Grid Integration of Renewable Energy - Trends, Challenges, and Opportunities

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Outline

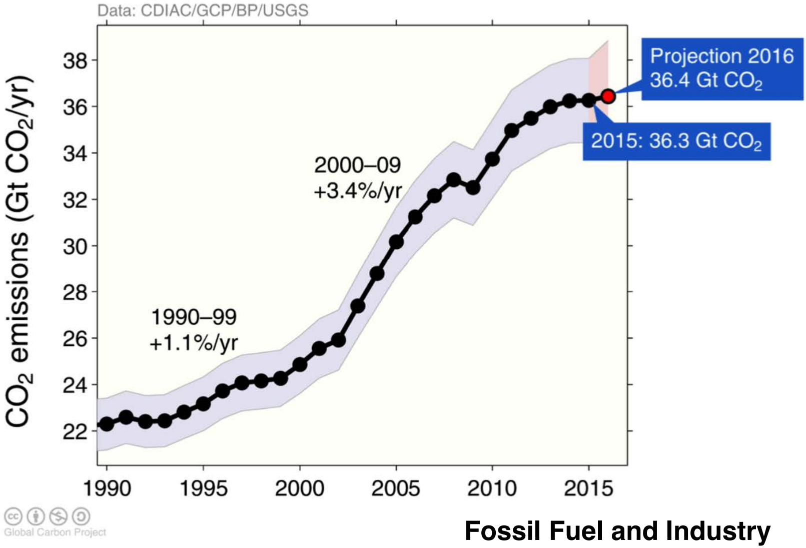
Drivers for Renewable Electric Energy

Toward 100% Renewable Future

Key Collaborative Research Directions
- Distributed Control and Price of Anarchy
- Stochastic Optimization for Smart Homes and Neighborhoods

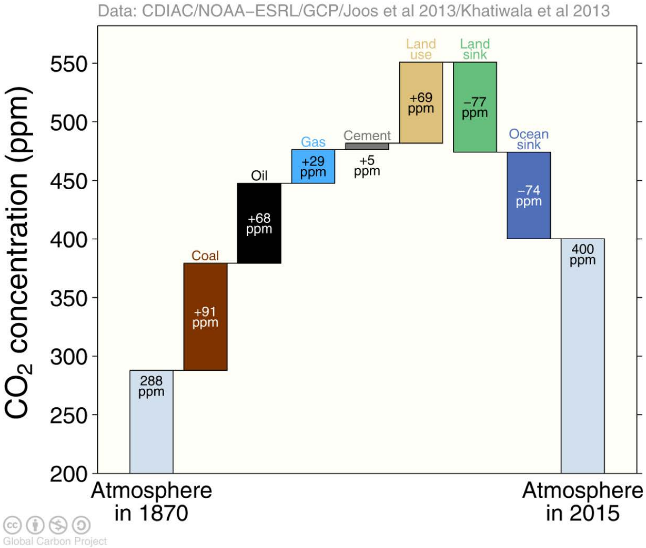
Conclusions

Global CO_2 Emissions



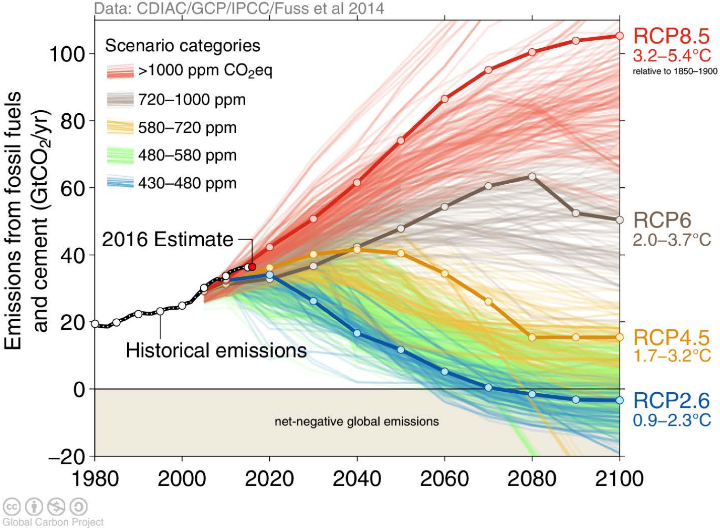
Source: CDIAC; Le Quéré et al 2016; Global Carbon Budget 2016

Cumulative Net CO_2 Increase



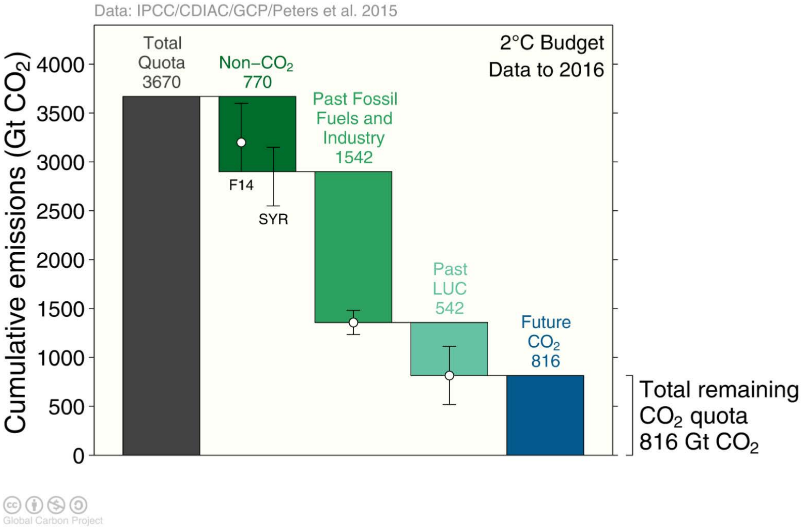
Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2016; Global Carbon Budget 2016

