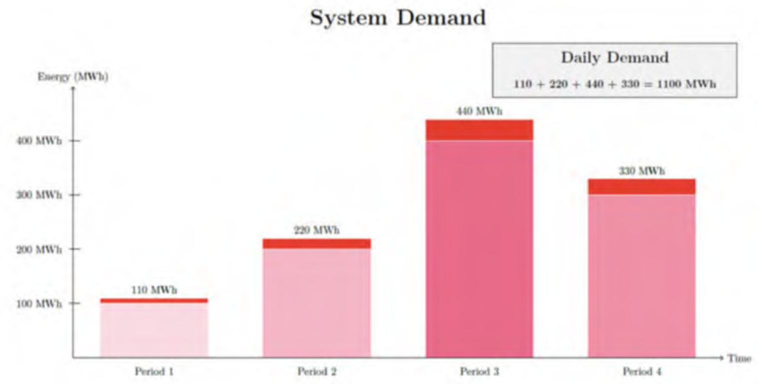


Figure 4: Hourly System Demands (10 Percent Higher)

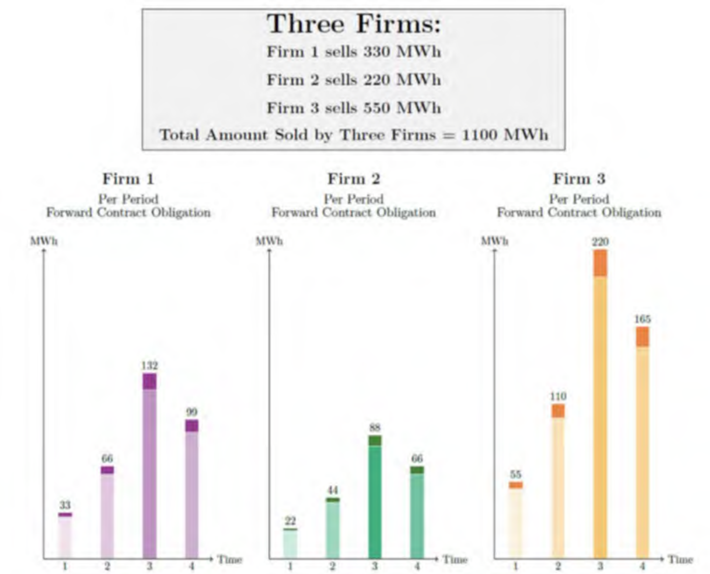


Figure 5: Hourly Forward Contract Quantities for Three Suppliers (10 Percent Higher)

Figure 6: Hourly Forward Contract Quantities for Four Retailers (10 Percent Higher)

Ex Post Sale for 100% Coverage

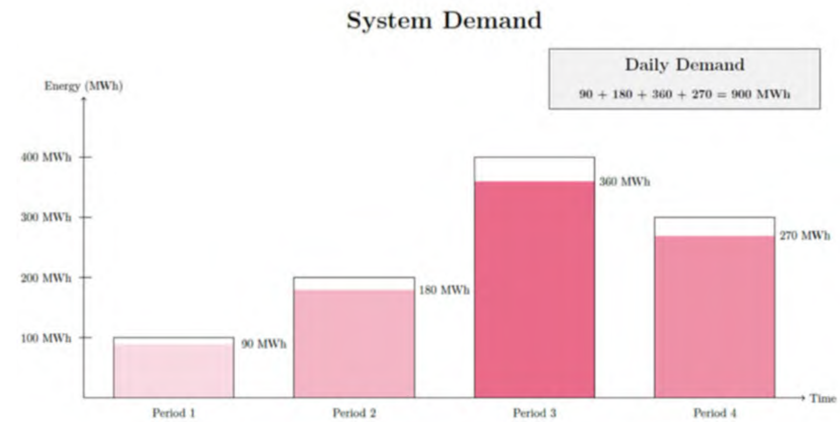


Figure 7: Hourly System Demands (10 Percent Lower)

Three Firms:
Firm 1 sells 270 MWh
Firm 2 sells 180 MWh
Firm 3 sells 450 MWh
Total Amount Sold by Three Firms = 900 MWh

