Networked Distributed Energy Resources

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Electrical Engineering
Computing + Math Sciences
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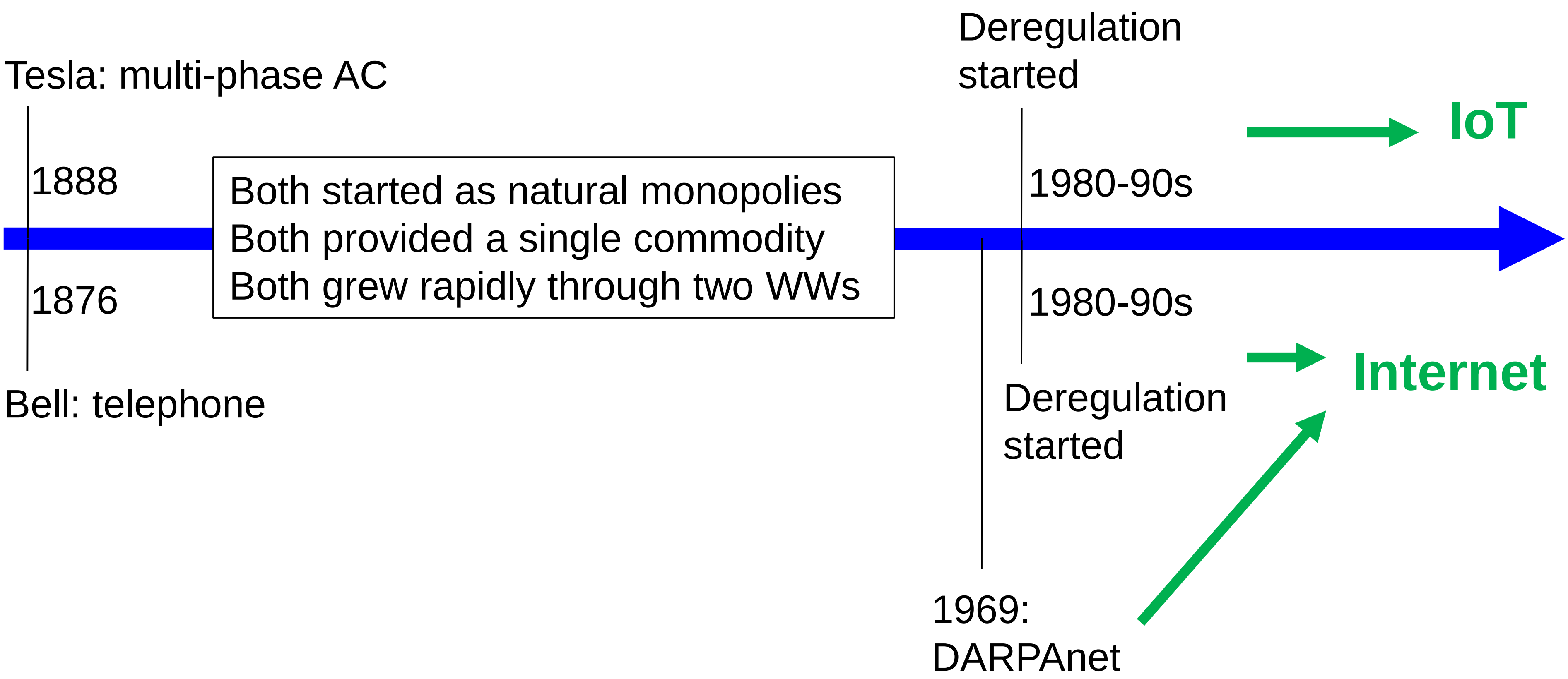
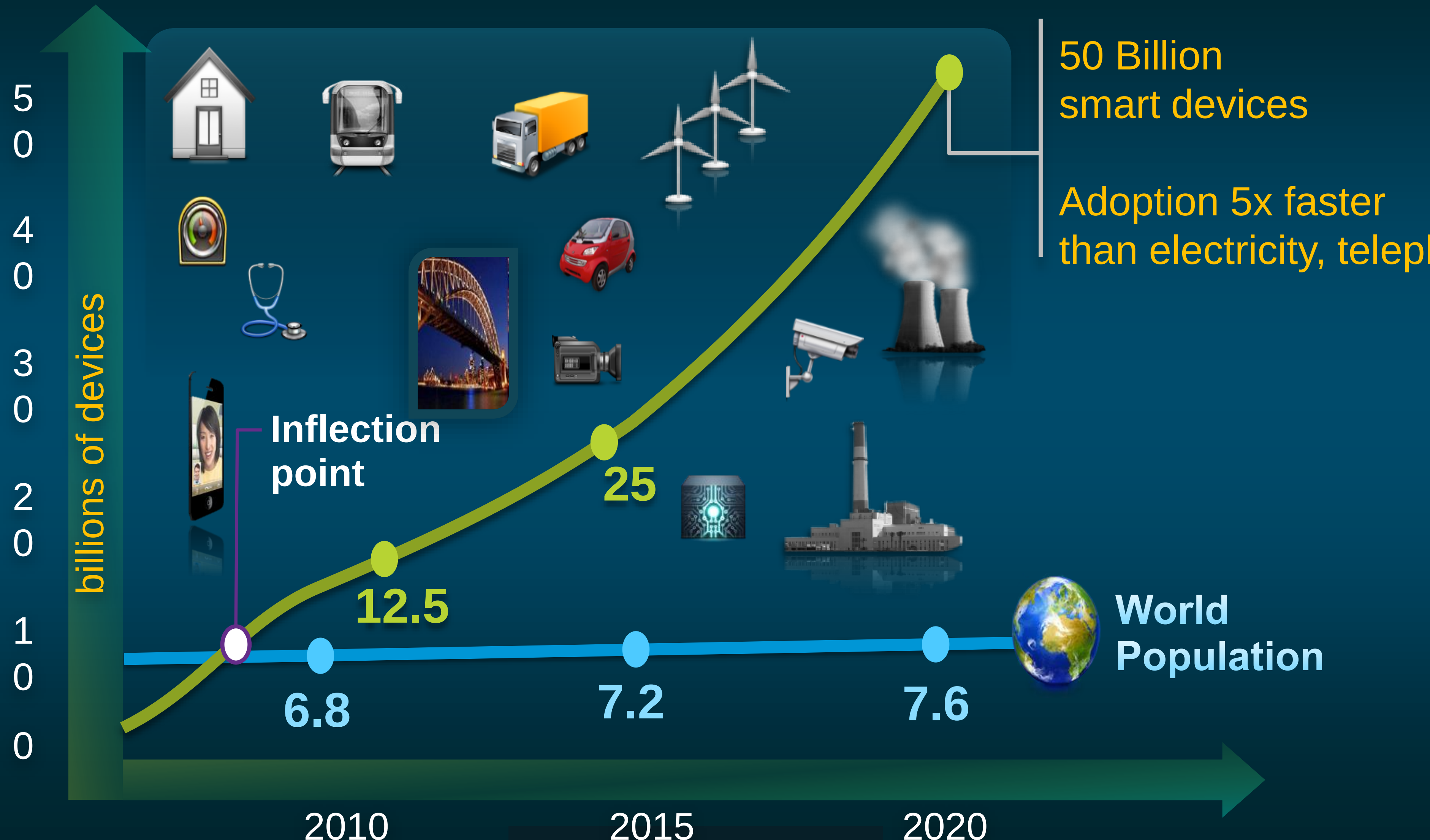
Sept 2015
Energy Colloquium, Skoltech, Moscow

Watershed moment

Power network will undergo similar **architectural transformation** that phone network went through in the last two decades



Internet of Things (IoT)



Source: Cisco
IBSG, 2011

Challenges & opportunities

Industries will be destroyed and created

AT&T, MCI, McCaw Cellular, Qualcom

Google, Facebook, Twitter, Amazon, eBay, Netflix

Infrastructure will be reshaped

Centralized intelligence, vertically optimized

Distributed intelligence, layered architecture

What will drive power network transformation ?

Four drivers

Proliferation of renewables

Electrification of transportation

challenges

Advances in power electronics

Deployment of sensing, control, comm

enablers

Outline

Big picture

- Energy stats and trends

Challenges and opportunities

- Implications on smart grid

Sample Caltech research

- Control and optimization
- Power flow and dynamics

World energy stats (2011)

Consumption	519 quad BTU
petroleum	34%
coal	29%
gas	23%
renewable (elec)	8%
nuclear	5%

top 5 countries

Consumption	519 (quad BTU)	per capita (mil BTU)
China	20%	78
US	19%	313
Russia	6%	209
India	5%	20
Japan	4%	164
total	**54%**	

Source: EIA

World energy stats (2011)

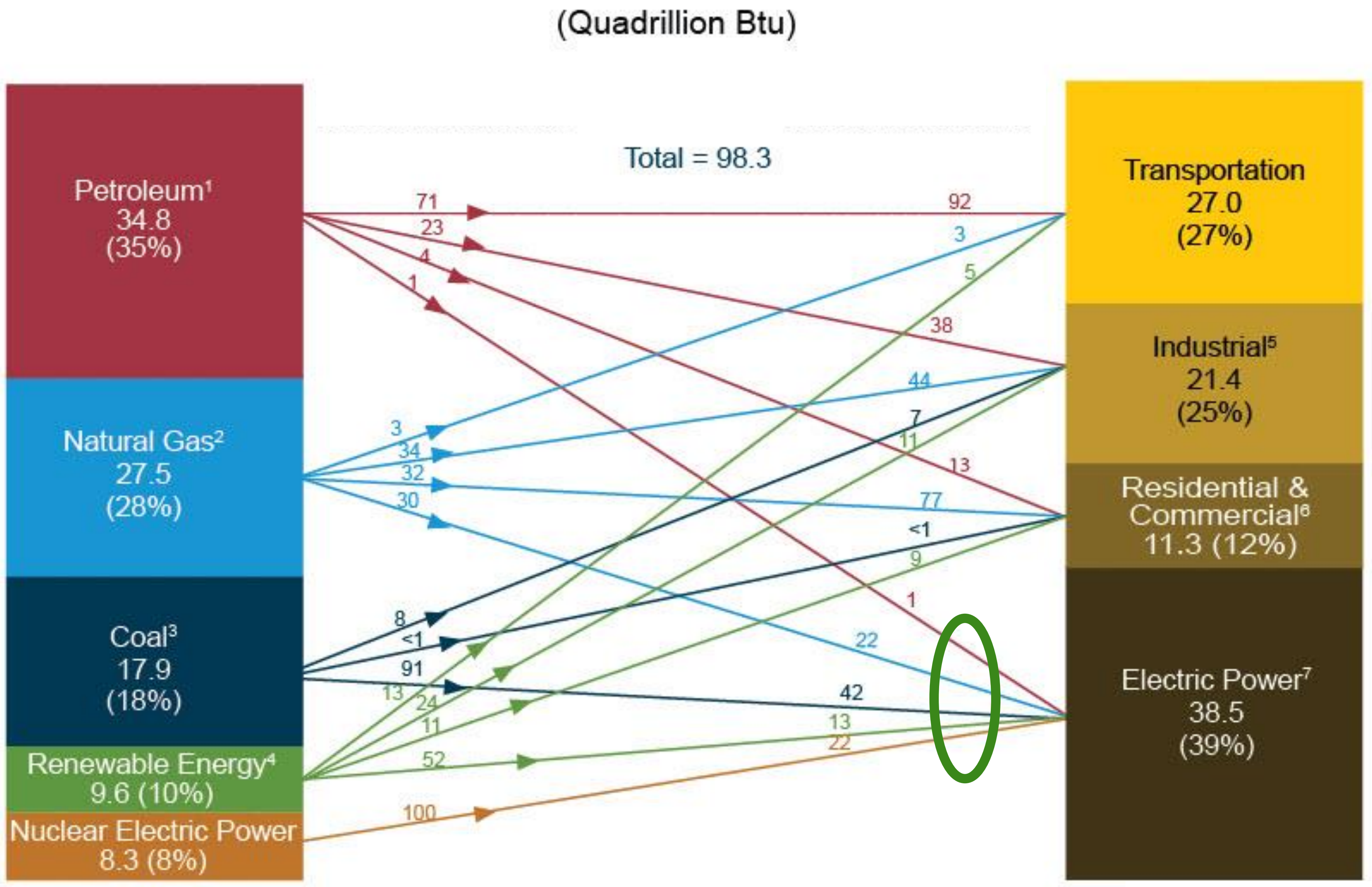
Consumption	519 quad BTU
petroleum	34%
coal	29%
gas	23%
renewable (elec)	8%
nuclear	5%

