Smart Grid and Renewable Electric Generation

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Outline

- Electric Grid - Background
- Smart Grid
- Renewable Generation
- Grid Integration
- Storage
- Future Directions

Focus on system operations,
not on specific hardware technologies

Electric Grid Characteristics

High voltage transmission network - a *mesh* network

Distribution networks - largely *radial* networks

Dynamic system with multiple time scales

Milliseconds, seconds, minutes, hours, days, months, and years

Electric energy storage - very expensive

Energy produced must equal energy consumed on a second-by-second basis – *power balance*

A complex hierarchical control system to ensure stability and performance of the large scale networked power system

Power System Operations

Power balance – balance power generation and consumption on a second-by-second basis

Main Approach: *adjust supply to meet demand with reliability*

Natural uncertainty in consumption [load]

Use of reserve capacity to manage uncertainty and contingencies

Day-ahead – hourly schedules, one day ahead

Real-time – 5 minute schedules, 15 minutes ahead

Automatic generation control using system frequency

Fast relays and circuit breakers for protection

Deregulation of the electricity sector – *unique mix of engineering and economics*

Aging Grid Infrastructure

Transmission and distribution infrastructure is aging in the US

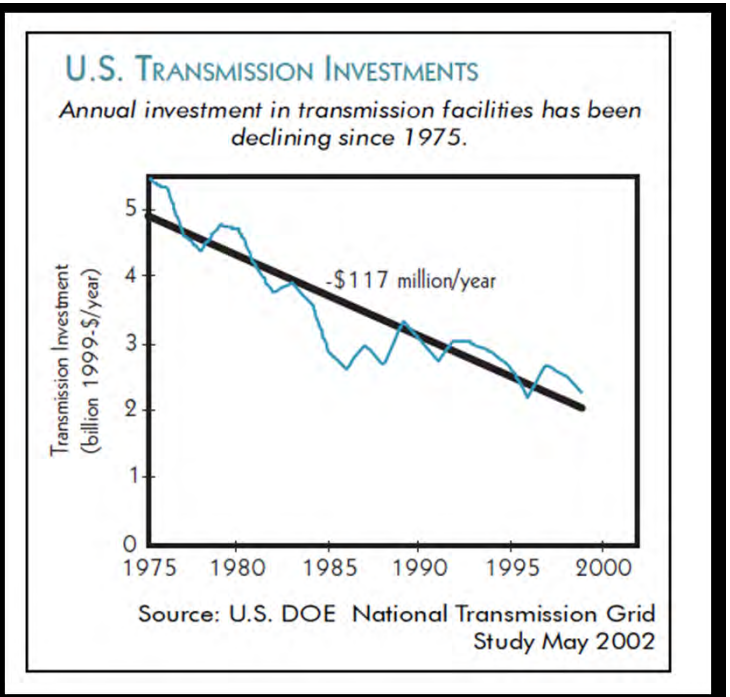
More than 70% of transmission lines and transformers are 25 years or older

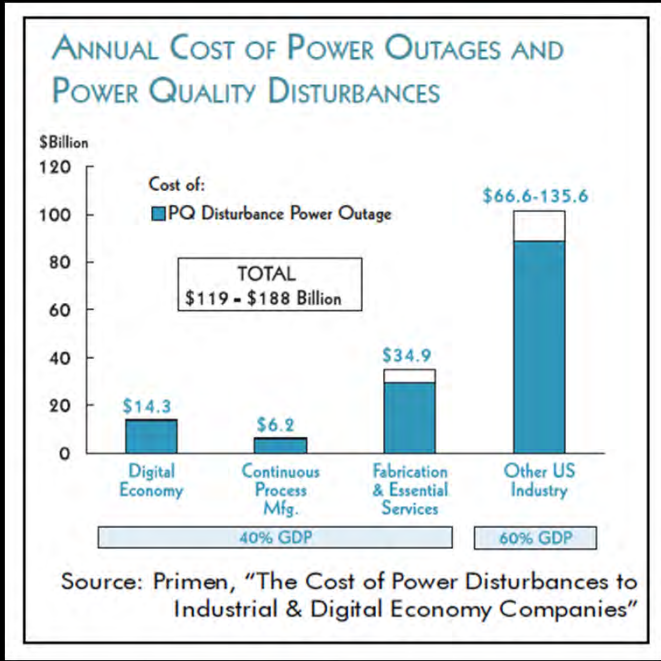
More than 65% of circuit breakers are 25 years or older

25-35% of generation and transmission nearing end of useful life and 8% are already beyond useful life