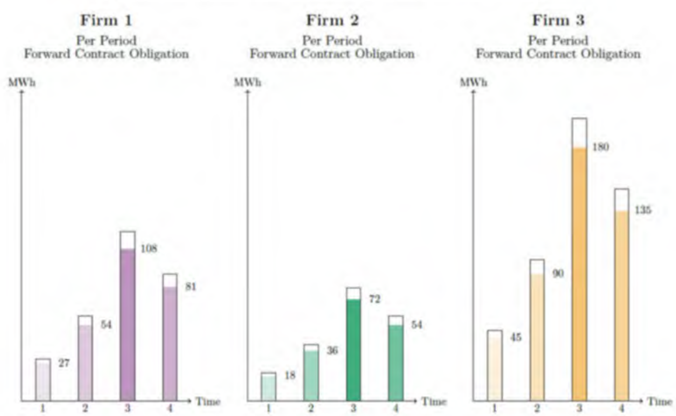


Figure 8: Hourly Forward Contract Quantities for Three Suppliers (10 Percent Lower)

Four Retailers:
Retailer 1 holds 90 MWh
Retailer 2 holds 180 MWh
Retailer 3 holds 270 MWh
Retailer 4 holds 360 MWh
Total Amount Held by Four Retailers = 900 MWh

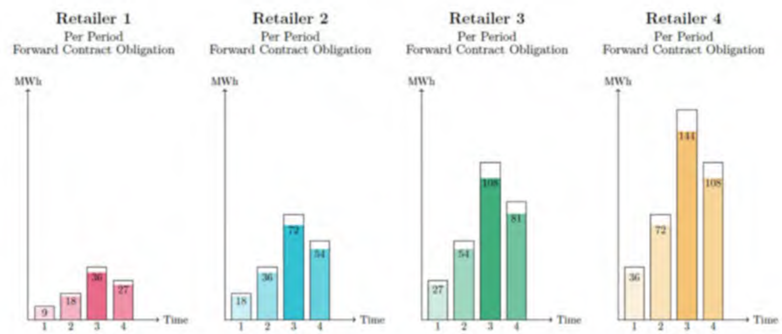


Figure 9: Hourly Forward Contract Quantities for Four Retailers (10 Percent Lower)

Energy-Contracting Resource Adequacy Process

To extent there is concern that appropriate mix of generation capacity may not be constructed to meet ancillary services requirement can run similar forward procurement process for each ancillary service

- ISO/PUCs can run standardized long-term contracts for each ancillary service tailored to hourly demand for that ancillary service
- Contract clear against short-term price for that ancillary service
- Same difference equation used to determine remaining quantity of each ancillary services

Ensures that aggregate demand for each ancillary service is purchased in forward market

- Lets suppliers figure out least cost way to meet system demand for each ancillary services
  - Allocates quantity risk associated with hourly variation in QC(h) for each ancillary services
- Creates level playing field for demand-side and supply-side solutions
- Note that sellers of ancillary service price hedge need not be supplier of ancillary services to short-term market
  - Seller bears full financial consequences of failure to meet forward market obligation for ancillary services

Energy-Contracting Resource Adequacy Process

Aggregate forward contract obligation for all suppliers should cover hourly system demand

- Interval level difference payments can be recovered from retailers and large loads over longer time interval
- Allocate to loads based on their monthly share of system demand

Contracts allocated to individual retailers and large consumers cannot be sold, they must be held to delivery

- This ensures that system demand is fully hedged
- Output of suppliers not fully hedged by their sales of this contract
- Aggregate, but not individual, consumption of retailers and large consumers fully hedged by this contract

Energy-Contracting Resource Adequacy Process

Hourly variable profits for retailers

(P(retail) – P(spot))Q(retail)+(P(spot) - P(contract))Q(contract)

= (P(retail) - P(contract))Q(contract)

+ (P(retail) – P(spot))(Q(retail)-Q(contract))

Hourly variable profits for generation unit owners

P(spot)Q(spot) + (P(contract) – P(spot))Q(contract) – C(Q(spot))

= P(contract)Q(contract) + P(spot)(Q(spot) – Q(Contract) – C(Q(spot)

Generation unit owner that produces no energy during hour earns

(P(contract) – P(spot))Q(contract)

Retailers that consumes Q(contract) during hour earns

= (P(retail) - P(contract))Q(contract)

Energy-Contracting Resource Adequacy Process

Contract sales by generators and purchases allocated to retailers do not preclude other bilateral contracts