top 5 countries

Consumption	519 (quad BTU)	CO2 emission
China	20%	27%
US	19%	17%
Russia	6%	5%
India	5%	5%
Japan	4%	4%
total	**54%**	**58%**

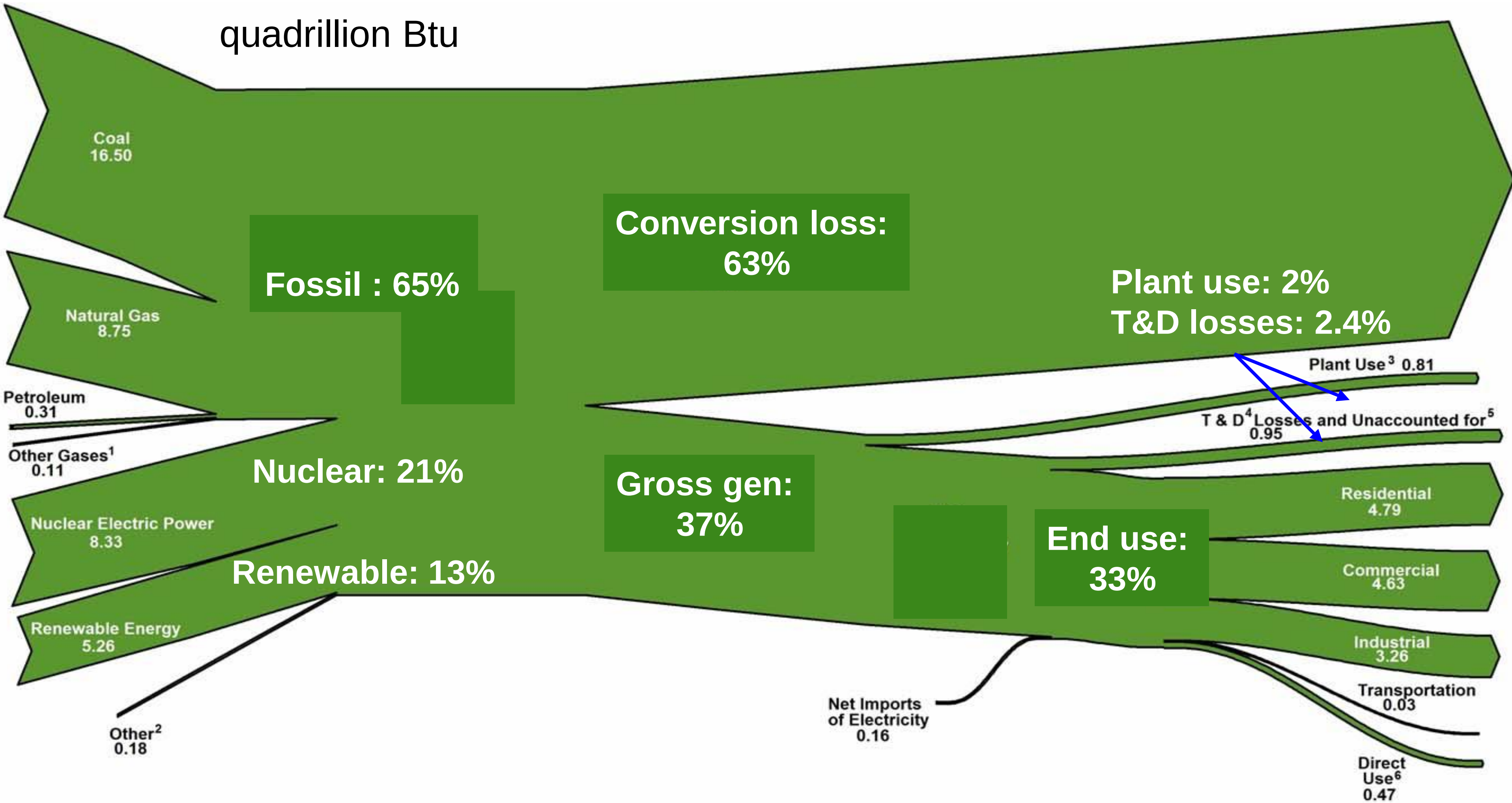
Source: EIA

US Primary Energy Flow 2014



Source: EIA March 2015
Monthly Energy Review

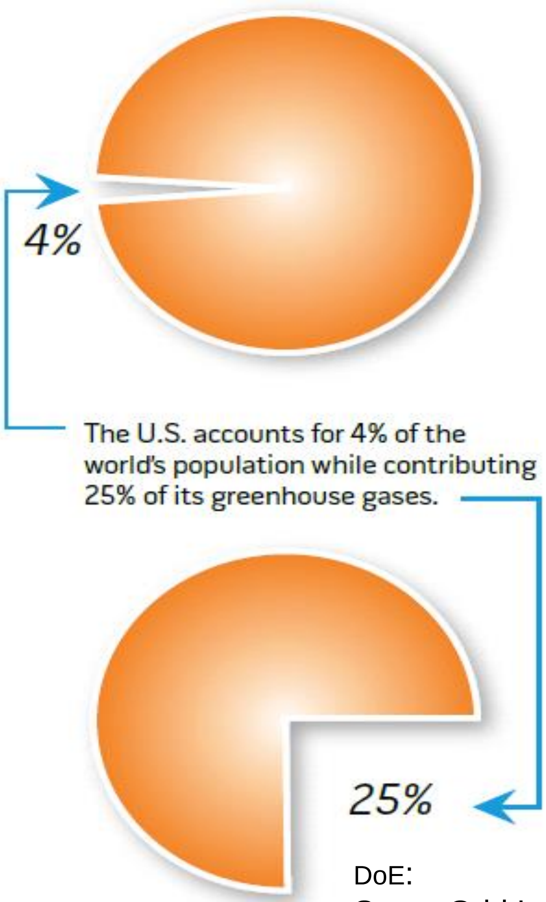
US electricity flow 2014



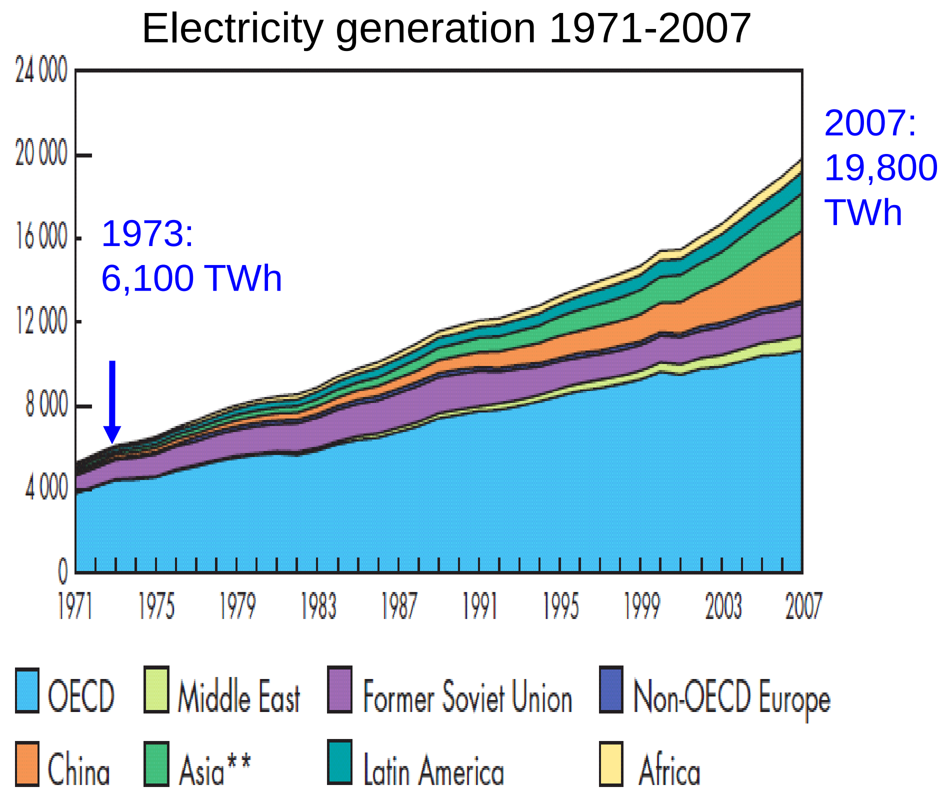
US total energy use: 98.3 quads
For electricity gen: 39%