CO_2 Emissions and Temperature Change



Source: Fuss et al 2014; CDIAC; IIASA AR5 Scenario Database; Global Carbon Budget 2016

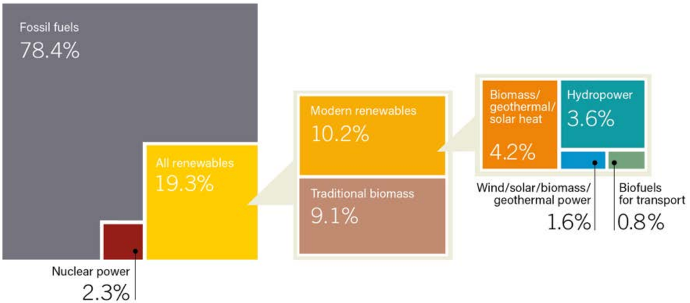
Remaining CO_2 Quota for 66% Chance to Keep Below 2^0 C



Source: Peters et al 2015; Global Carbon Budget 2016

Global Energy Consumption

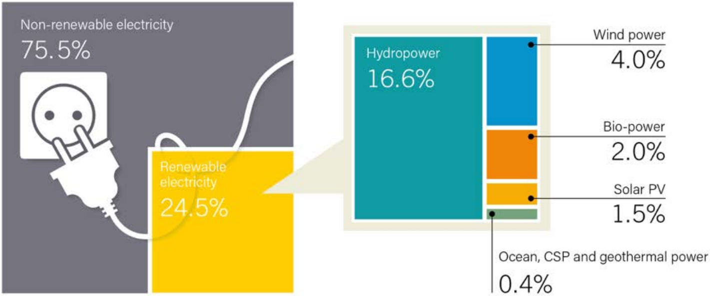
Estimated Renewable Energy Share of Total Final Energy Consumption, 2015



REN21 *Renewables 2017 Global Status Report*

Electric Energy Sector

Estimated Renewable Energy Share of Global Electricity Production, End-2016



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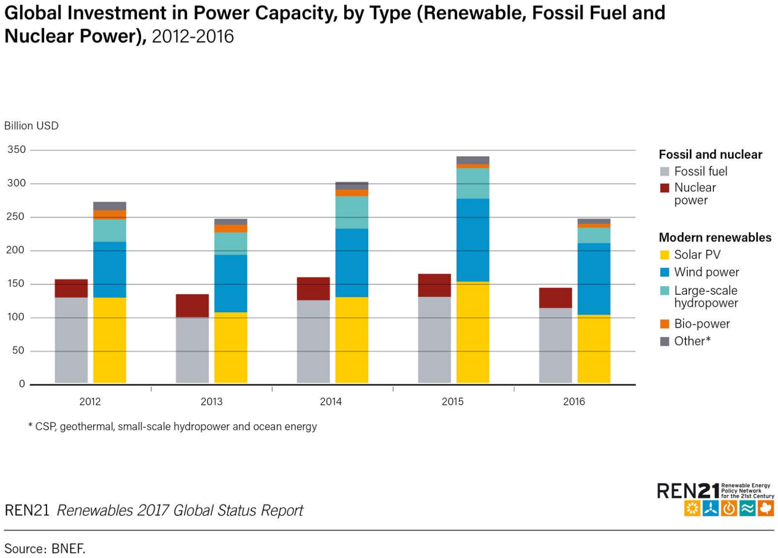
Major Energy Transitions are Slow

- Coal: 5% to 50% in 60 years starting in 1840
- Oil: 5% to 40% in 60 years starting in 1915
- Natural gas: 5% to 25% in 60 years starting in 1930
- Modern renewables $\approx$ 5%

1.2 billion people lack access to electricity
2.8 billion people rely on biomass for cooking and heating