Almost 50% of GT assets will be replaced by 2030

Total investment ~ $975B

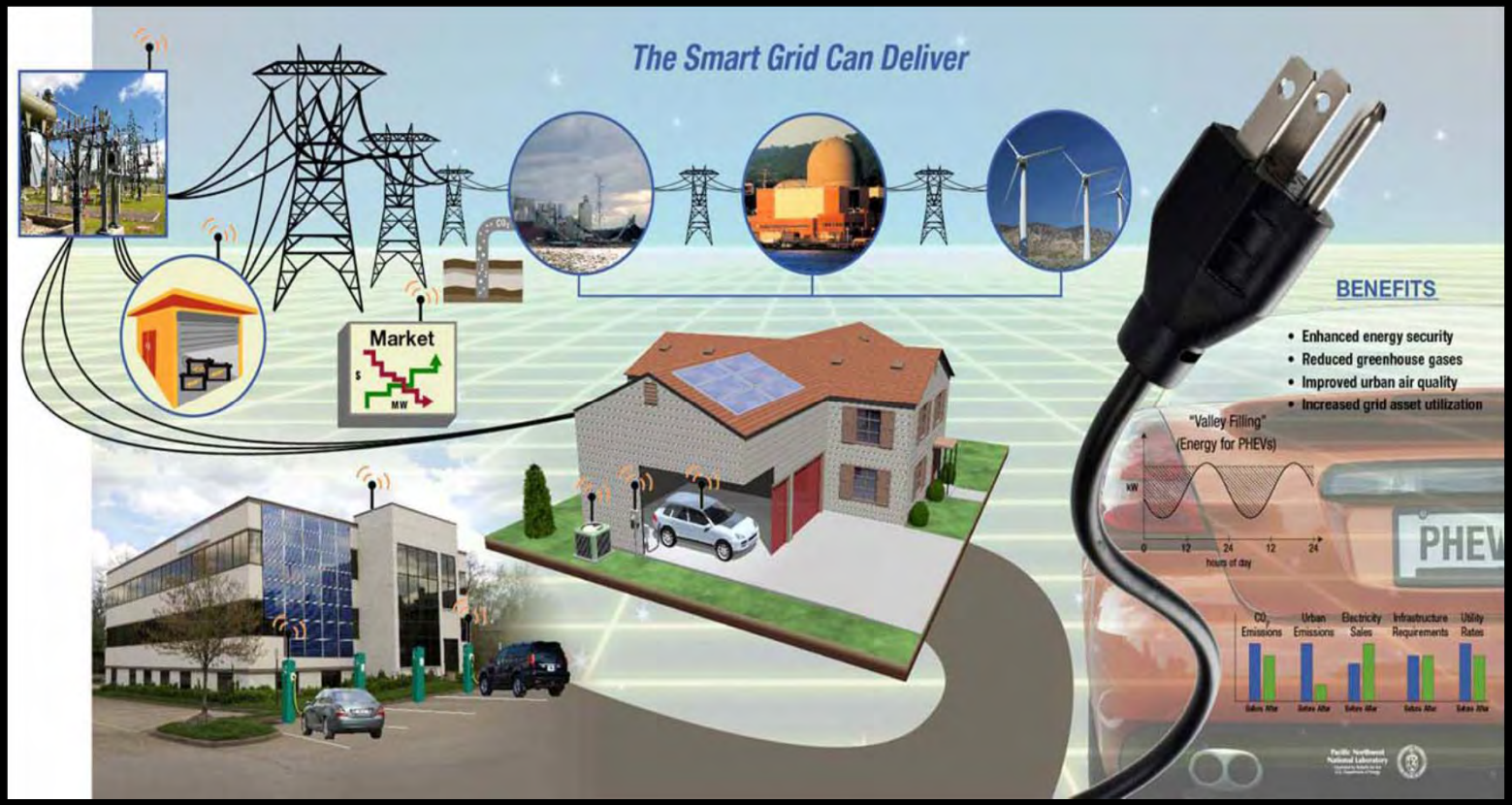




Source: Black and Veatch, 2009

Smart Grid =

Power Grid + Sensors + Communications + Computation + Control



Source: DOE

Smart Grid is a Vision

"a stronger, smarter, more efficient electricity infrastructure that will encourage growth in renewable energy sources, empower consumers to reduce their energy use, and lay the foundation for sustained, long-term economic expansion"

Steven Chu, U.S. Energy Secretary, 2009

Source: Smart Grid System Report, U.S. DOE, July 2009

Smart Grid Assets

Demand response (DR)

- communications and controls for end-use devices
- coordination of multitude of resources

Distributed generation (DG)

- micro-generators, wind turbines, and solar connected at the distribution level.

Distributed storage (DS)

- batteries, flywheels, magnetic storage connected to distribution

Distribution/feeder automation (DA/FA)