Source: EIA March 2015 Monthly Energy Review

Sustainability challenge



DoE:
Smart Grid Intro 2008



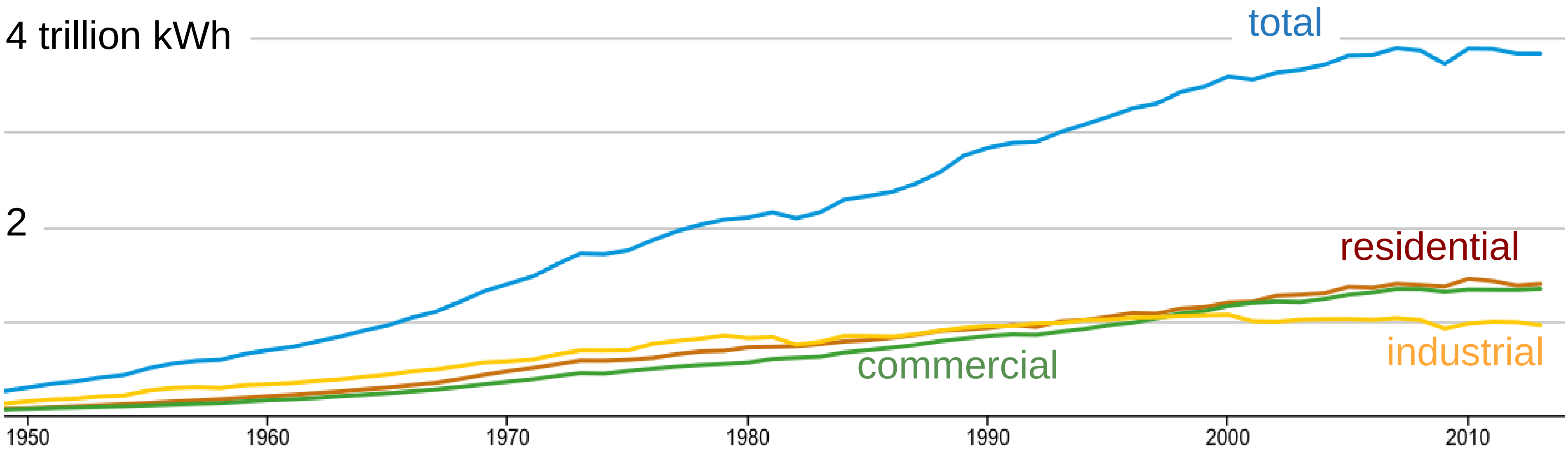
US CO_2 emission

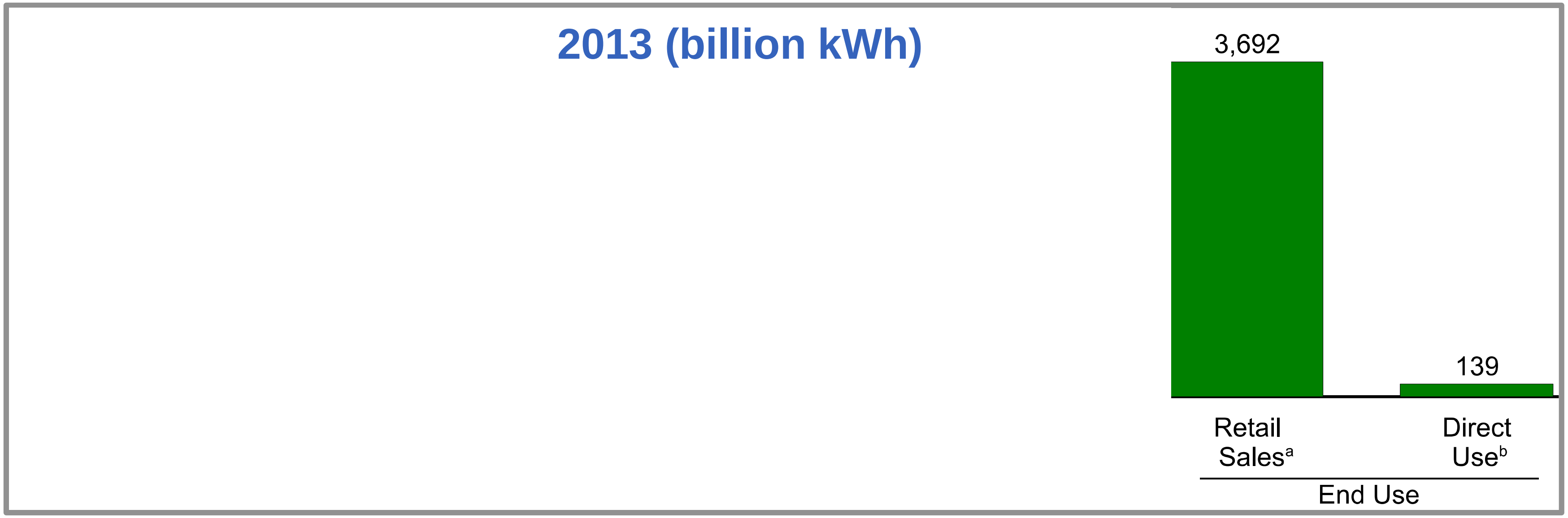
- Elect generation: 40%
- Transportation: 20%