Toward 100% Renewable Future

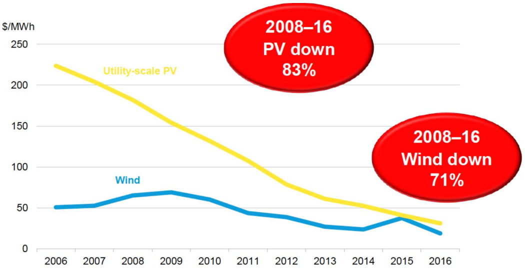
Investment in Renewable Power



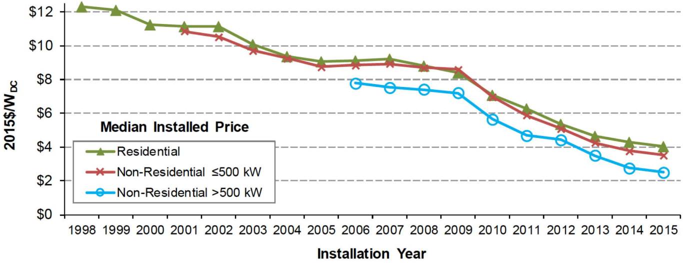
Source: Bloomberg New Energy Finance

PV and Wind Get Cheaper by the Year

Average US Power Purchase Agreements Prices

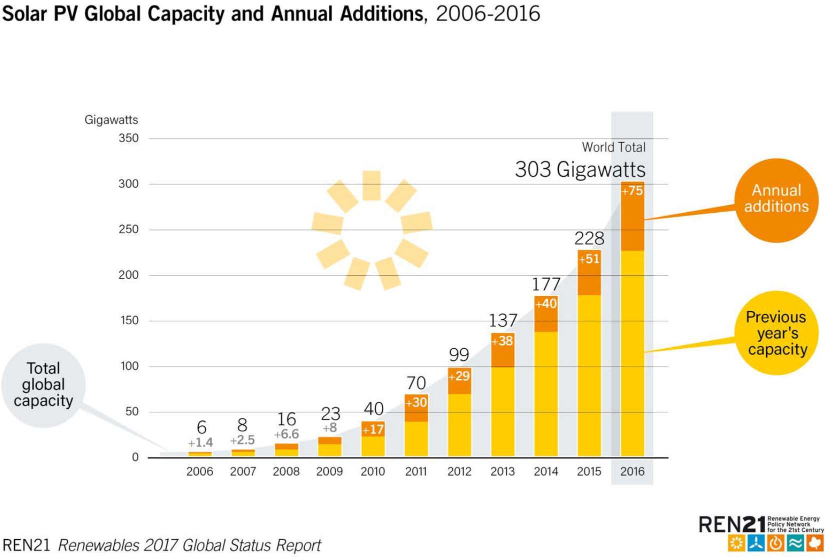


Souce: Bloomberg New Energy Finance



Source: Tracking the Sun, LBNL

Solar PV Growth



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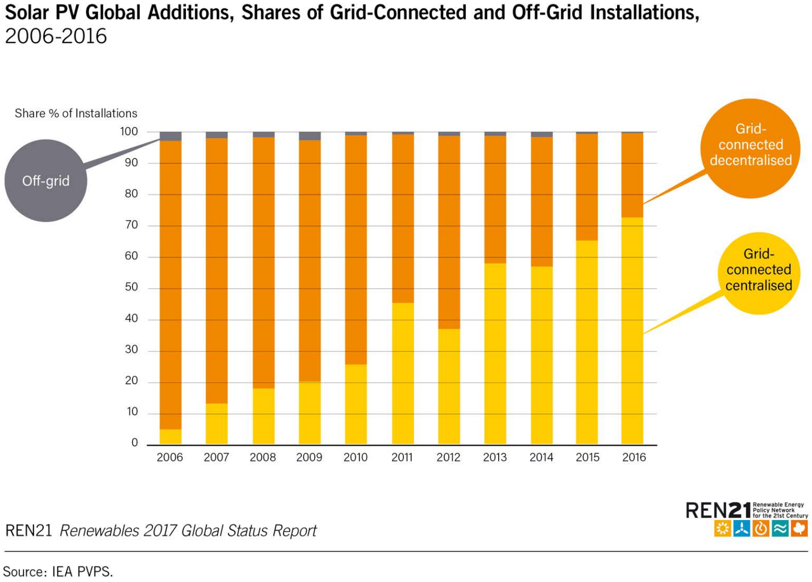
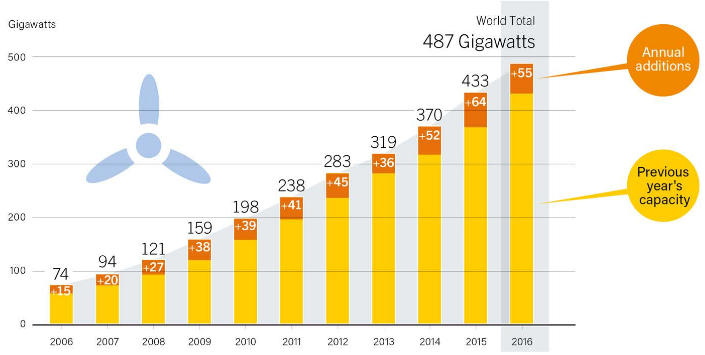
Solar PV Deployment



Wind Growth

Wind Power Global Capacity and Annual Additions, 2006-2016



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Net Result: Record Low Prices

Solar PV

Country:	Mexico
Bidder:	FRV
Signed:	September 2016
Construction:	2019
Price:	**US$ 2.69 c/kWh**

Onshore wind

Country:	Morocco
Bidder:	Enel Green Power
Signed:	January 2016
Construction:	2018
Price:	**US$ 3.0 c/kWh**

Offshore wind

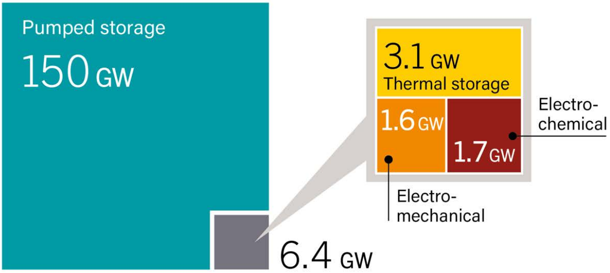
Country:	Germany
Bidder:	DONG/EnBW
Signed:	April 2017
Construction:	2024
Merchant Price:	**US$ 4.9 c/kWh**

Note: The offshore wind merchant price is estimated based on project LCOE in real 2016 terms