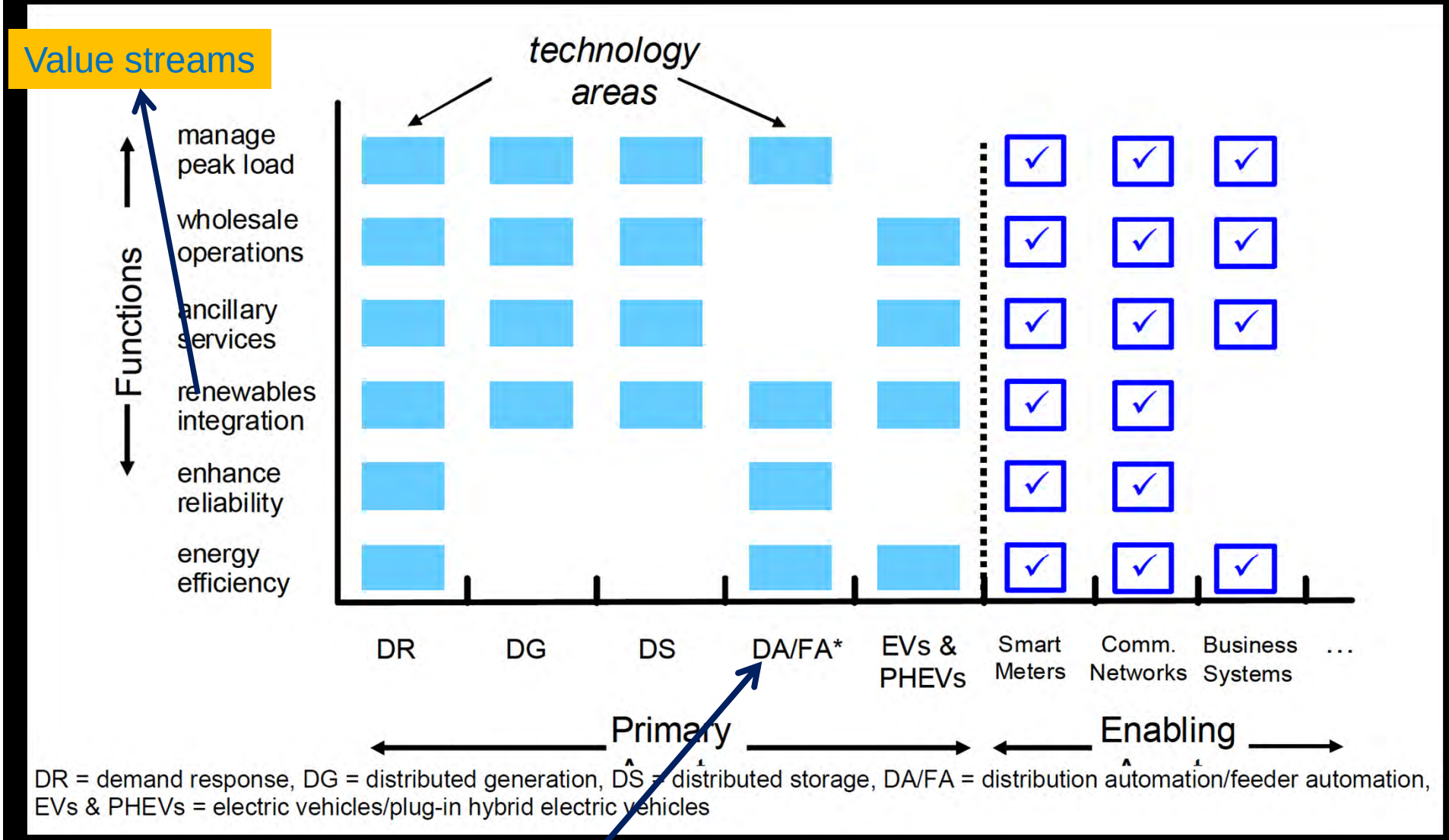
- communications and control in substations and feeders with remotely actuated switches for reconfiguration