In 2009, 1.5B people have no electricity

Sources: International Energy Agency, 2009
DoE, Smart Grid Intro, 2008

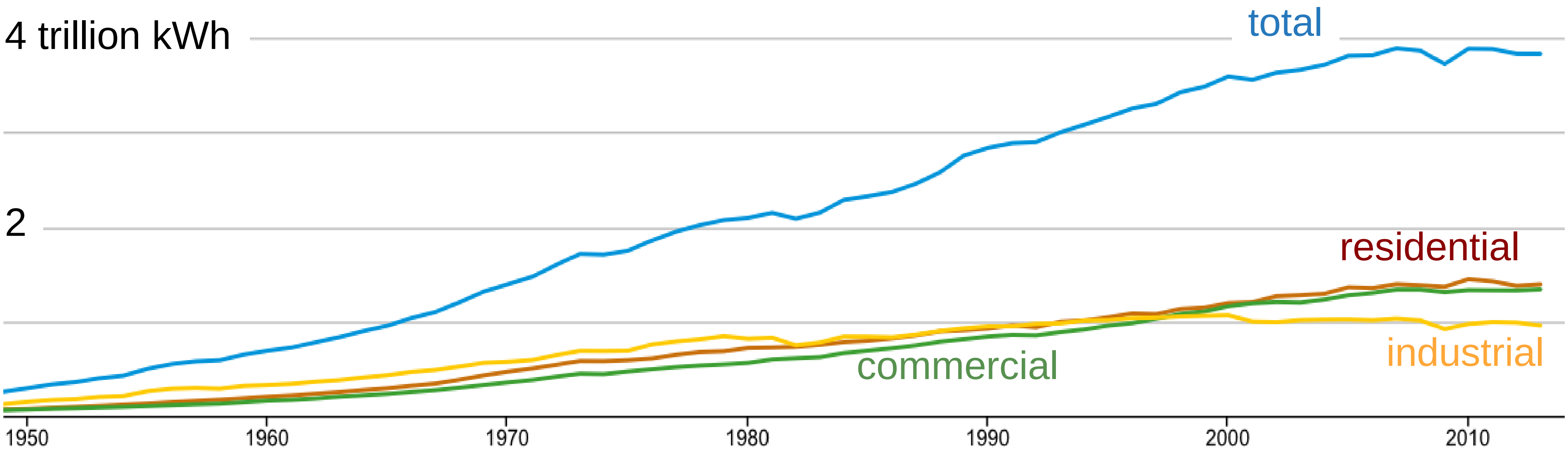
US electricity use

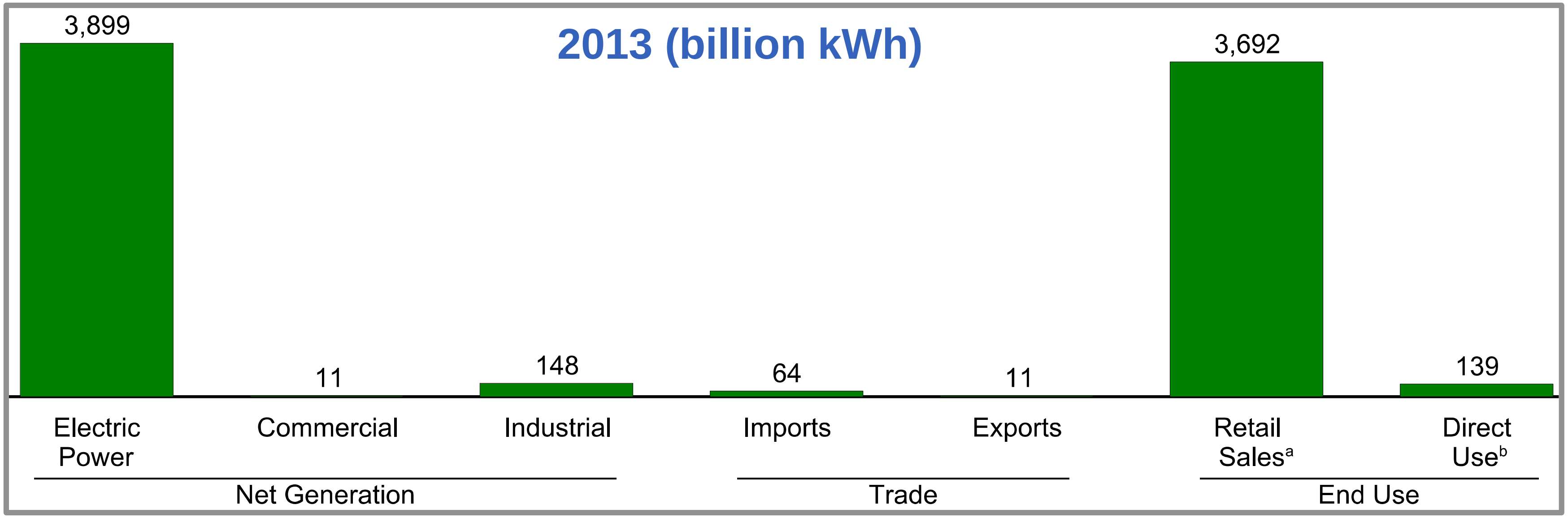




Source:
US EIA

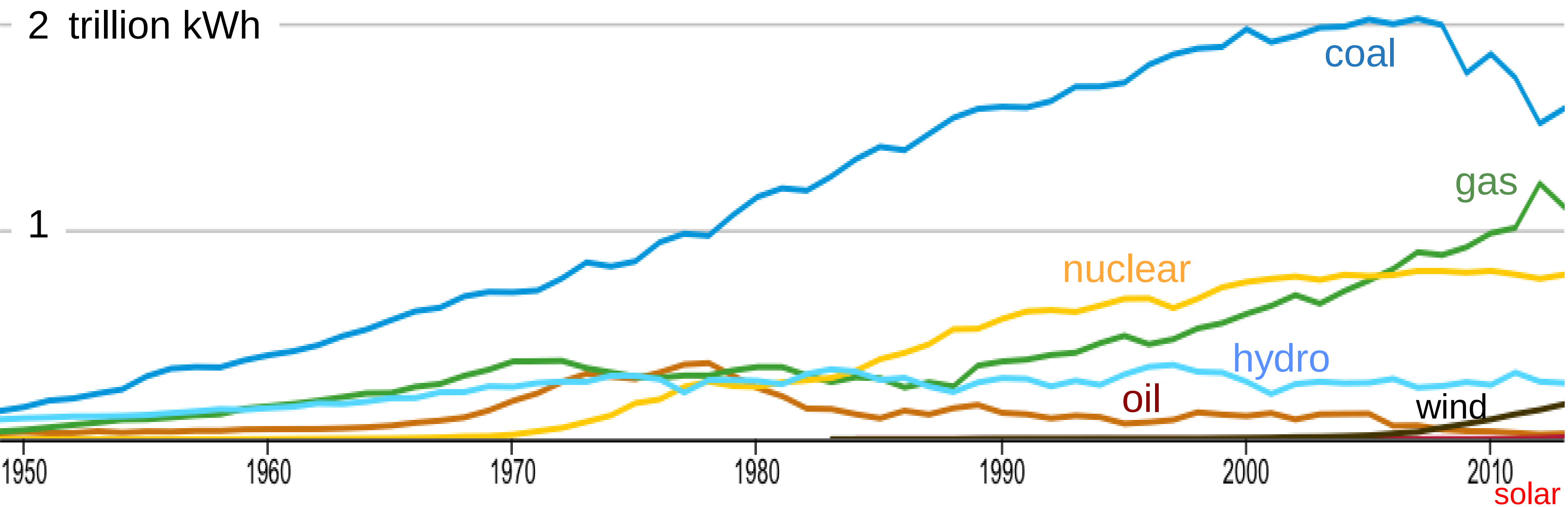
US electricity use

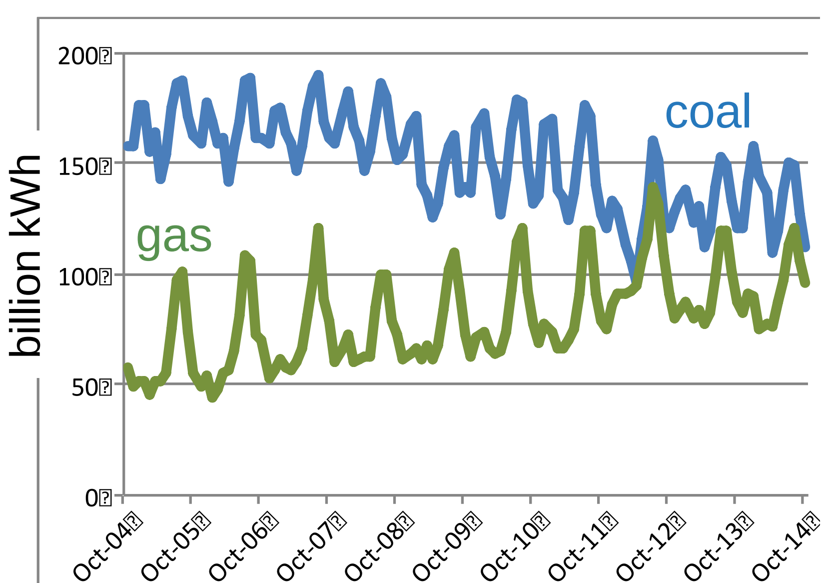


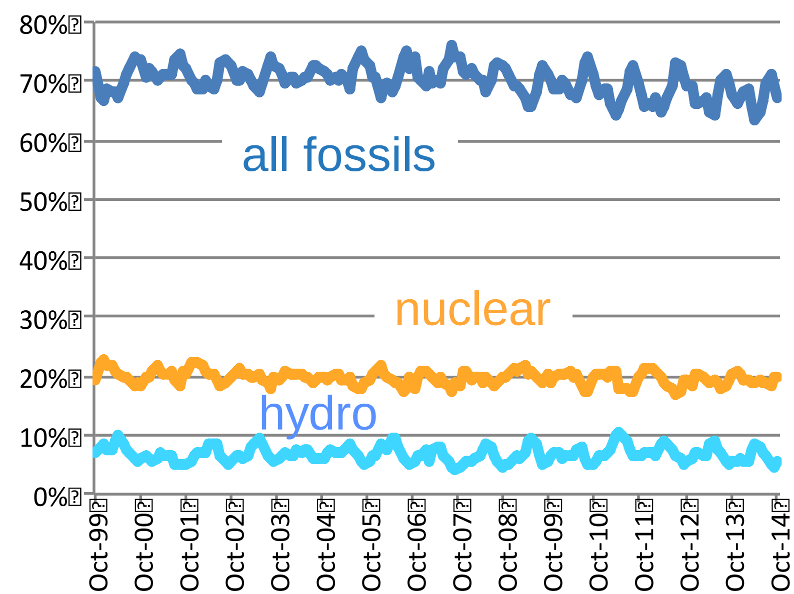


Source: US EIA

US dirty supply

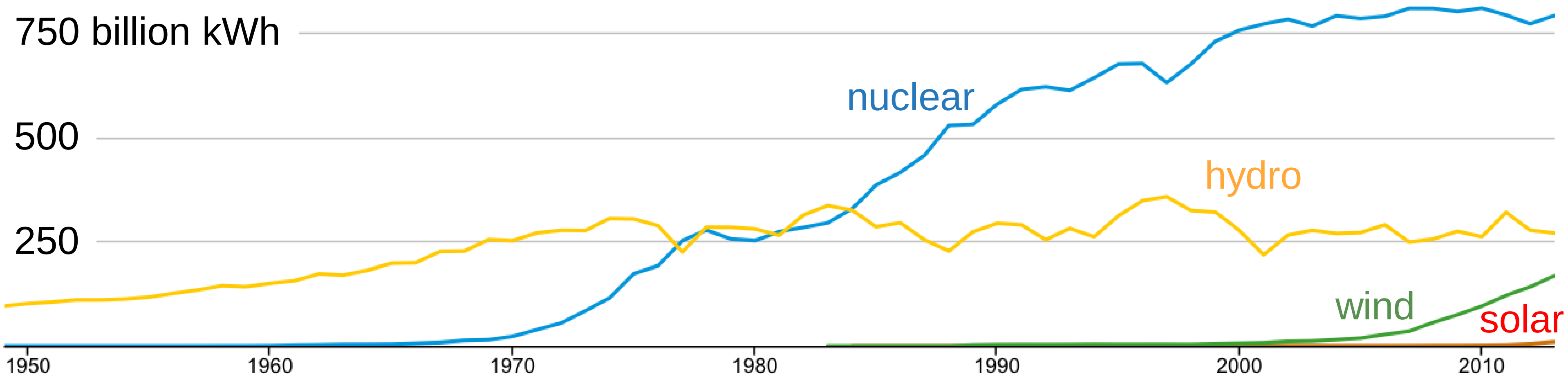