Source: Bloomberg New Energy Finance; ImagesSiemens; Wikimedia Commons

Storage

Global Grid-Connected Energy Storage Capacity, by Technology, 2016



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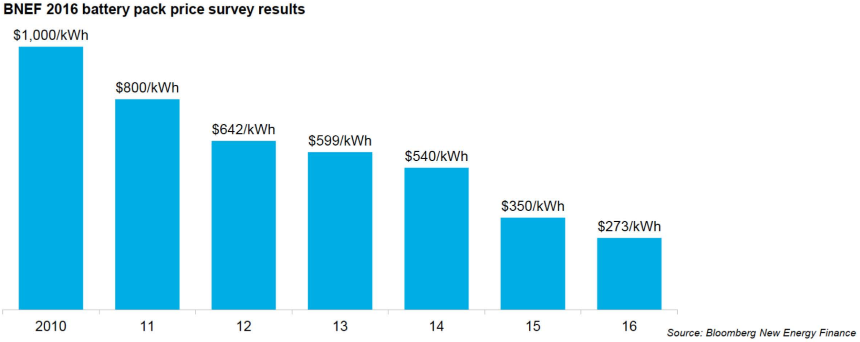
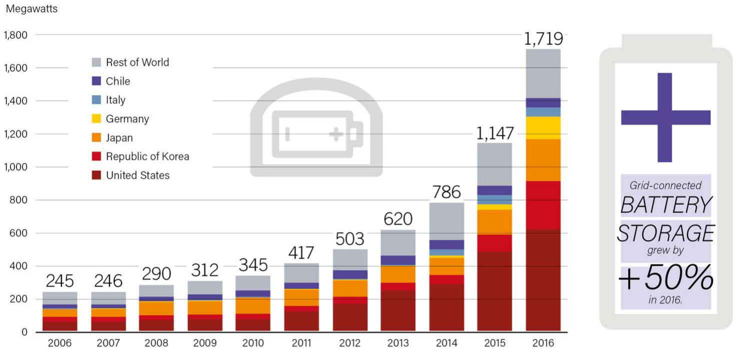
Li Ion Battery Prices



Grid Connected Battery Storage

Global Grid-Connected Stationary Battery Storage Capacity, by Country, 2006-2016



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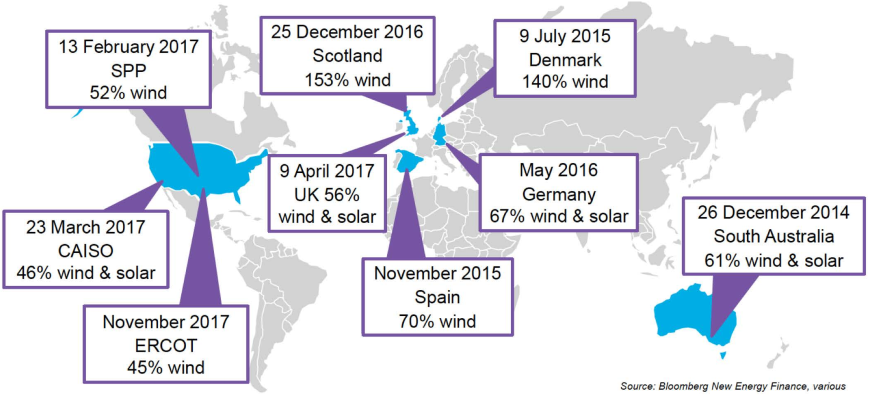
REN21 Renewable Energy Policy Network for the 21st Century

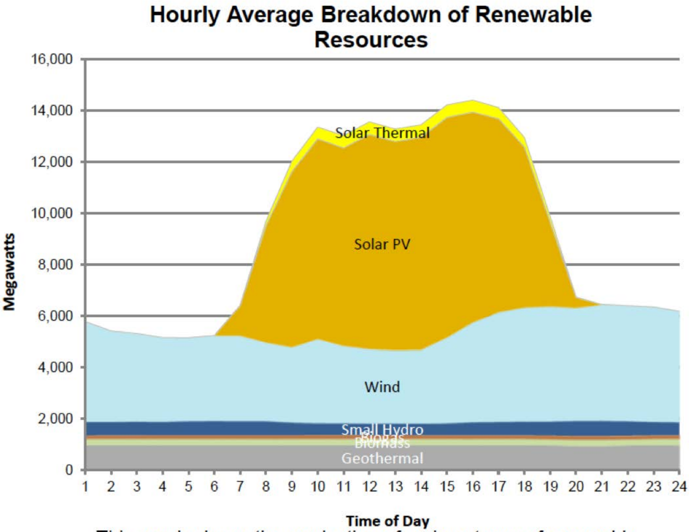
Examples of Deep Penetration of Renewable Generation



California on May 13, 2017

California grid sets record, with 67% of power from renewables

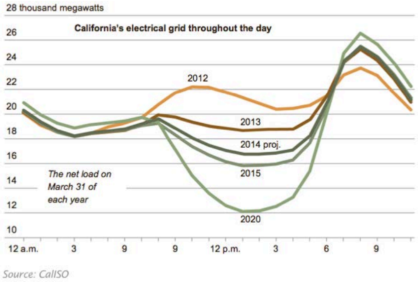
By Dominic Fracassa Updated 5:10 pm, Thursday, May 18, 2017