- Standardized contracts for long-term resource adequacy mechanism

Generators can hedge their remaining wholesale price and quantity risk associated with production of energy from their generation units through bilateral contracts

- Standardized contracts designed to jump-start active forward market for energy

Retailers can hedge their remaining wholesale price and quantity risk through bilateral contracts

- QR_{ih} = hourly load obligation of retailer, P_h = hourly wholesale price
- Retailer can use combination of financial instruments and active demand side participation to manage remaining wholesale cost risk
  - $P_h(QR_{ih} - QC_{ih})$ = net energy purchases for retailer i in hour h

Energy-Contracting Resource Adequacy Process

There is no requirement that seller of contract must actually produce electricity sold in standardized forward contract

- Because producing electricity is only way to physically hedge this contract, some market participant will produce the electricity

This requirement addresses issue of futures contract sales by dispatch (thermal) generation unit owners

- These owners will often buy energy from short-term market instead of produce energy when there is a substantial amount of wind and solar energy is being produced

Encourages active demand-side participation in wholesale market (no need for low offers caps on short-term market)

- Consumers protected from high wholesale prices by financial contract coverage of final demand
- Consumers willing to manage short-term price risk can sell bilateral contract to expose themselves to this risk

Energy-Contracting Resource Adequacy Process

Making ISO comfortable with transition to an energy-contracting based resource adequacy mechanism

- The firm energy construct from capacity mechanism should be used to limit the amount of a standardized contract of energy a unit owner can sell
- Do not want unit owners in the aggregate selling more standardized energy than they are able to provide under all possible future system conditions

Dispatchable (typically thermal) resources will typically produce less energy than they are capable of producing during extreme system conditions

Intermittent resources will typically produce more energy than they are capable of producing during extreme system conditions

Mechanism supports necessary cross-hedging between dispatchable resources and intermittent resources required to ensure demand is met under all possible future system conditions

- Intermittent units purchase quantity insurance from dispatchable resources for standardized energy contracts sold
- Intermittent unit owner can purchase cap contract with payment stream max(0,P(spot)-P(strike))Q(contract)

Energy-Contracting Resource Adequacy Process

Ensuring cross-hedging between intermittent and dispatchable resources

- Allow existing resources only to sell up to their firm capacity
  - Amount of capacity unit can produce under stressed system conditions (determined by California ISO and CPUC)
  - Engineers determine this value as they do under existing capacity construct under current Resource Adequacy (RA) process
- Define Annual Firm energy (AFE) in MWh = Firm Capacity (in MW) x 8760

Each participant in standardized contract auction can only sell a total amount of annual energy than is less than or equal to annual firm energy value (AFE)

- Note this AFE value is more about financial viability of supplying this amount of forward energy during delivery period rather than physical viability
- Seller of standardized energy contract that owns intermittent resource, should purchase price and quantity insurance from dispatchable resources to hedge residual net revenue risk
  - Q_{ih} = actual output of supplier j in hour h
  - $P_h(Q_{jh} – QC_{jh})$ = net revenue of supplier j in hour h

Ensures that total standardized contracts for energy sold can actually be delivered under all possible future system conditions

- Under typical conditions, most energy produced by intermittent resources and dispatchable (thermal) resources purchase this energy to meet standardized energy contract obligations
- Under scarcity conditions, most energy produced by dispatchable (thermal) resources and intermittent resources only provide their firm energy

Energy-Contracting Resource Adequacy Process

To make efficient "make versus buy" decision to meet standardized forward contract obligation, thermal suppliers will submit offer to supply energy at marginal cost

- If Price > MC, supplying from unit is cheapest way to meet forward contract obligation
- If Price < MC, buying from short-term market is cheapest way to meet obligation

Allocation of standardized contracts across dispatchable (thermal) suppliers ensures that all are committed to the short-term market at marginal cost for at least the hourly value of QC

Allocation of standardized contracts across intermittent suppliers ensures that they have strong incentive to make arrangements to supply or purchase at least hourly value of QC

- Can purchase price spike insurance from dispatchable (thermal) resources against hourly value of QC
  - To extent ISO and CPUC does not believe renewable resource can provide actual required energy to meet obligations under standardized forward contracts, they should reduce value of firm capacity and therefore AFE that supplier can sell in standardized energy contracts
  - Increases demand for standardized energy from fast start dispatchable resources

Energy-Contracting Resource Adequacy Process

How do new entrants compete in these auctions?