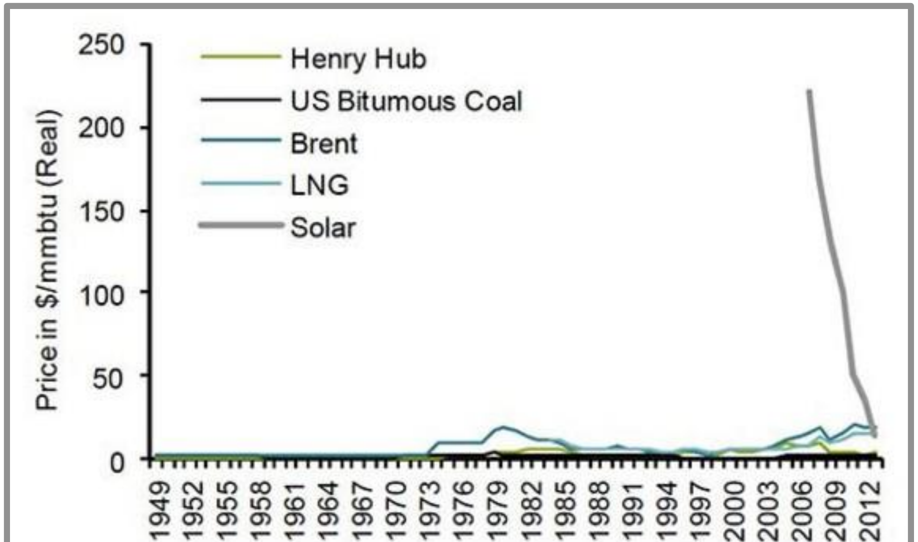




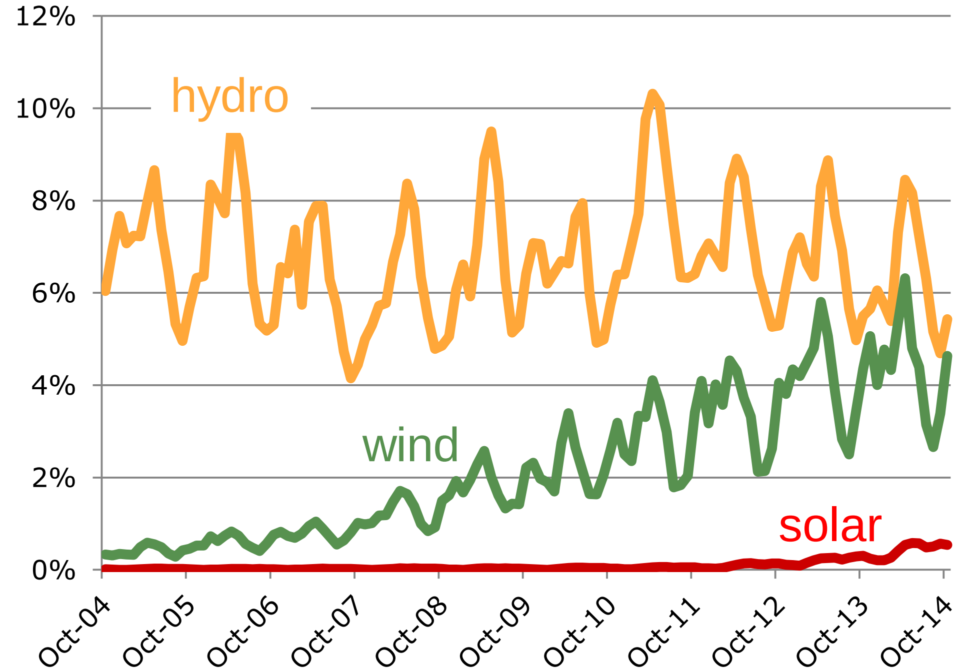
Source:
US EIA

US renewable generations





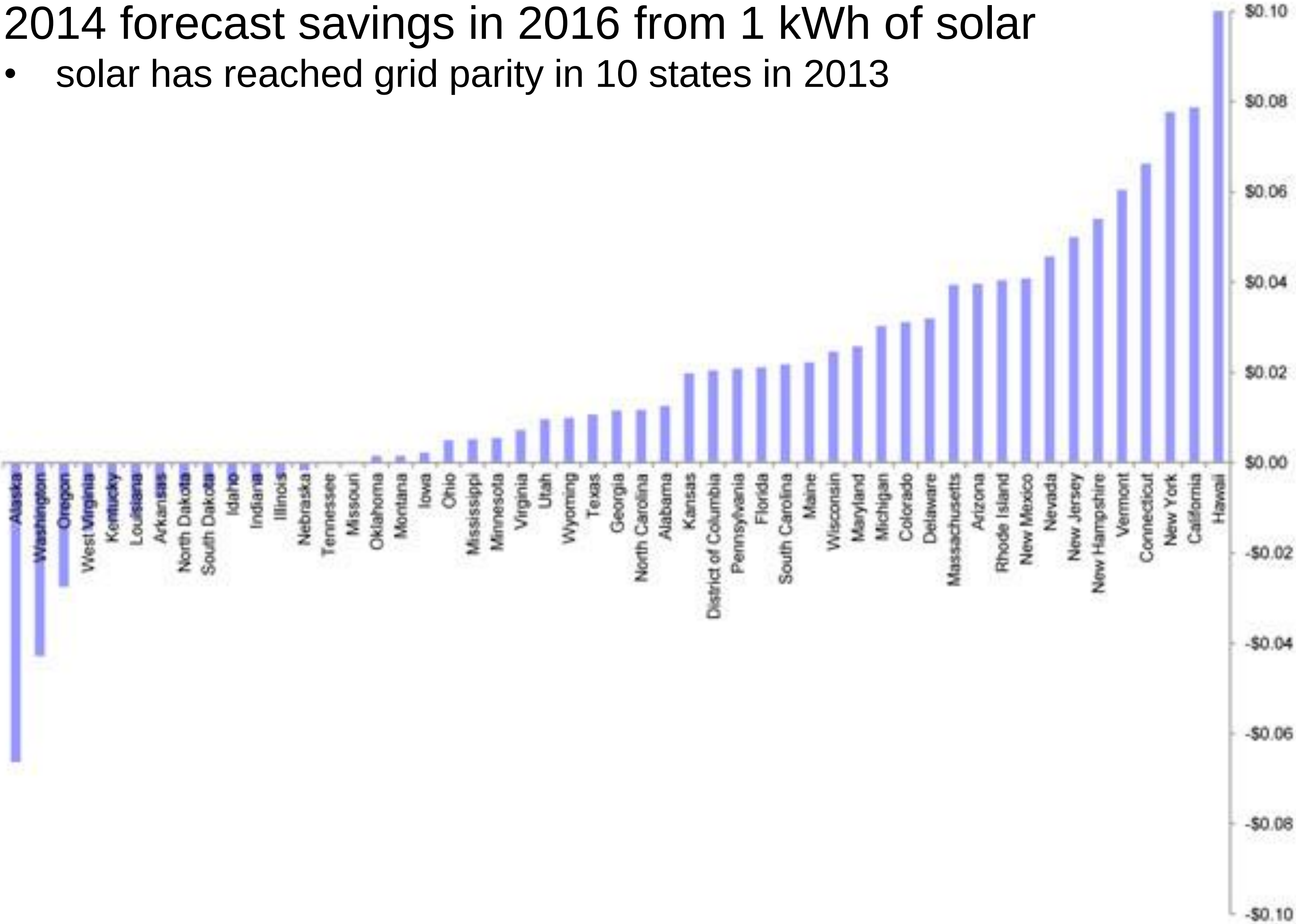
Bernstein Research 2014



Source: US EIA

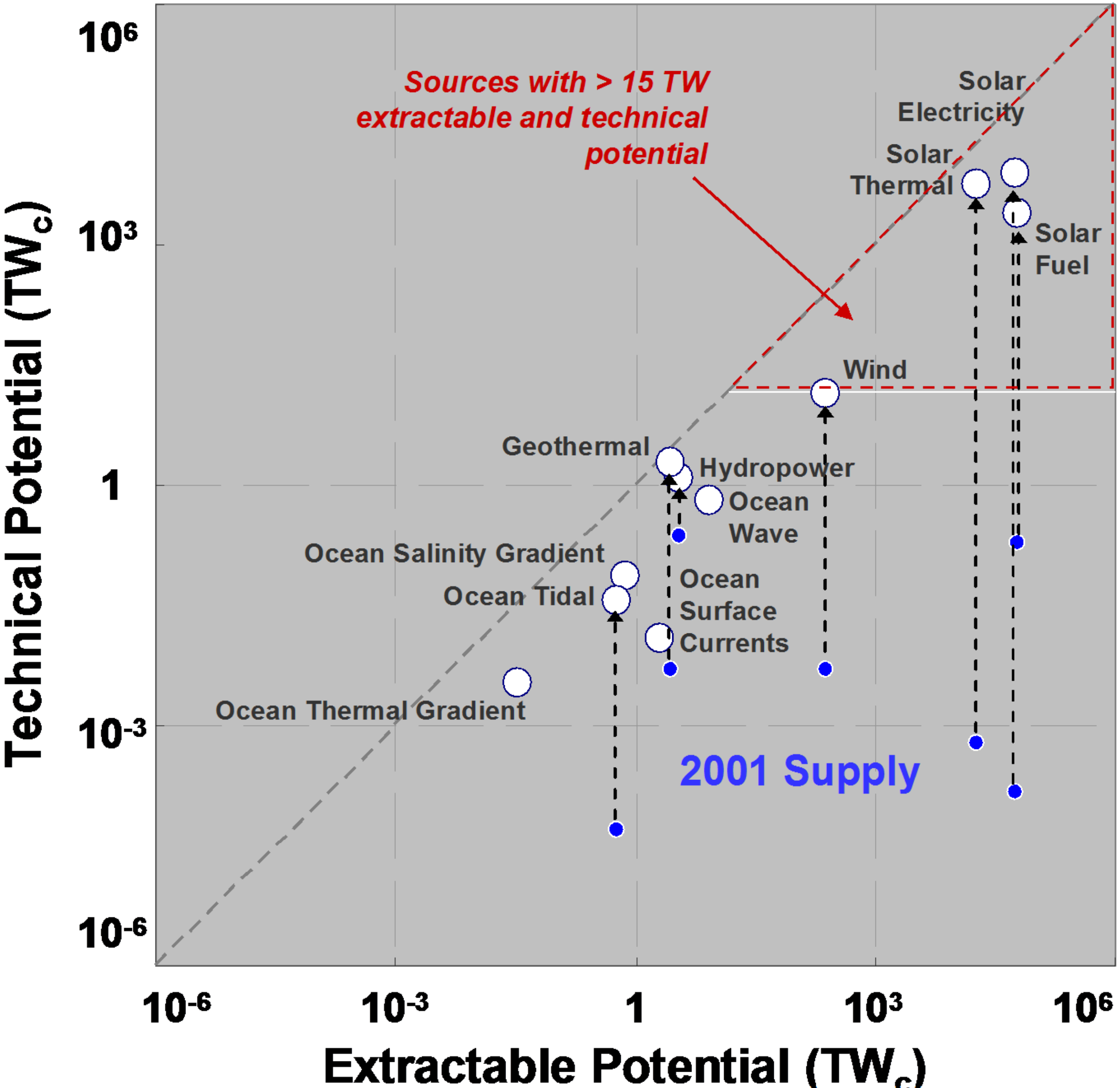
2014 forecast savings in 2016 from 1 kWh of solar

- solar has reached grid parity in 10 states in 2013



Source: Deutsche Bank 2014

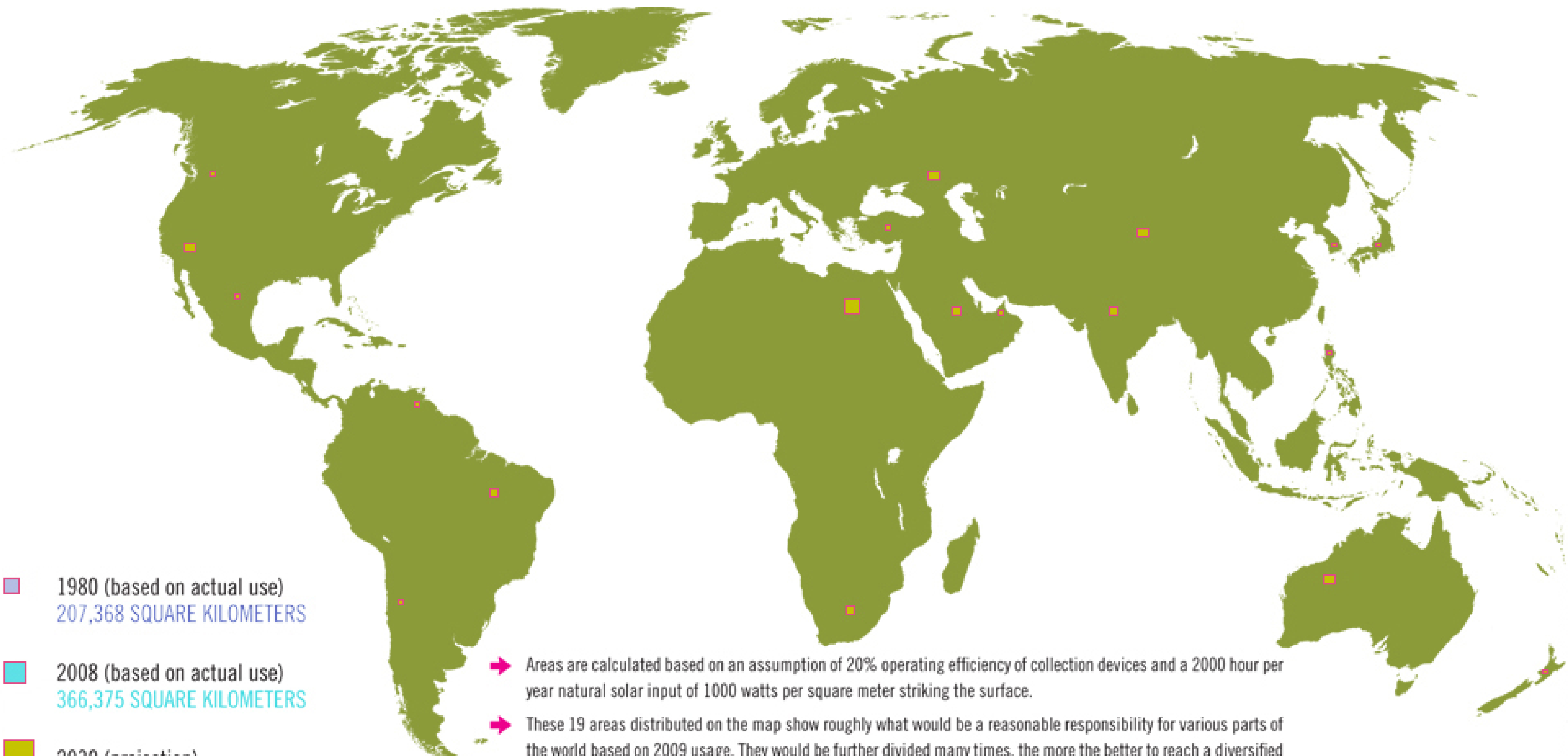
Technical potential of renewable sources