Electric and plug-in electric hybrid vehicles

Enablers: *communications, computing, control/automation*

Source: Pratt et al., PNNL-19112, Revision 1

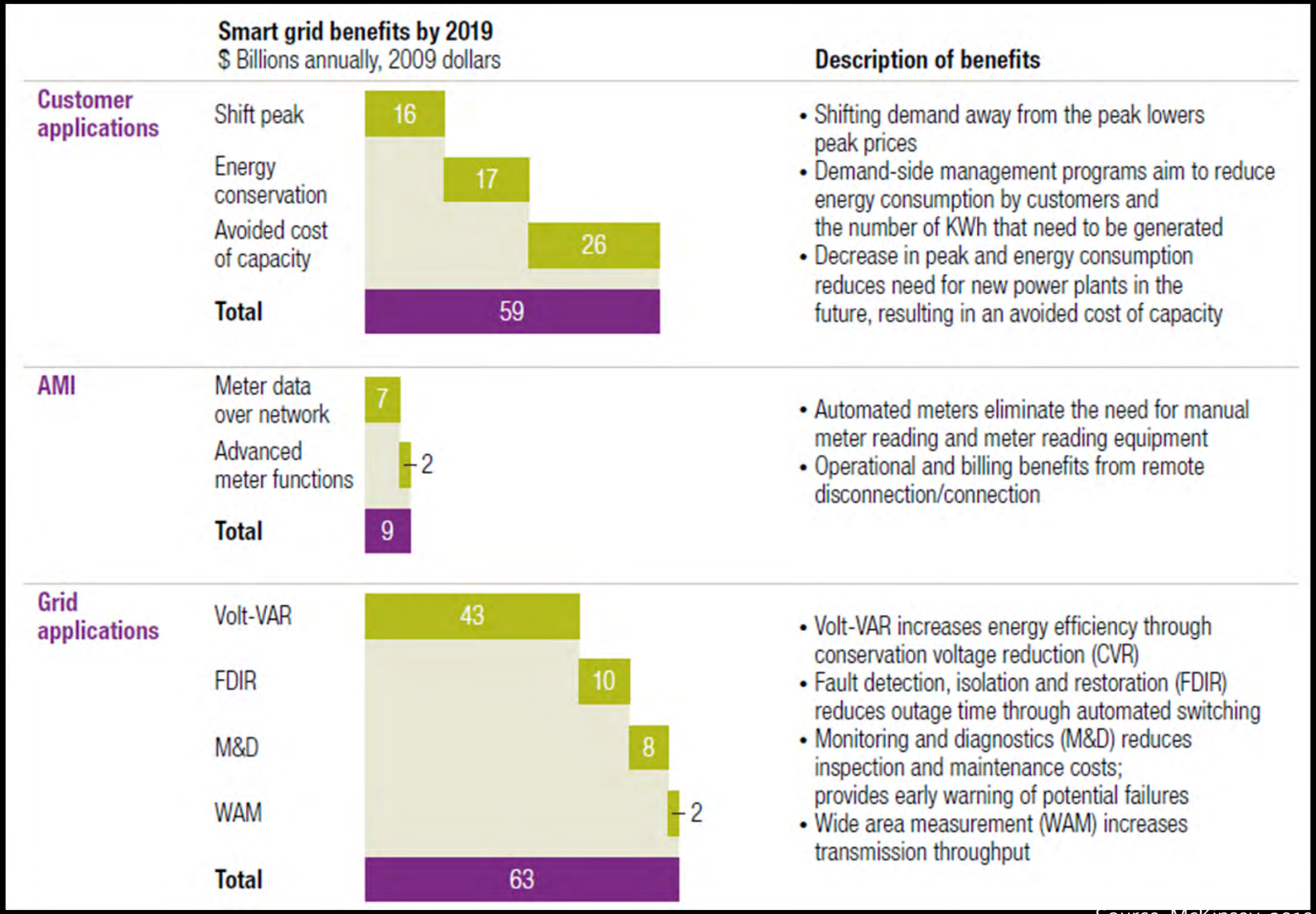
Smart Grid – Assets and Functions



Investments

Source: Pratt et al., PNNL-19112, Revision 1

Uncertainty is the main problem and opportunity



Source: McKinsey, 2010

Smart Grid Projected Impact

Source: Pratt et al., PNNL-19112, Revision 1

Table S.1. Potential Reductions in Electricity and CO_2 Emissions in 2030 Attributable to Smart Grid Technologies

Mechanism	Reductions in Electricity Sector Energy and CO_2 Emissions[(a)]	
	Direct (%)	Indirect (%)
Conservation Effect of Consumer Information and Feedback Systems	3	-
Joint Marketing of Energy Efficiency and Demand Response Programs	-	0
Deployment of Diagnostics in Residential and Small/Medium Commercial Buildings	3	-
Measurement & Verification (M&V) for Energy Efficiency Programs	1	0.5
Shifting Load to More Efficient Generation	<0.1	-
Support Additional Electric Vehicles and Plug-In Hybrid Electric Vehicles	3	-
Conservation Voltage Reduction and Advanced Voltage Control	2	-
Support Penetration of Renewable Wind and Solar Generation (25% renewable portfolio standard [RPS])	<0.1	5
Total Reduction	**12**	**6**

(a) Assumes 100% penetration of the smart grid technologies.

"while a smart grid is not the primary mechanism for achieving aggressive national goals for energy and carbon savings, it is capable of providing a very substantial contribution"