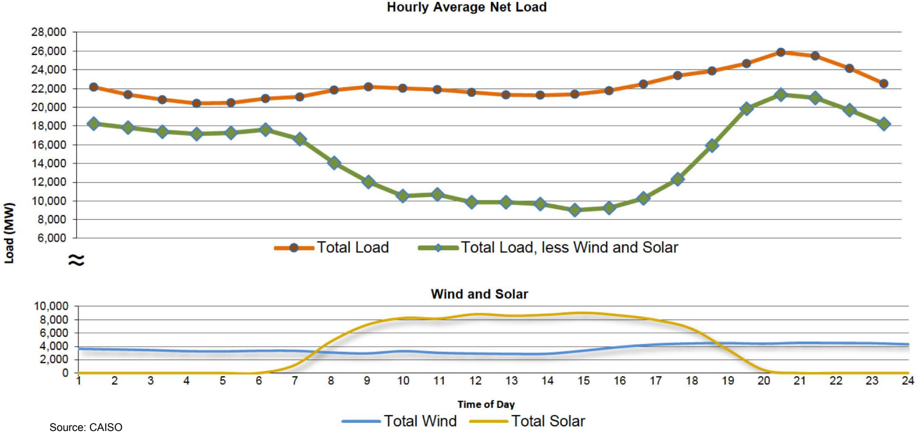


This graph shows the production of various types of renewable generation across the day.

Source: CAISO

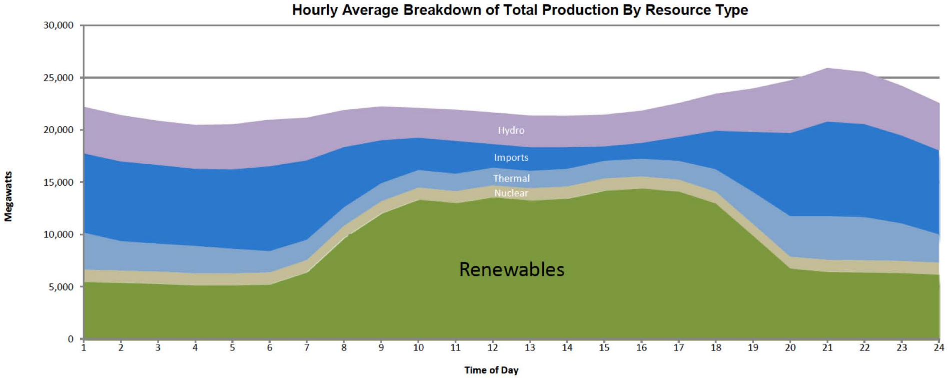
California on May 13, 2017





Source: CAISO

California on May 13, 2017



Source: CAISO

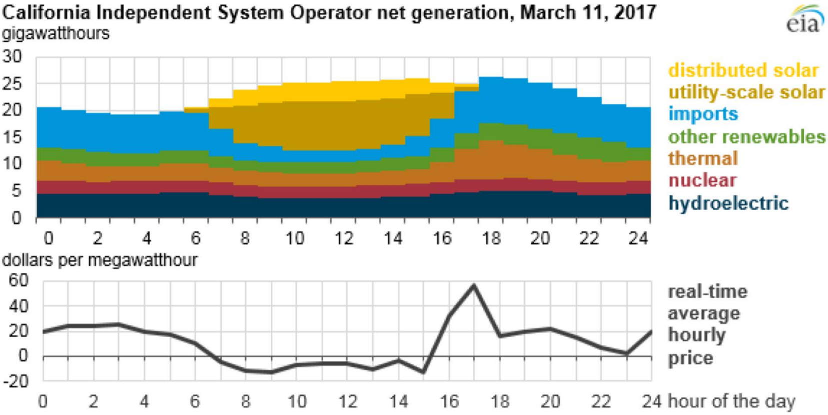
California on May 13, 2017

24-Hour Renewables Production

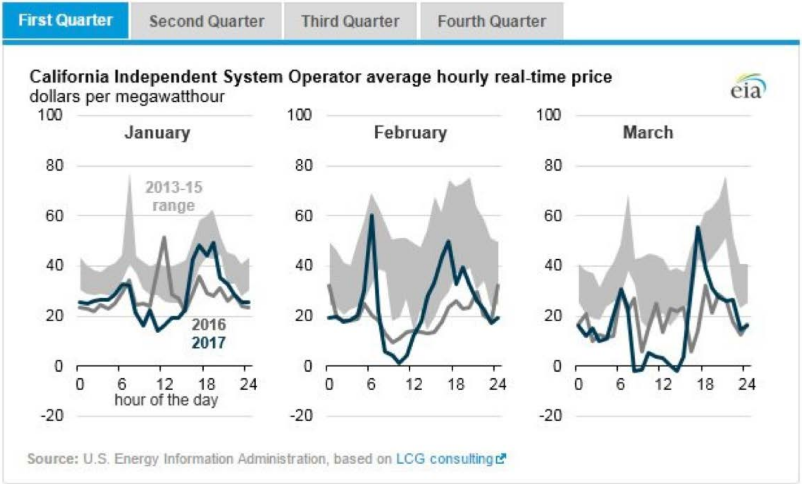
Renewable Resources	Peak Production Time	Peak Production (MW)	Daily Production (MWh)
Solar Thermal	12:15	494	5,032
Solar	14:45	8,669	86,902
Wind	20:27	4,576	87,068
Small Hydro	20:37	605	12,643
Biogas	19:24	154	3,575
Biomass	9:52	244	5,754
Geothermal	6:46	978	23,282
Total Renewables			**224,256**
Total 24-Hour System Demand (MWh):			*534,956*