- New entrant sells energy to be delivered three years in the future must show reasonable progress towards having amount of AFE sold in real-time
- If reasonable progress according to CAISO and CPUC is not shown, then contract is liquidated and purchase must be made in upcoming standardized energy auction to meet this shortfall
- Reasonable progress showing can be done every six months through filing by new entrant and site review by CPUC and CAISO staff
- Cost of forward energy purchased to replace energy not supplied by new entrant is allocated to all loads in proportion to load share as described earlier

Energy-Contracting Resource Adequacy Process

Two approaches to managing local long-term resource adequacy

- Allow suppliers to sort out least cost way to meet local reliability constraints
- Can run auctions for standardized contracts that clear against different pricing hubs
  - Different spatial aggregated prices for each retailer
  - Need to determine service territory-level demands that sum to total system demand

Suppliers with fixed-price forward contract obligations that clear against geographically aggregated prices have a strong incentive to keep these short-term prices as low as possible until cover fixed price forward contract obligations

Suppliers that have sold contracts have strong incentive to limit price dispersion across locations

- Meet aggregate demand at lowest possible costs

Each supplier has a strong incentive to make the efficient “make versus buy” decision for its hourly forward contract quantity within in the service territory

Energy-Contracting Resource Adequacy Process

Products must be purchased far enough in advance of delivery to allow new entrants to compete to supply products

- Suppliers with local market power can be disciplined by actions of suppliers that have sold forward standardized forward contracts
- Reduce regulatory burden to manage local market power
- Important goal of standardized contract-based resource adequacy approach is to allow entities best able to manage supply risk, manage this risk
  - Avoid costly legal process at FERC and CPUC to obtain necessary generation capacity to meet demand under all possible future system conditions

Energy-Contracting Resource Adequacy Process

Transitioning to this approach to long-term resource adequacy requires significant advance notice

- First procurement of contracts should start delivery at least three years in advance

Retailers and generation owners need sufficient time to adapt to an energy-contracting resource adequacy process

Significantly more cross-hedging between resources to ensure system demand is met under all possible future system conditions

- Intermittent resources re-insurance with dispatchable resources
- Dispatchable resources earn premium for providing this insurance

Mechanism values a firm MWh more than a non-firm MWh

Bonus Topic:

Experimental Comparison of Capacity-Based versus Energy Contracting-Based Long-Term Resource Adequacy Mechanisms

Application to Long-Term Resource Adequacy

www.energymarketgame.org

Energy Market Game

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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.

PESD gratefully acknowledges funding support from the following organizations:

William and Flora Hewlett Foundation

HEISING-SIMONS FOUNDATION

www.energymarketgame.org/pages/about-us.html

Energy Market Game

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Game Creators

Frank Wolak 	Frank is the Director of the Program on Energy and Sustainable Development (PESD) and the Holbrook Working Professor of Commodity Price Studies in the Department of Economics at Stanford University. His recent work studies methods for introducing competition into infrastructure industries - telecommunications, electricity, water delivery, and postal delivery services - and on assessing the impacts of competition policies on consumer and producer welfare. From January 1, 1998 to March 31, 2011, Frank was the Chair of the Market Surveillance Committee of the California Independent System Operator for the electricity supply industry in California. Frank was also a member of the Emissions Market Advisory Committee (EMAC), which advised the California Air Resources Board on the design and monitoring of the state's cap-and-trade market for Greenhouse Gas Emissions allowances.
Mark Thurber 	Mark is Associate Director of the Program on Energy and Sustainable Development (PESD) at Stanford University. He uses the energy market game as a central teaching tool in a course he teaches with Frank in the Stanford Graduate School of Business ("Energy Markets and Policy"). Mark studies markets for oil, natural gas, and coal in addition to electricity markets. He coedited and contributed to *Oil and Governance*, a 2012 book on state-controlled oil companies, and *The Global Coal Market*, a 2015 book on how policies toward coal in the most important coal producing, consuming, and exporting countries (specifically, China, India, Indonesia, Australia, South Africa, and the United States) affect economic and environmental outcomes.
Trevor Davis 	Trevor Davis is a Postdoctoral Scholar in the Department of Economics at Stanford University. He researches policy impacts on electricity markets and is the lead developer of the Energy Market Game. Prior to arriving at Stanford Trevor worked at the Federal Reserve Board of Governors in Washington, DC.