Renewable Integration

Main RG Technologies

Wind

Solar

Ocean

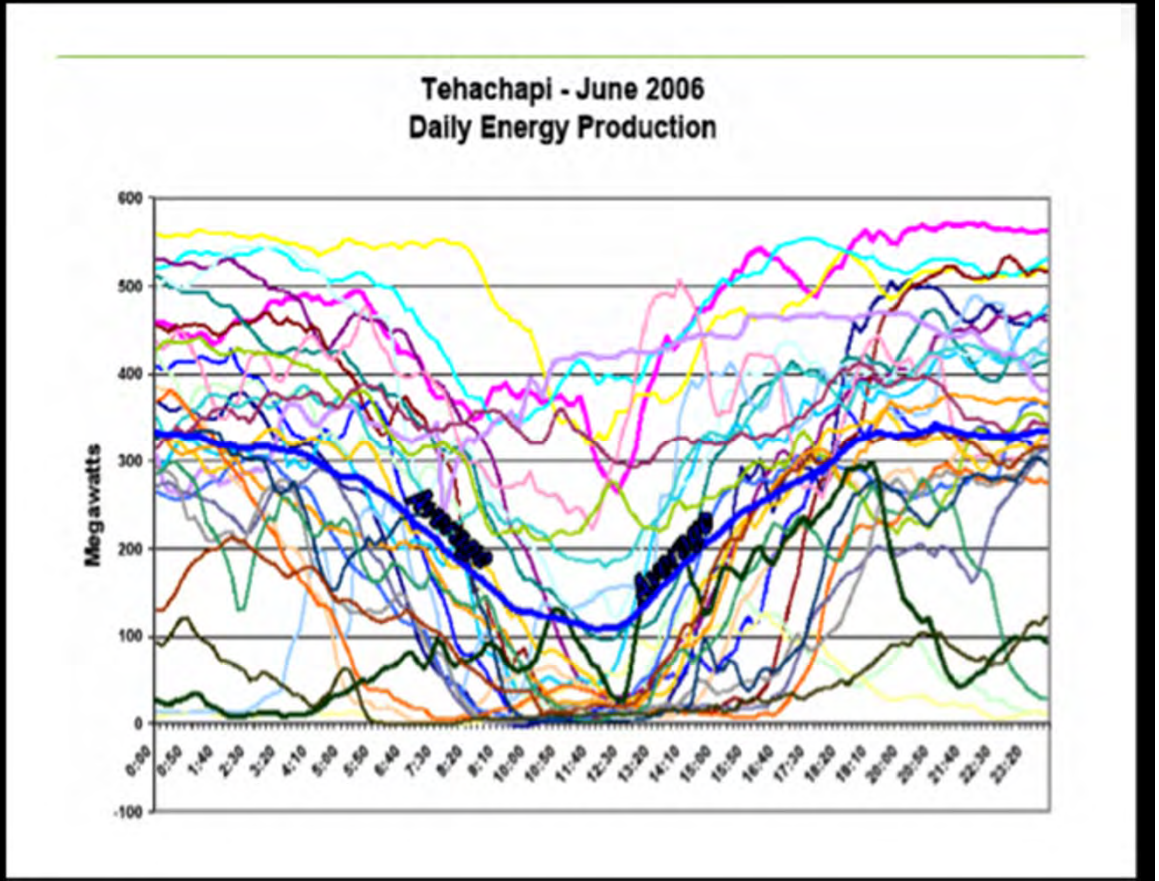
Biomass

Variability of Wind and Solar

Source: CAISO

Power output varies in all time frames:

- Annual
- Seasonal
- Daily
- Hours
- Minutes
- Seconds



Intermittency, uncontrollability, and uncertainty - principal causes of difficulty at the operational level in integration of wind and solar into the grid.

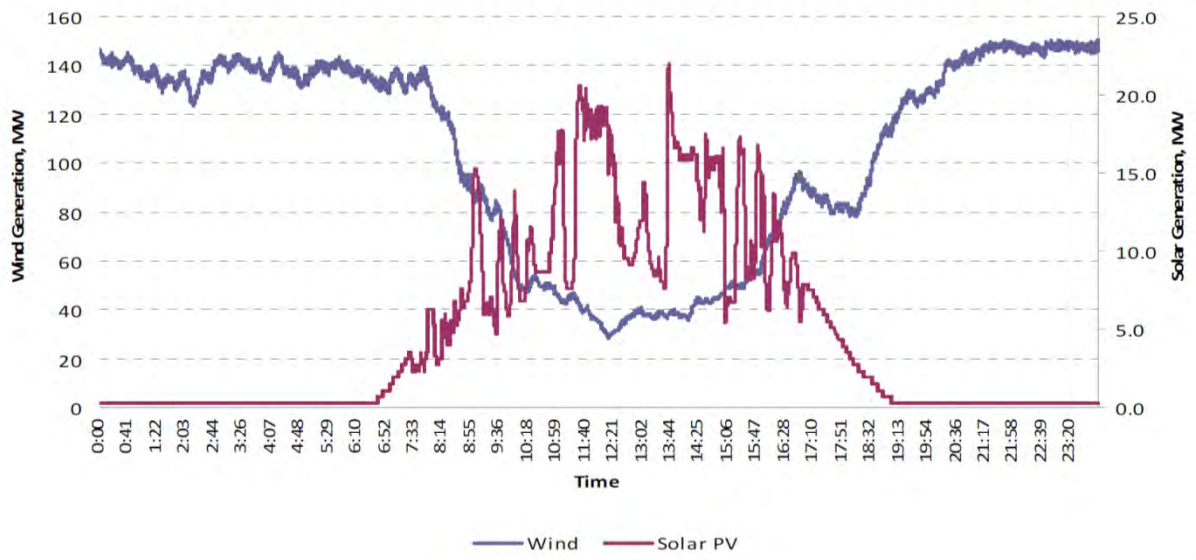


Figure 1-2: Sub-hourly wind and solar generation for a day for a 150 MW wind generator and a 24 MW Solar PV plant

Figure 1-3: Sub-hourly wind and solar generation profiles for an hour

Large ramps, up and down, pose particular difficulties

Source: Integration of Renewable Resources at 20% RPS, CAISO, 2010

Variability – Three Distinct Issues

Uncertainty – reliable predictions of power output are hard, particularly day ahead

Uncontrollability – power output cannot be controlled as desired

Intermittency – even if we could predict perfectly, the power output is inherently variable

"Variable Generation" captures all three aspects

Capacity Credit

Resource Adequacy (RA) requirements

- Particularly challenging in deregulated markets; capacity markets

Capacity credit

- Nameplate capacity fraction for meeting RA requirements

What is the capacity credit of VG (wind)?