solar can supply <u>total</u> world energy demand

Source: Tsao, Lewis, Crattree, 2006

Area to power the world by solar



1980 (based on actual use)
207,368 SQUARE KILOMETERS

2008 (based on actual use)
366,375 SQUARE KILOMETERS

2030 (projection)
496,805 SQUARE KILOMETERS

- Areas are calculated based on an assumption of 20% operating efficiency of collection devices and a 2000 hour per year natural solar input of 1000 watts per square meter striking the surface.
- These 19 areas distributed on the map show roughly what would be a reasonable responsibility for various parts of the world based on 2009 usage. They would be further divided many times, the more the better to reach a diversified infrastructure that localizes use as much as possible.
- The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is 18 times less than the total area of that desert.
- The definition of "power" covers the fuel required to run all electrical consumption, all machinery, and all forms of transportation. It is based on the US Department of Energy statistics of worldwide Btu consumption and estimates the 2030 usage (678 quadrillion Btu) to be 44% greater than that of 2008.
- Area calculations do not include magenta border lines.

LAND ART GENERATOR INITIATIVE

Outline

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Challenges and opportunities

- Implications on smart grid

Sample Caltech research

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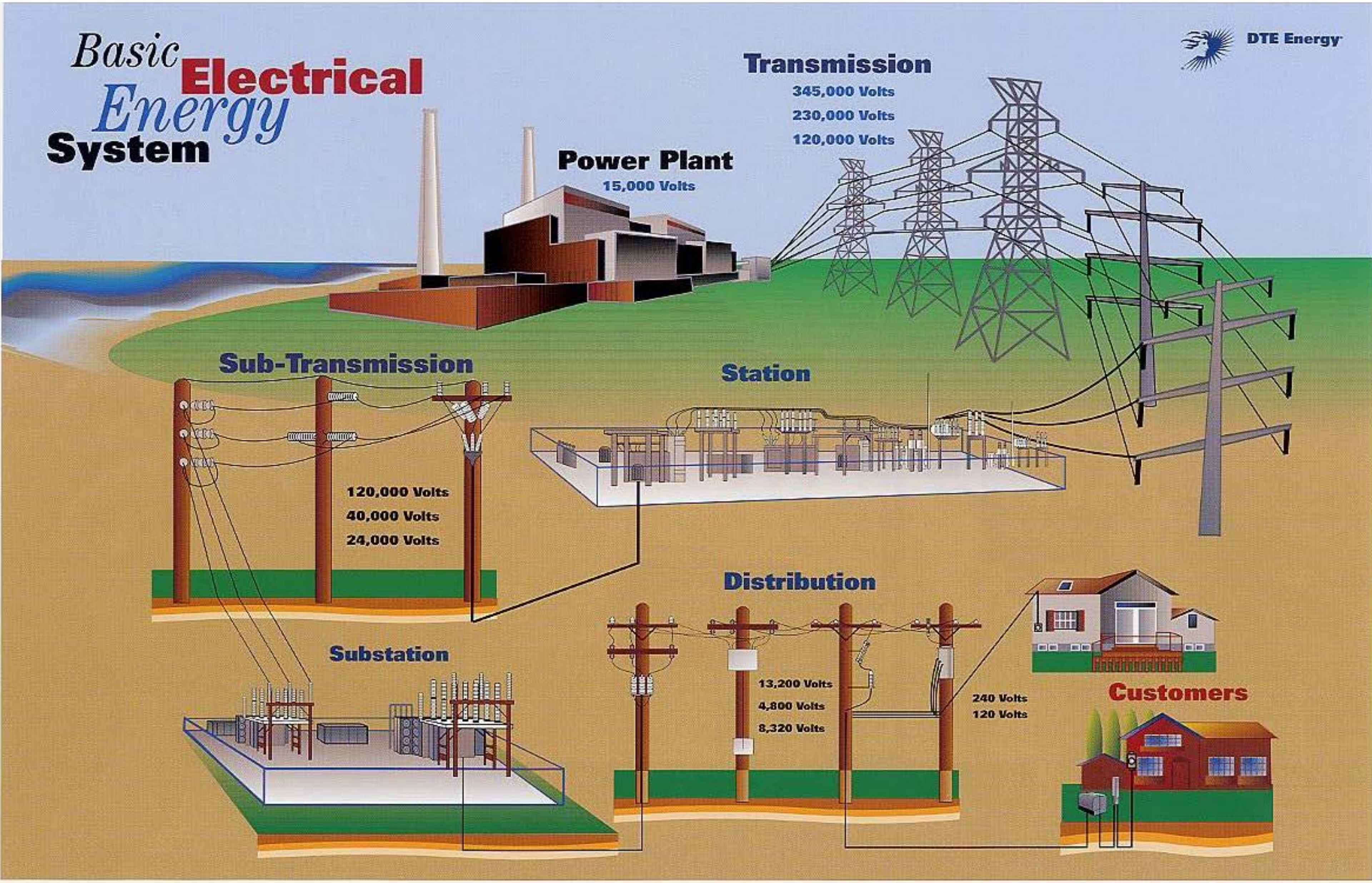
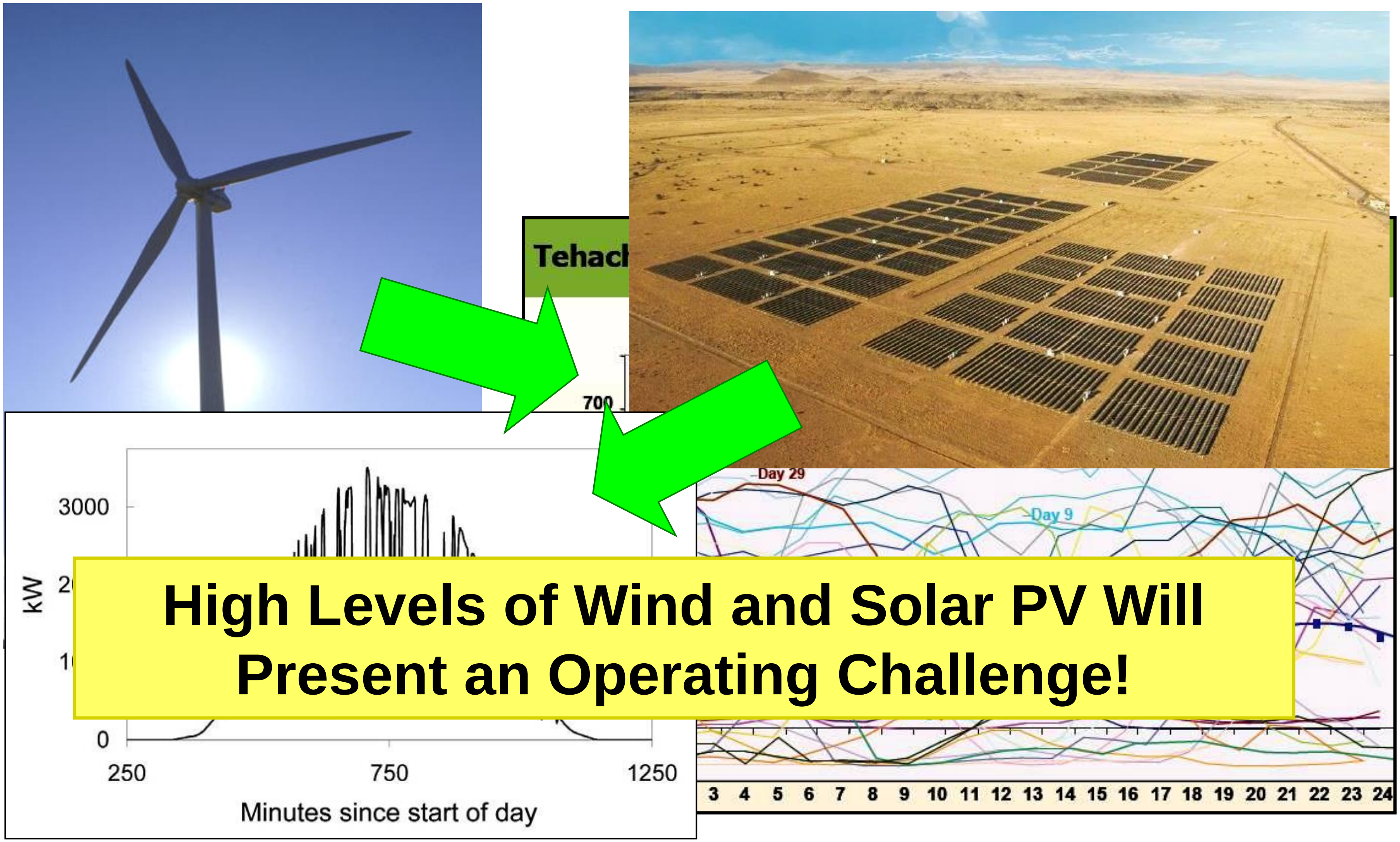
- Power flow and dynamics


Basic Electrical Energy System
DTE Energy
Transmission
345,000 Volts
230,000 Volts
120,000 Volts
Power Plant
15,000 Volts
Sub-Transmission
Station
120,000 Volts
40,000 Volts
24,000 Volts
Distribution
Substation
13,200 Volts
4,800 Volts
8,320 Volts
240 Volts
120 Volts
Customers