Source: CAISO

Negative Prices in California



Negative Prices in California



Projected Solar Curtailment

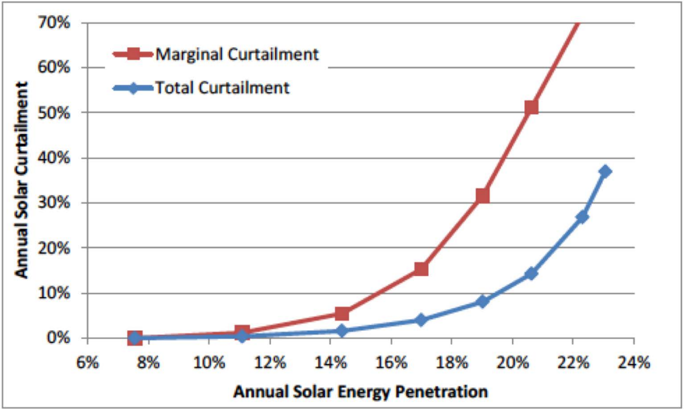


Figure 6. Annual marginal and total solar curtailment due to overgeneration under increasing penetration of PV in California in a system with limited grid flexibility

Source: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System, NREL

Impact of Curtailment on Cost of PV

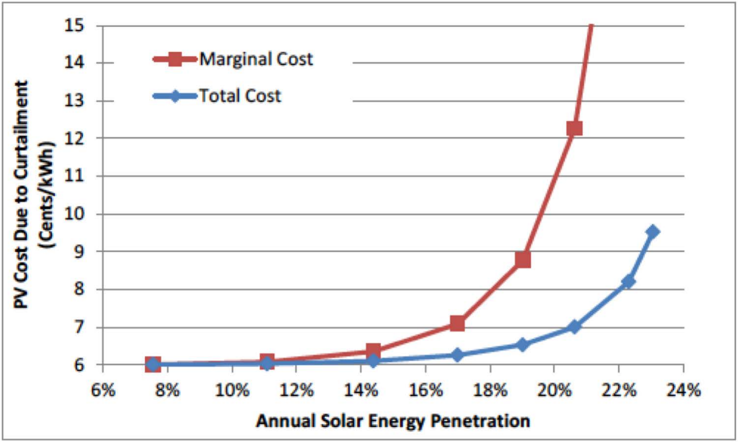


Figure 7. Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California in a system with limited grid flexibility

Source: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System, NREL

Capacity Credit Declines with Increasing Penetration

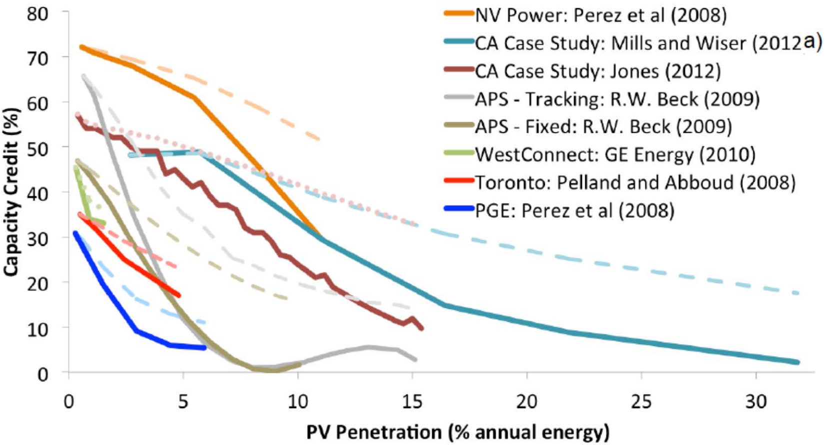
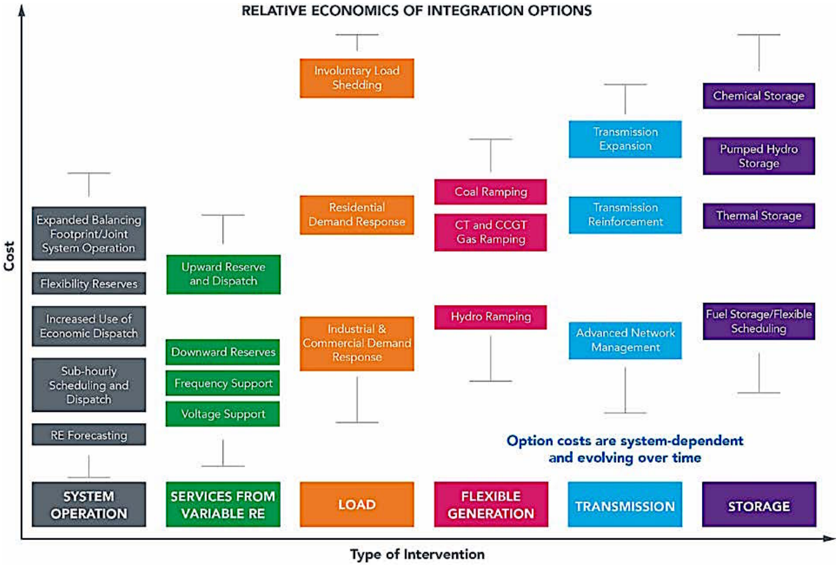


Figure 10. Summary of PV capacity credit estimates

Source: Mills and Wiser 2012b

Source: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System, NREL

Options for Flexibility



Source: Chochran et al, 2014

Key Enablers to Deep Renewable Integration

- New transmission infrastructure
- Larger geographic balancing areas
- Greater flexibility in all aspects of power system operations
- Cost-effective energy storage
- Grid management and control

Key Collaborative Research Directions

- Renewable producers in electricity markets
- Strip Packing for Peal Load Minimization
- Causation based Cost Allocation Principles and Algorithms
- Cybersecurity and smart grid
- Distributed control for integration of renewable sources
- Stochastic optimization for residential energy management

Renewable Generators in Electricity Markets

- Scenario: One or more wind or solar producers operating in a wholesale electricity market
- What is the optimal bid by a renewable generator in a two-settlement market?
- Is there a benefit from several renewable generators combining their production?
- What are the strategies to keep the coalition stable?
- What is the optimal operating policy for a renewable generator with local energy storage?