- PJM, MISO – 13%, NYISO – 10% (summer), SPP – 10%, E.ON – 8%

What are the impacts on power system planning?

How much traditional generation can be displaced by VG?

What happens at deep penetration of VG?

Current Strategy

Subsidies and public policy – absorb all renewable power

- Deal with variability injected by the renewables
- Adds to natural load variability
- Increases the need for additional reserves

Consequence:

- Increased reserves
- Expensive
- Reduce carbon reduction benefits
- May increase emissions due to cycling

This will become almost impossible at 30-40% renewable penetration

Optimal Offering by Renewable Producers

Contracts for fixed level of power output over 1 hour.

Questions:

- What is the optimal offering strategy for the wind producer?
- What is the optimal multi-stage bidding strategy to maximize its profits?
- What is the value of better prediction?

Answers:

- Optimal bid = γ quantile of the averaged wind power cdf
- Formulae for multi-stage optimal bids
- Formulae for the economic value of extra information

Bitar et al CDC'2010, ACC'2011, HICSS'2012

Quantile Policy

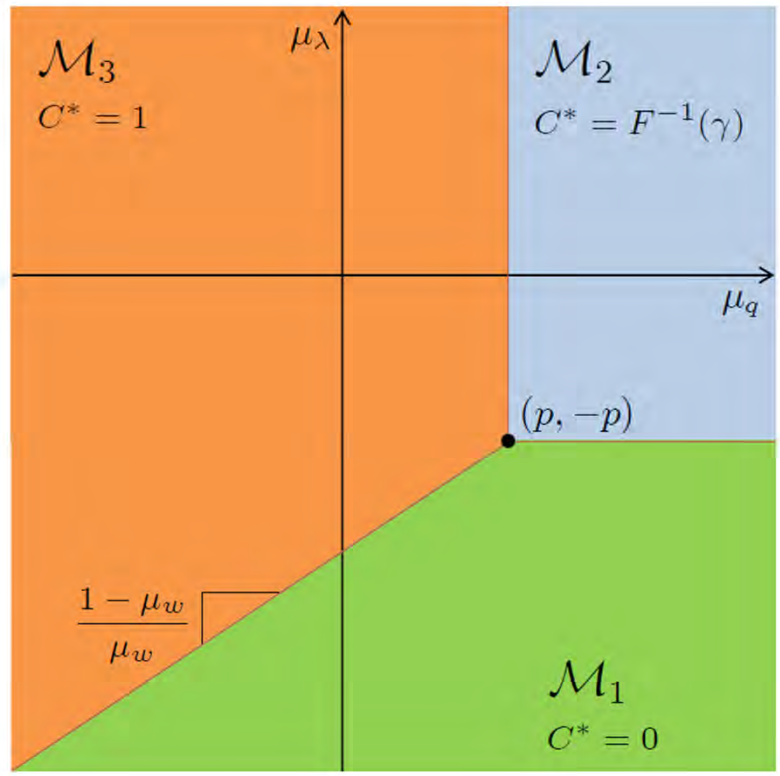


Fig. 1. Graphical illustration of the optimal bidding policy C^* as a function of the expected imbalance prices (μ_q, μ_λ).

amounts to price based curtailment
provides a price signal to "firm" variable output

Benefits of Aggregation

Consider a collection of geographically dispersed VG producers.

Intuition: *Averaging can reduce variability*

Question:

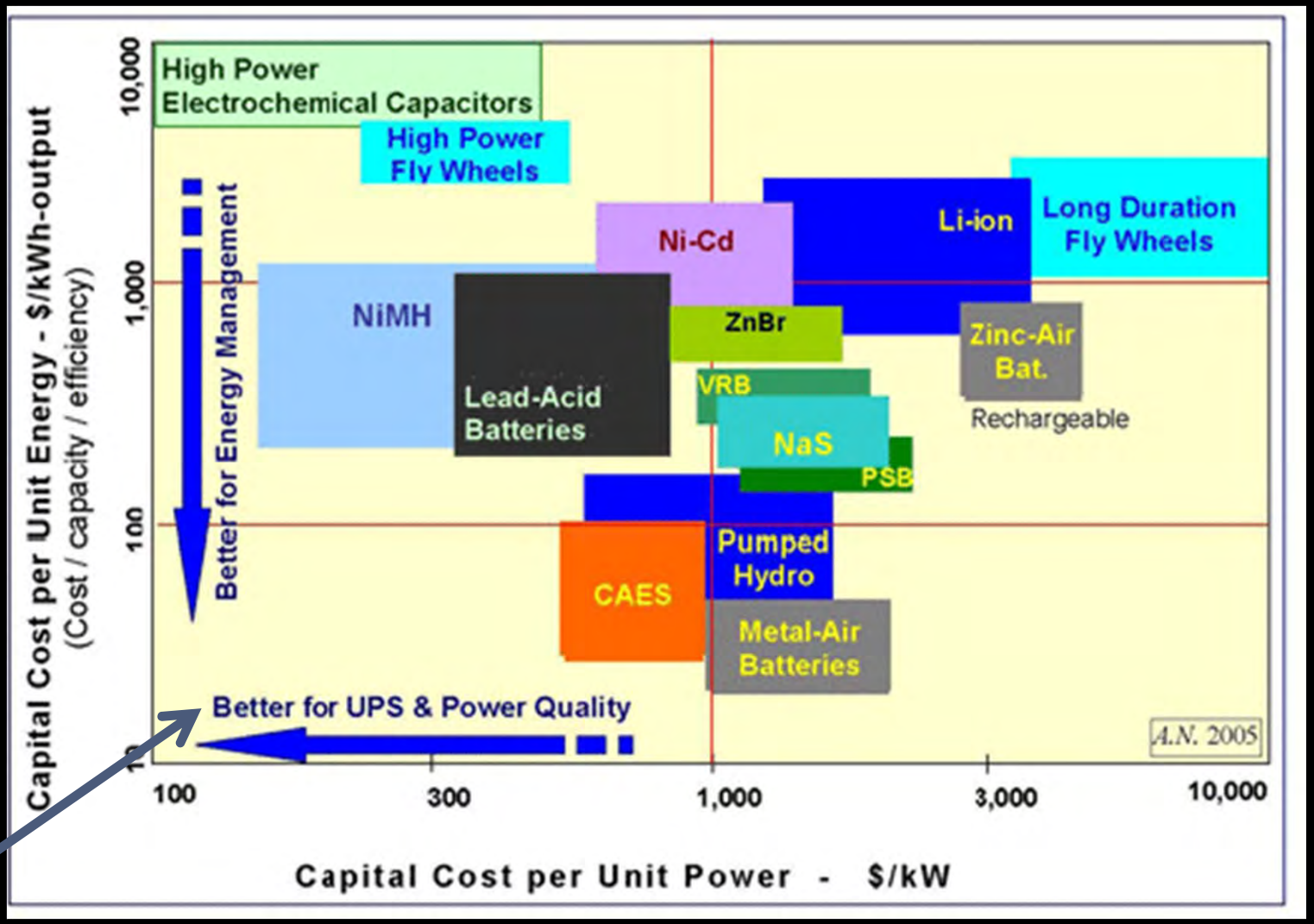
Can a group of VG producers increase their collective profits by aggregating and offering their power output as a single entity?

Answer: *For the single bus case:*

1. Yes. *Theory of coalitional games.*
2. There exists a distribution of profits that keeps the coalition *stable*.
3. The coalitional game is not convex and the famous Shapley value does not satisfy the required stabilizing property.

Bayens et al. CDC'2011

Storage



Source: Electrical Storage Association

Big hole

Storage

Power system applications: arbitrage, peak load shifting, reserves, frequency regulation

Questions:

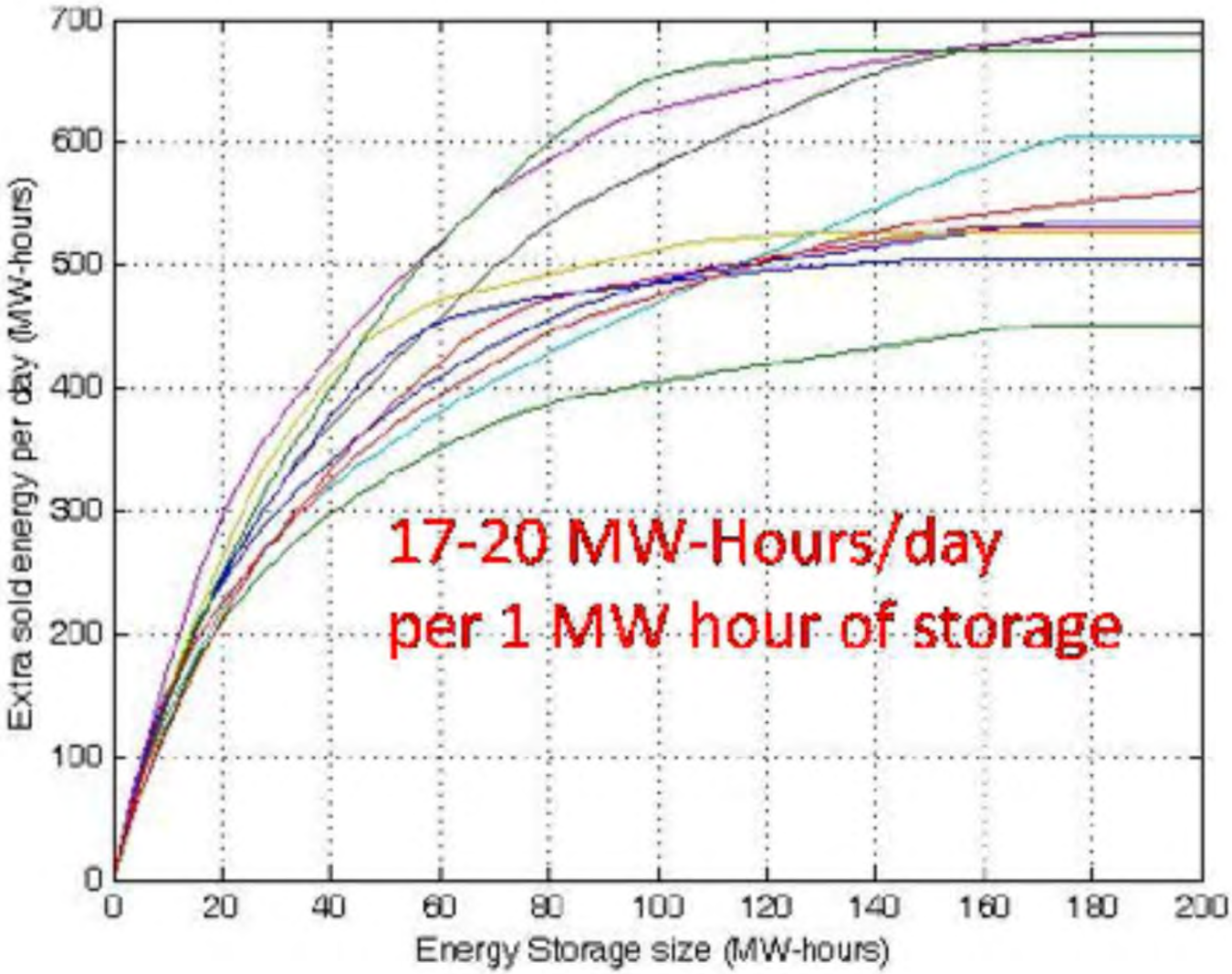
- What is the optimal location and operations policy for storage?
- Given a VG resource with some small amount of storage, what is the optimal policy for storage operation?