Application to Long-Term Resource Adequacy

- Run capacity market versus energy contracting market experiment with Western US States regulators and members of staff of ANEEL, Brazilian Electricity Regulator (separately)
- In each game players face identical demand and renewable energy realizations
  - Only difference in games is long-term resource adequacy process
- Capacity Market—Players compete to sell firm capacity equal to 110 percent of peak demand in a uniform price auction
- Players given table of firm capacity, fixed cost, variable for each possible technology they can build
- Players must construct at least the amount of firm capacity they won in capacity auction
- Players required to meet 33% renewables portfolio standard
- Players then compete to sell electricity in offer-based short term market

- Energy Contracting Market—Players compete to sell long-term energy contracts tailored to daily load shape equal to 100 percent of expected demand in game
- Players given same table of fixed cost and variable cost for each technology
- Players were free to construct any mix of generation units to meet their forward contract obligations
- Players required to meet 33% renewables portfolio standard
- Players then compete to sell electricity in offer-based short-term market

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Players required to meet 33% renewables portfolio standard

Players then compete to sell electricity in offer-based short term market

Energy Contracting Market—Players compete to sell long-term energy contracts tailored to daily load shape equal to 100 percent of expected demand in game

Players given same table of fixed cost and variable cost for each technology

Players were free to construct any mix of generation units to meet their forward contract obligations

Players required to meet 33% renewables portfolio standard

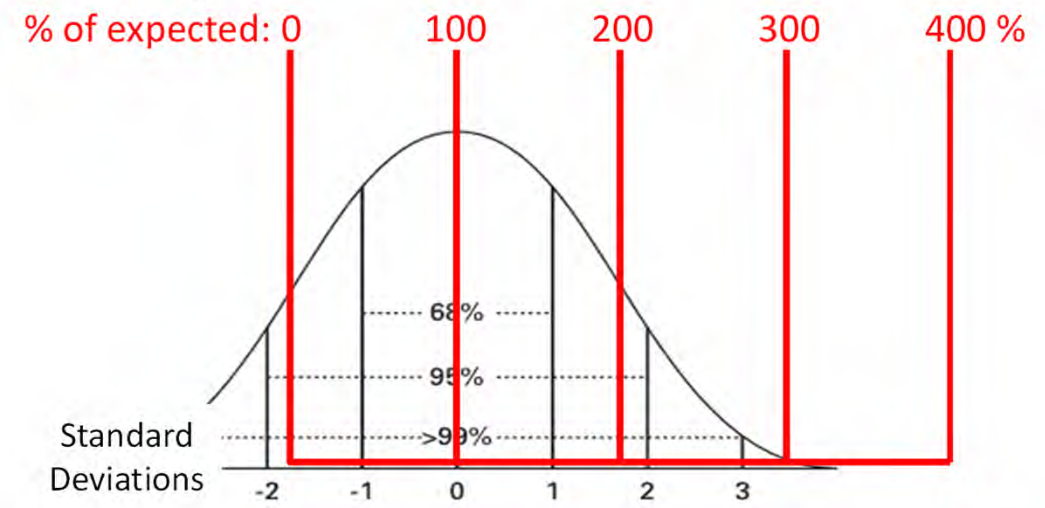
Players then compete to sell electricity in offer-based short-term market

Variable Energy Resources

- Intermittent renewable generation units produce throughout day in similar pattern to actual pattern of production in California

Type	Expected Generation (Normalized to Overall Average)				Variable Cost ($/MWh)
	4am	10am	4pm	10pm	
Wind	1.3	0.7	0.7	1.3	$0
Solar PV	0	2.0	2.0	0	$0

Variability



Renewable generation will fall between 40% and 160% of its “expected” value 68% of the time