Collaboration with Baeynes, Bitar, Poolla, and Varaiya

Stochastic Optimization for Residential Energy Management

- Scenario: one more more homes in a residential setting with local renewable generation, storage, and elastic and inelastic loads
- What are stable policies for servicing the loads while optimizing the total cost of operation?
- Approach: put the loads into a queue and use Lyapunov based stochastic optimization techniques that guarantee queue stability, storage limits, upper bounds on delays in serving the elastic loads, and bound on deviation from optimal performance
- Similar approach for data center optimization with local renewable generation and storage, virtual power plants, etc.

Collaboration with Guo, Fang, Pan, Gong and Geng

Strip Packing for Peak Load Minimization

- Scenario: constant interruptible and non-interruptible power flexible loads with start and end times
- How can these loads be scheduled so that the resulting peak load is as small as possible?
- NP hard problems
- Approach: strip packing algorithms from computer science literature
- Results: guaranteed bounds on deviation from optimality

Collaboration with Ranjan and Sahni

Causation based Cost Allocation Principles and Algorithms

- Variability of renewable generation imposes costs on the system
- How should these costs be allocated as tarrifs?
- Principle: allocate costs to those who "cause" them
- Approach: tools from cooperative game theory
- Results: algorithms for cost allocation

Collaboration with Chakraborty and Baeynes

Cybersecurity for Smart Grid

- Scenario: Adversary attacks data in energy management system
- How can false data injection attacks be detected?
- How can sensors help mitigate such attacks?
- Results: algorithms for detection and mitigation

Collaborations with Gianni, Poolla, Bitar, Garcia, McQueen, Bretas, Baeynes, Carvalho

System Scenario

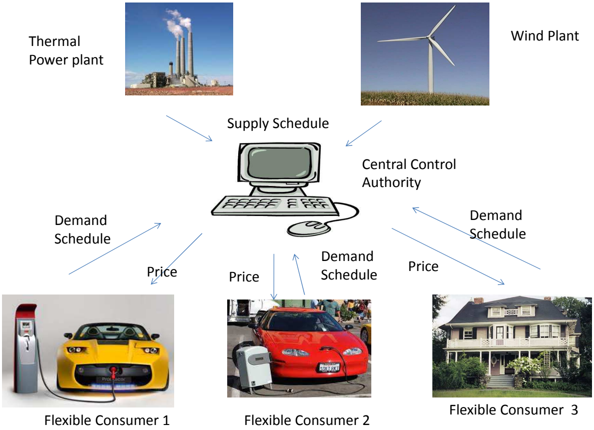


Figure: System Model

Demand Side Management

- Goal: exploit the inherent *flexibility* of electric loads
- Two approaches: incentive based and price based
- Centralized control of loads — ex: direct load control
- Distributed control
  - The central authority sends the control signal, e.g., price, to the consumers.
  - The consumers optimize their consumption schedules accordingly.

Price-Anticipating Consumers

- Game theoretic modeling to capture the price anticipating behavior under distributed control
- Key Question: What is the loss of efficiency in terms of social objective by distributed control as compared with centralized control?
- Price of Anarchy (PoA) : Worst-case ratio of the objective function value of an equilibrium solution of the game to that of a centralized optimal solution.

Nash Equilibrium

- The Nash equilibrium for the distributed control problem with price anticipators is the set of expenditures $\{\mathbf{k}_i^G : i \in \mathcal{N}\}$ such that

$$U_i(\mathbf{q}_i(\mathbf{k}_i^G, \mathbf{k}_{-i}^G)) - \mathbf{1}^\top \mathbf{k}_i^G \geq U_i(\mathbf{q}_i(\mathbf{k}_i, \mathbf{k}_{-i}^G)) - \mathbf{1}^\top \mathbf{k}_i,$$
$$\mathbf{k}_i \in \mathcal{S}_i^{pa}(\mathbf{k}_{-1}^G), \; i \in \mathcal{N}. \qquad (1)$$

Theorem (Existence of Nash equilibrium)

The non-cooperative game has a Nash equilibrium if the search space is nonempty.

Price of Anarchy is Less Than 25%

Theorem

Let $\{\mathbf{q}_i^C : i \in \mathcal{N}\}$ *be a solution of the centralized problem (**??**) and* $\{\mathbf{q}_i^G : i \in \mathcal{N}\}$ *a Nash equilibrium for the distributed problem with price anticipating consumers. Let PoA be defined by:*

$$\mathrm{PoA} := \frac{\sum_{i \in \mathcal{N}} U_i(\mathbf{q}_i^G)}{\sum_{i \in \mathcal{N}} U_i(\mathbf{q}_i^C)}.$$

then $\mathrm{PoA} \geq 0.75$.