Renewables → uncertainty

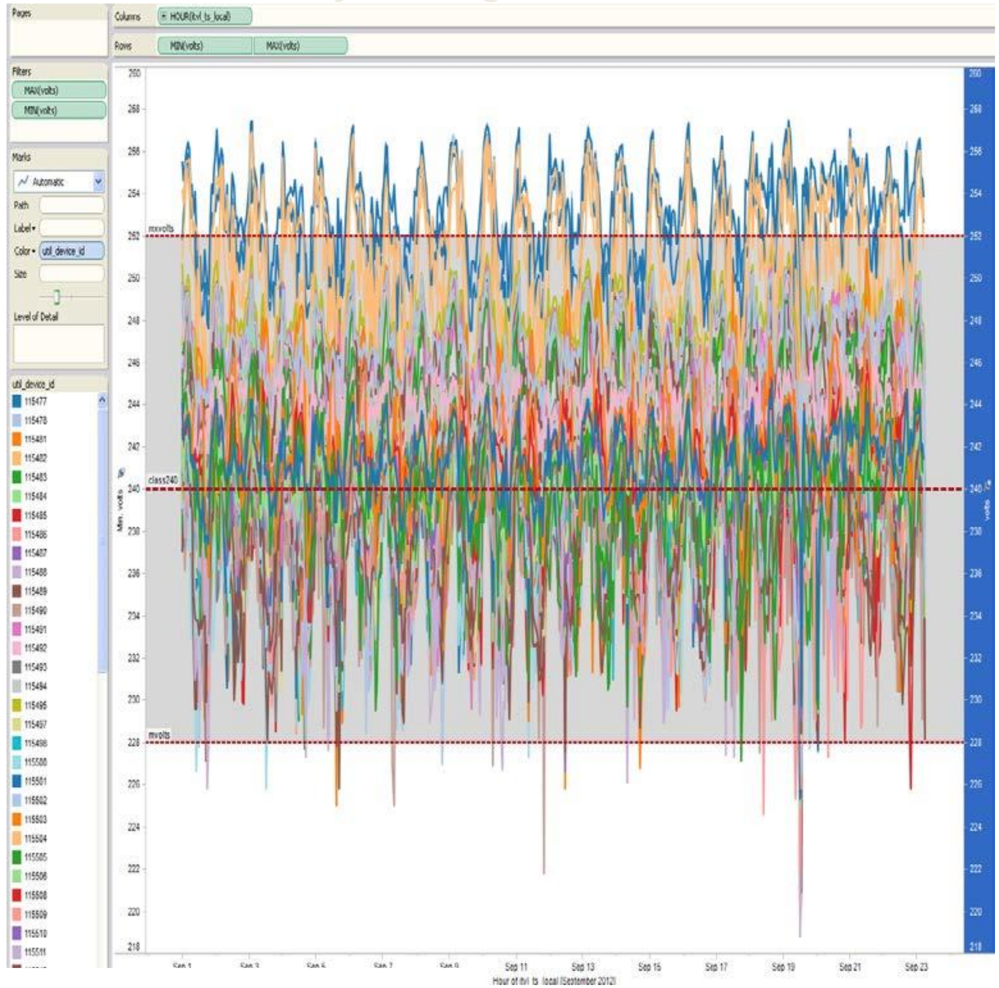


High Levels of Wind and Solar PV Will Present an Operating Challenge!

Source: Rosa Yang, EPRI

- 68 meters (residential)
- Sept 2012 (23 days)
- 240 volts
- +-5% min-228/max-252
- Hourly by meter #
- A few “high” meters
- Larger # of low meters

Hourly Voltage Overview[1]



Voltage violations are frequent

SunShot U.S. Department of Energy

GO solar CALIFORNIA

High Penetration

2013
Feb 13-14, San Diego, CA

Source: Leon Roose, University of Hawaii
Development & demo of smart grid inverters for high-penetration PV applications

Hourly Voltage Overview[1]

Hawaii's solar power flare-up: Too much of a good thing?

So many private solar panels are returning power to the grid that utilities' systems can't handle it all.

November 17, 2013

Germany's Green Energy Destabilizing Electric Grids

"Energiewende"

JANUARY 23, 2013

Power struggle: Green energy versus a grid that's not ready

Minders of a fragile national power grid say the rush to renewable energy might actually make it harder to keep the lights on.

December 02, 2013 | By Evan Halper

Grid Instability ... Solutions

By Catalina Schröder

Sudden fluctuations in Germany's power grid are causing major dam... companies. While many of them have responded by getting their ow... help minimize the risks, they warn that companies might be forced t... with the issues fast.

... Initiative

... up to us.

Power customers opt to go off grid

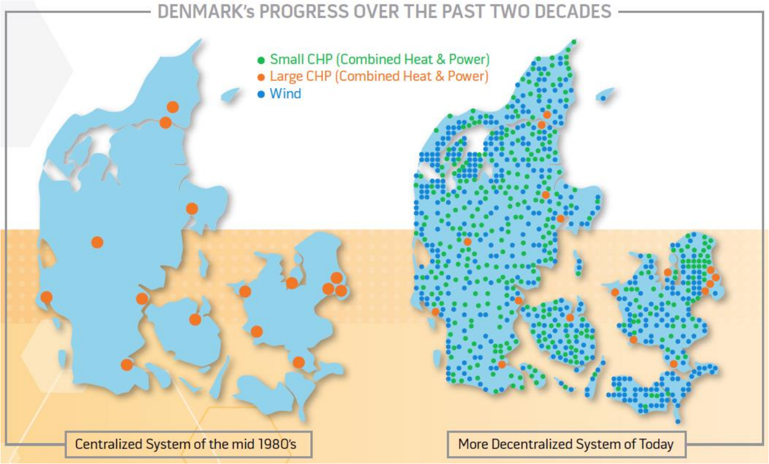
Global trends

1 Proliferation of renewables

- Driven by sustainability
- Enabled by policy and investment

2 Migration to distributed arch

- 2-3x generation efficiency
- Relief demand on grid capacity



Global trends

1 Proliferation of renewables

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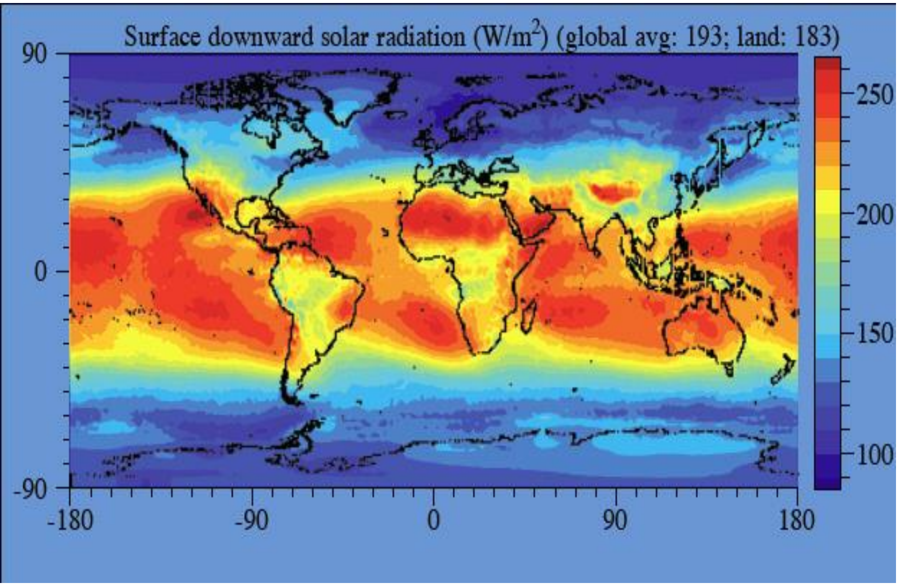
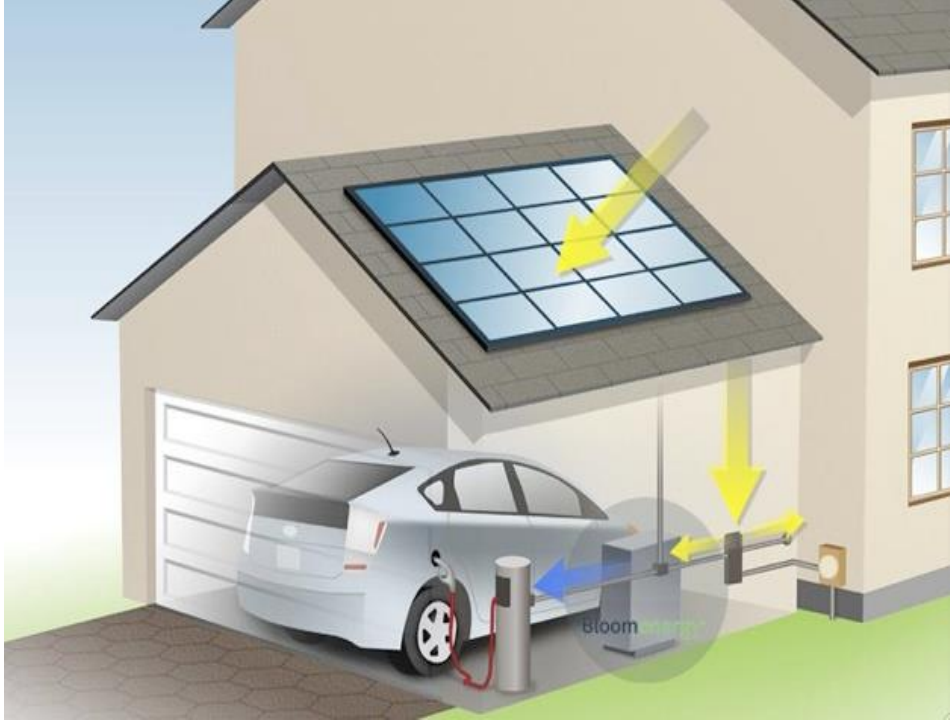
- 2-3x generation efficiency
- Relief demand on grid capacity

3 Rise of Internet of Things (IoT)

- 5x adoption rate of electricity & phone
- Impact on industry and residential

Solar power over land:
> 20x world energy demand



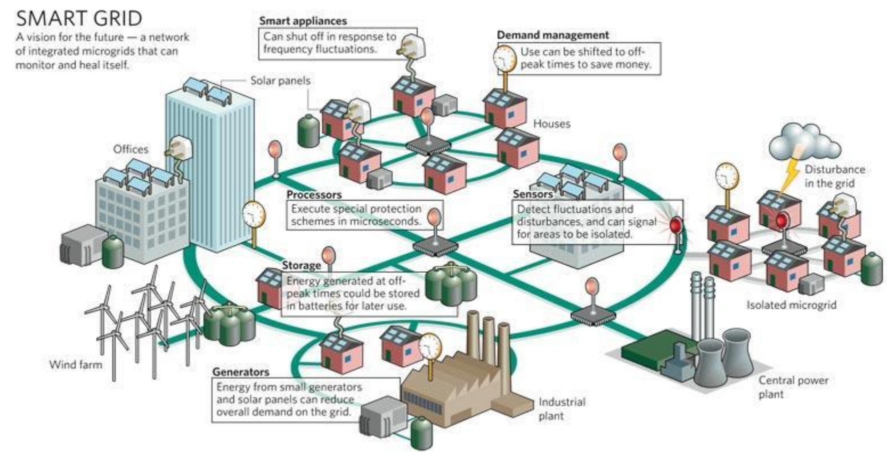


network of billions of active distributed energy resources (DERs)