Answers: Tool: *stochastic dynamic programming*

- Optimal contract: convex optimization problem
- Optimal profit: concave and monotonic in storage size
- Optimal storage operation
- Formula for marginal value of storage capacity

Bitar et al ACC'2011

Marginal Value of Storage



Paradigm Change

Current: adjust the generation to meet random demand

Future: *adjust demand to meet random generation*

Flexible Demand: heating, air-conditioning, refrigeration, EVs,

Questions:

How can we optimize aggregate and optimize flexibility of large numbers of individual flexible loads?

How can sensing and communications be used for distributed control of flexible loads?

What incentive and pricing mechanisms will be effective in getting consumers to participate in adjustable demand programs?

How can these distributed resources be integrated into power system operations with large RG penetration?

GRIP: Grid with Intelligent Periphery

Bakken et al, SmartGridCom, 2011

Smart Grid - Cybersecurity

New sensor - PMU:

GPS time stamped measurements of voltage and current magnitude and phase across the electric grid

Questions:

What wide area control loops become feasible as a result of PMUs?

Can we design better algorithms for prevention of cascading failures using PMU measurements?

Can PMUs help improve the cybersecurity of the SCADA system?

Answer: Graph-theoretic characterization of small coordinated attacks and mitigation strategy

Giani et al, SmartGridCom'2011

Our Publications

- E. Bitar, A. Giani, R. Rajagopal, D. Varagnolo, P. P. Khargonekar, K. Poolla, P. P. Varaiya, "Optimal Contracts for Wind Power Producers in Electricity Markets," Proc. 50th IEEE Conference on Decision and Control, pp. 1919-1926, 2010.
- E. Bitar, R. Rajagopal, P. P. Khargonekar, and K. Poolla, "Optimal Bidding Strategies for Wind Power Producers: the Role of Reserve Margins and Energy Storage," Proc. American Control Conference, pp. , June 2011.
- E. Bitar, P. P. Khargonekar, and K. Poolla, "Systems and Control Opportunities in Smart Grid and Renewable Integration," Proc. 2011 IFAC World Congress, Milan, ITALY.
- D. Bakken, A. Bose, K. M. Chandy, P. P. Khargonekar, A. Kuh, S. Low, A. von Meier, K. Poolla, P. P. Varaiya, and F. Wu, "GRIP – Grids with Intelligent Periphery: Control Architectures for Grid2050," Proc. IEEE SmartGridComm, 2011.
- A. Giani, E. Bitar, M. Garcia, M. McQueen, P. P. Khargonekar, and K. Poolla, "Smart Grid Data Integrity Attacks: Characterizations and Countermeasures," Proc. IEEE SmartGridComm, 2011
- E. Baeyens, E. Bitar, P. P. Khargonekar, and K. Poolla, "Wind Energy Aggregation: A Coalitional Game Approach," Proc. IEEE Conference on Decision and Control, 2011.
- E. Bitar, K. Poolla, P. P. Khargonekar, R. Rajgopal, P. Varaiya, and F. Wu, "Selling Random Energy," Hawaii International Conference on Systems Science, 2012.
- E. Bitar, R. Rajagopal, P. P. Khargonekar, K. R. Poolla, and P. Varaiya, "Bringing Wind Energy to Market," submitted for publication to IEEE Transactions on Power Systems.

Questions?

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