Special Cases

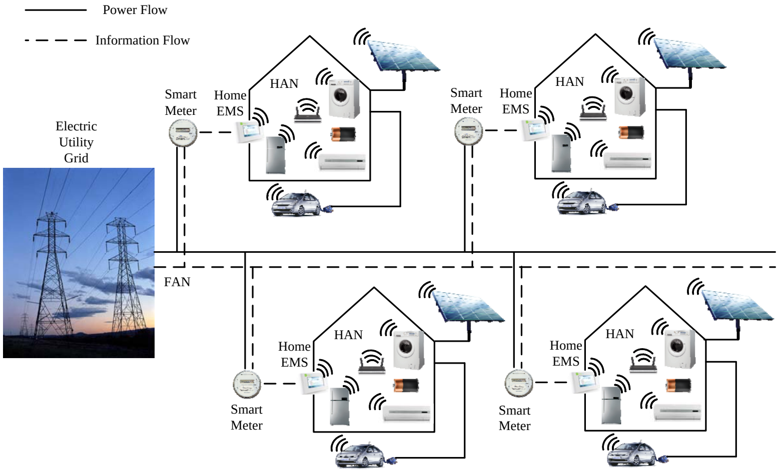
Corollary

If all the consumers have same utility function, i.e., $U_i = U$, there is no efficiency loss at Nash equilibrium solution, i.e. PoA is 1.

Corollary

Suppose $\mathbf{q}_i = \mathbf{0}$ for all $i \in \mathcal{N}$ belongs to the set of load operational constraints, then the PoA approaches 1 as the number N of flexible consumers goes to infinity.

Smart Neighborhood[1]



[1]Y. Guo, M. Pan, Y. Fang, and P. P. Khargonekar, "Decentralized Coordination of Energy Utilization for Residential Households in the Smart Grid," *IEEE Transactions on Smart Grid*, Vol. 4, No. 3, pp. 1341-1350, September 2013.

System Model

- Load serving entity (LSE)
  - Supply cost function Φ: quadratic in aggregate demand in the neighborhood
- Household $i \in [1, N]$
  - Energy storage dynamics: $E_i(t+1) = E_i(t) + \eta_i^+ r_i^+(t) - r_i^-(t)/\eta^-$
  - Inelastic loads: $d_{i,1}(t)$
  - Elastic loads: $Q_i(t+1) = [Q_i(t) - y_i(t) + d_{i,2}(t)]^+$
  - Local renewable generation: $s_i(t)$
  - Net grid energy demand: $g_i(t)$
  - Virtual queue to ensure worst-case delay for elastic loads: $Z_i(t+1) = [Z_i(t) - y_i(t) + \epsilon_i 1_{Q_i(t)>0}]^+$
- Goal: LSE coordinates the energy usage of households to minimize the total cost of supplying electricity to the neighborhood

$$\limsup_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T-1} \mathbb{E}\Big\{ \underbrace{\Phi\Big(\sum_{i=1}^{N} g_i(t)\Big)}_{\text{power supply cost}} + \underbrace{\sum_{i=1}^{N} \beta_i(r_i^+(t) + r_i^-(t))}_{\text{storage operation cost}} \Big\}$$

Analytical Performance Results

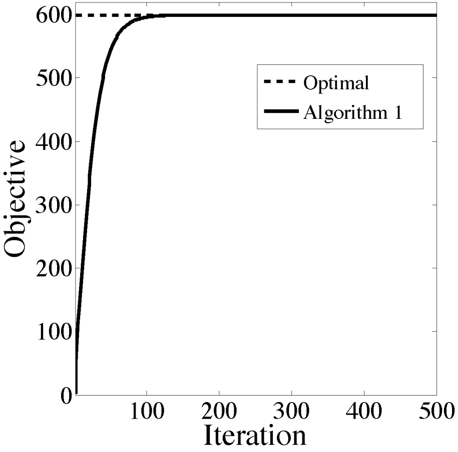
Theorem

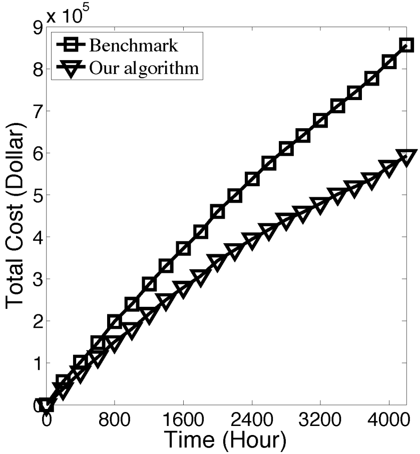
- Storage energy level bound: $E_i^{\min} \leq E_i(t) \leq E_i^{\max}, \forall t$
- Worst-case elastic load delay guarantee: $\text{Delay}_i \leq \left\lceil \frac{2V\Phi' + d_{2,i}^{\max} + \epsilon_i}{\epsilon_i} \right\rceil$
- If random factors are i.i.d. over slots, and if $\epsilon_i \leq \mathbb{E}\{d_{i,2}(t)\}$, then

$$C^* \leq \text{Cost of Our Approach} \leq C^* + B/V,$$

where C^* is the optimal average cost.

Numerical Results





Future Opportunities

- Joint control of storage, renewables, demand and grid
- Wide area stability and control under deep renewable penetration scenarios
- Information and control architectures for future grid
- Negative carbon technologies

Conclusions

- Grid integration of renewable energy will be an increasingly important and difficult challenge
- Many opportunities for the systems and control field
- Energy systems present a unique mix of science, engineering, economics and social policy
- Decarbonization of the energy system remains a true grand challenge for humanity