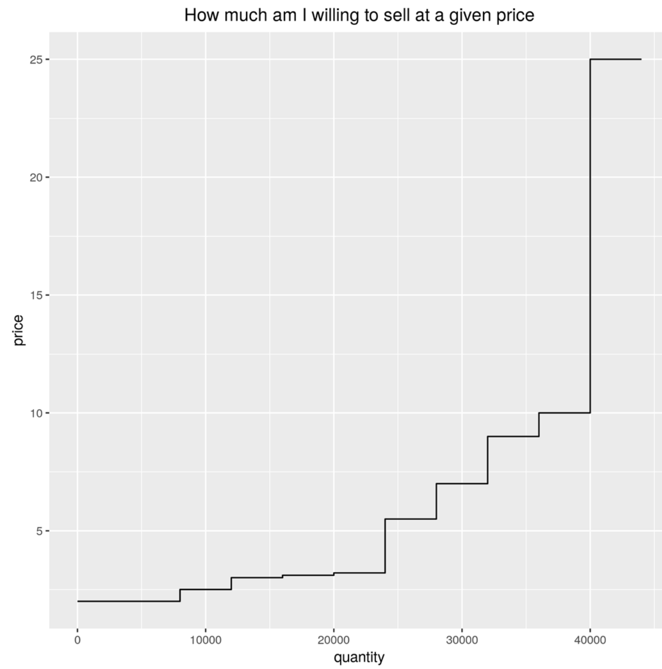
Capacity Market game mechanics

1) Submit auction bids ($/MW-hr) for available capacity

price	quantity
$2.00	8,000
$2.50	12,000
$3.00	16,000
$3.10	20,000
$3.20	24,000
$5.50	28,000
$7.00	32,000
$9.00	36,000
$10.00	40,000
$25.00	44,000

Enter new bids

bids submitted



- Minimum bid is $2/MW-hr (2/3 of fixed cost of Peak unit)
- Maximum bid is $25/MW-hr (full fixed cost of Base unit)
- Renewables counted at expected 4pm output
- Your existing capacity is bid in at minimum

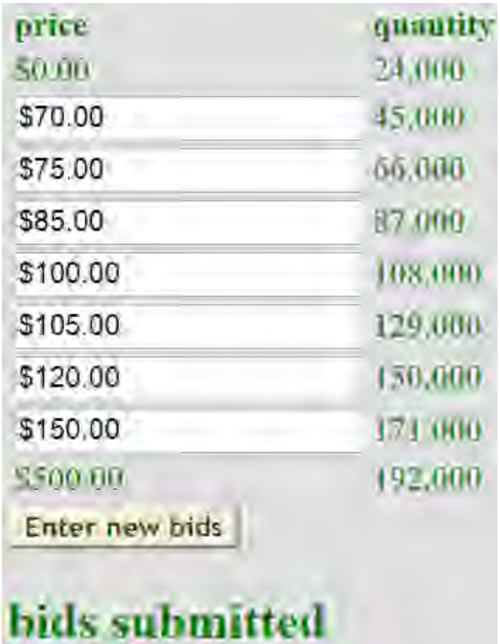
2) Buy/decommission units to meet capacity contracts you won (*required*)

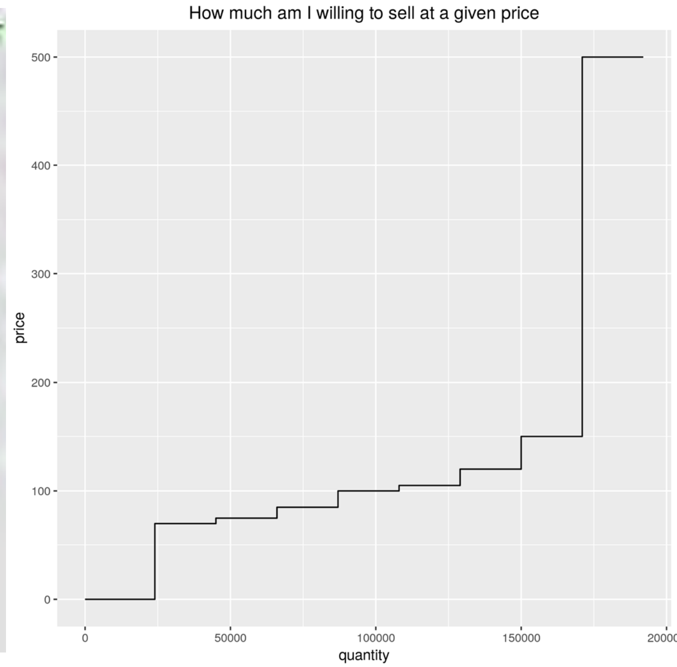
Plant Type	Capacity (MW)	Var Cost ($/MWh)	Fixed cost ($/hr)	Fixed cost ($/MW-hr)	LCOE ($/MWh) -- by portion of hours running 10%	25%	50%	75%	100%
Base	2000/1000	20	100,000/25,000	25	270	120	70	53	45
Intermediate	1000	45	10,000	10	145	85	65	58	55
Peak	1000	90	3,000	3	120	102	96	94	93

3) Bid in all thermal units to maximize returns

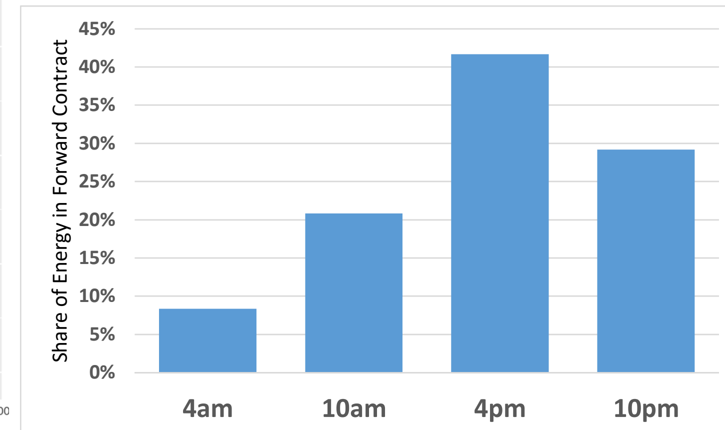
Forward Energy Contracting game mechanics

1) Submit auction bids ($/MWh) for available forward contracts (~100% of demand)





- Forward contracts have fixed load shape expected to meet demand



2) Buy/decommission units to physically hedge forward contracts you won

Plant Type	Capacity (MW)	Var Cost ($/MWh)	Fixed cost ($/hr)	Fixed cost ($/MW-hr)	LCOE ($/MWh) -- by portion of hours running				
					10%	25%	50%	75%	100%
Base	2000/1000	20	100,000/25,000	25	270	120	70	53	45
Intermediate	1000	45	10,000	10	145	85	65	58	55
Peak	1000	90	3,000	3	120	102	96	94	93

- Renewables are not firm! (Can hedge if desired with more extra thermal capacity)

3) Bid in all thermal units to maximize returns. (Remember incentives w/contracts!)

Summary of Experiment Results

- For both games and both set of players—Western US regulators and ANEEL staff--computed average revenues paid by load and average cost to serve demand for game
- Capacity payment mechanism
  - Capacity payments, energy contracting and short-term energy market revenues divided by total demand served ($/MWh)
  - Total cost of serving demand divided by total demand ($/MWh)
- Energy contracting market
  - Energy contracting and short-term energy market revenues divided by total demand served ($/MWh)
  - Total cost of serving demand divided by total demand ($/MWh)
- For both Western US regulators and ANEEL staff average wholesale revenues per MWh from capacity mechanism was close to double that for energy contracting approach
  - Average cost to serve demand slightly lower for energy contracting approach

Concluding Comments

- Hard to find empirical evidence anywhere in the world of a well-performing capacity market
  - Even capacity market based on peak energy rent refunds in Colombia appears to reduce rather that improve market efficiency
- Standardized forward financial contracting approach appears to come closest to achieving market design goals in Singapore
  - Buy necessary energy far enough in advance of delivery to allow maximum flexibility of suppliers to meet these obligations at least cost and limit market power in spot market
  - Regulator must set portfolio standards for adequate hedging if maintain price and bid caps or shield final demand from short-term prices
- Head-to-head comparison of capacity market approach to energy contracting approach for two diverse groups—Western US regulators and staff of ANEEL yields same conclusions
  - Energy contracting is lower average cost per MWh, for consumers, approach
  - Lower average cost of production approach
- Contract adequacy approach can allow significant demand-side involvement as part of retailer's hedging strategy
  - With symmetric treatment of load and generation, individual loads can choose level of exposure to short-term price risk
  - Retailers can offer short-term price risk and mean price profiles and consumers choose which combination they prefer
  - Forward contracting is then tailored to hedge remaining fixed price retail obligations

Concluding Thought

There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new."

– Niccolo Machiavelli (The Prince)

Thank you
Questions/Comments