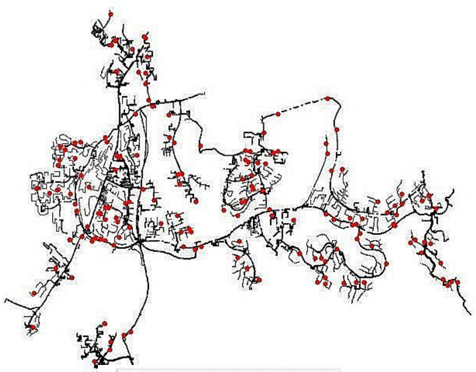
DER: PV, wind tb, EV, storage, smart bldg / appl

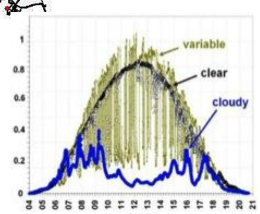
Risk: active DERs introduce rapid random fluctuations in supply, demand, power quality increasing risk of blackouts

Opportunity: active DERs enables realtime dynamic network-wide feedback control, improving robustness, security, efficiency



Caltech research: distributed control of networked DERs





- Foundational theory, practical algorithms, concrete applications
- Integrate engineering and economics
- Active collaboration with industry

NSF arpa·e SOUTHERN CALIFORNIA EDISON RESNICKINSTITUTE science + energy + sustainability Skoltech Skolkovo Institute of Science and Technology

Implications

Current control paradigm works well today

- Centralized, open-loop, human-in-loop, worst-case preventive
- Low uncertainty, few active assets to control
- Schedule supplies to match loads

Future needs

- Closing the loop, e.g. real-time DR, Volt/VAR control, EV/storage mgt
- Fast computation to cope with rapid, random, large fluctuations in supply, demand, voltage, freq
- Simple algorithms to scale to large networks of active DERs

intelligence

everywhere

connected

Recap

Global energy demand will continue to grow

Traditional supply is unsustainable

There is more renewable energy than the world ever needs

- Someone will figure out how to capture and store it

There will be connected intelligence everywhere

- Cost of computing, storage, communication and manufacturing will continue to drop

➔ Power system will transform into the largest and most complex Internet of Things

- Generation, transmission, distribution, consumption, storage

Recap

To develop technologies that will enable and guide the historic transformation of our power system

- Generation, transmission, distribution, consumption, storage
- Devices, systems, theory, algorithms
- Control, optimization, stochastics, data, economics

Key technical challenges

Large scale

- Distributed algorithms

Uncertainty

- Risk-limiting approach

Multiple timescales

- Decomposition

Nonconvexity

- Convex relaxations

Large scale

Example: Southern California Edison

- 4-5 million customers

SCE Rossi feeder circuit

- #houses: 1,407; #commercial/industrial: 131
- #transformers: 422
- #lines: 2,064 (multiphase, inc. transfomers)
- peak load: 3 – 6 MW
- #optimization variables: 50,000

SCE has 4,500 feeders

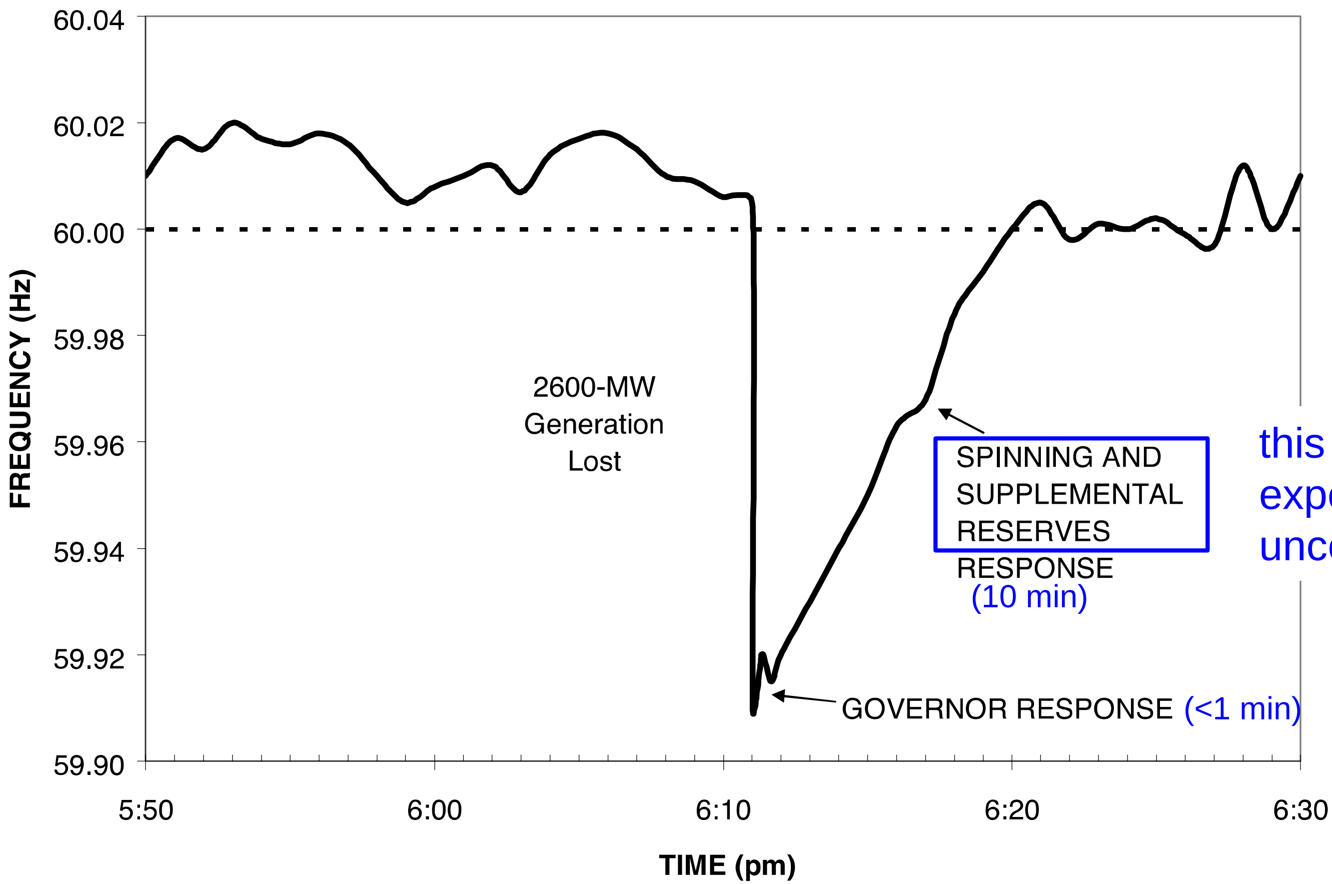
- ~100M variables

United States

- 131M customers, 300K miles of transmission & distr lines, 3,100 utilities

Uncertainty

Uncertainty creates difficulty in both control and markets



this can be very expensive as uncertainty grows

Loss of 2 nuclear plants in ERCOT

Kirby 2003 [ORNL/TM-2003/19]

Uncertainty

Real-time price can be more than 100x the average price !

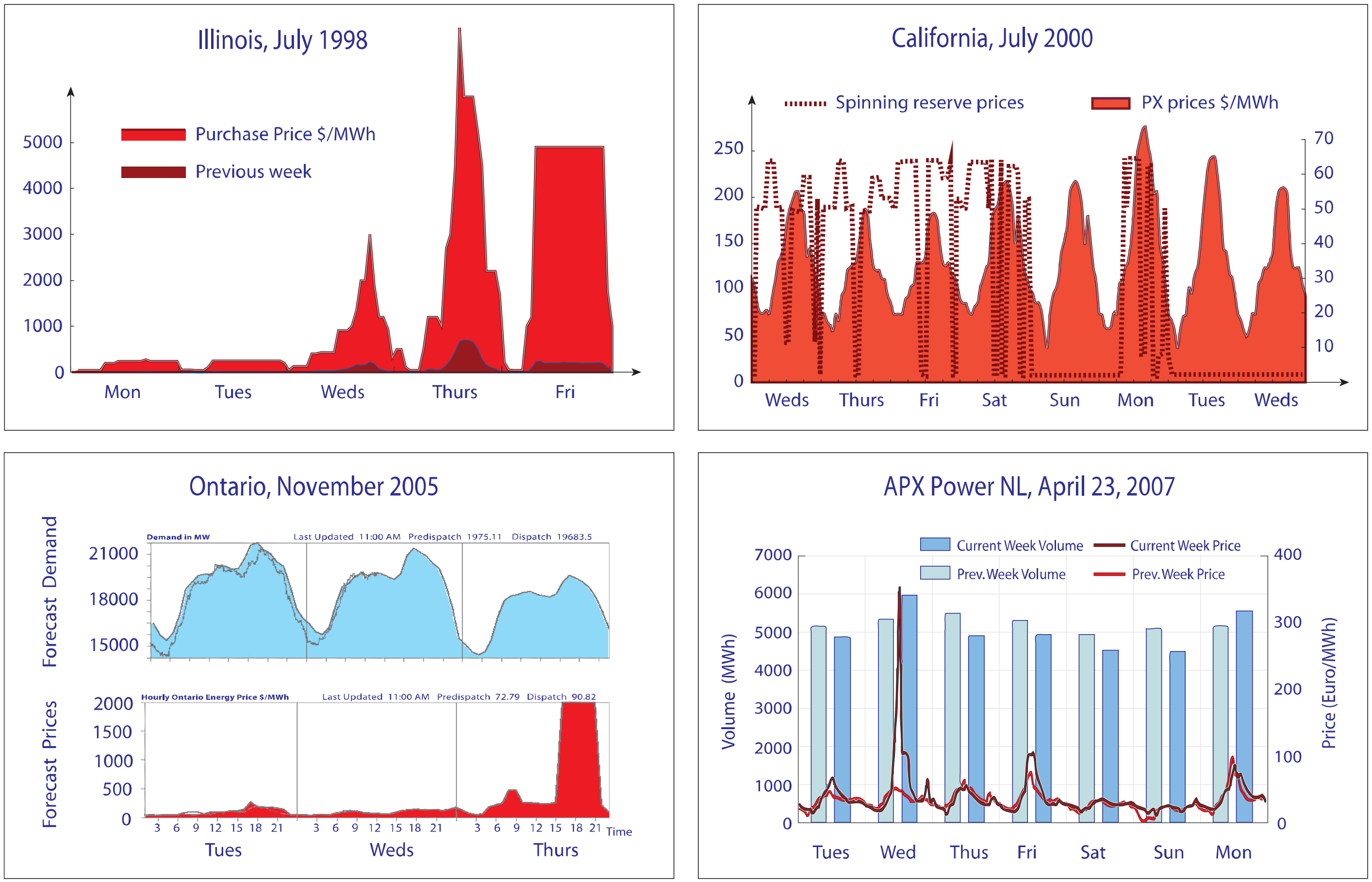


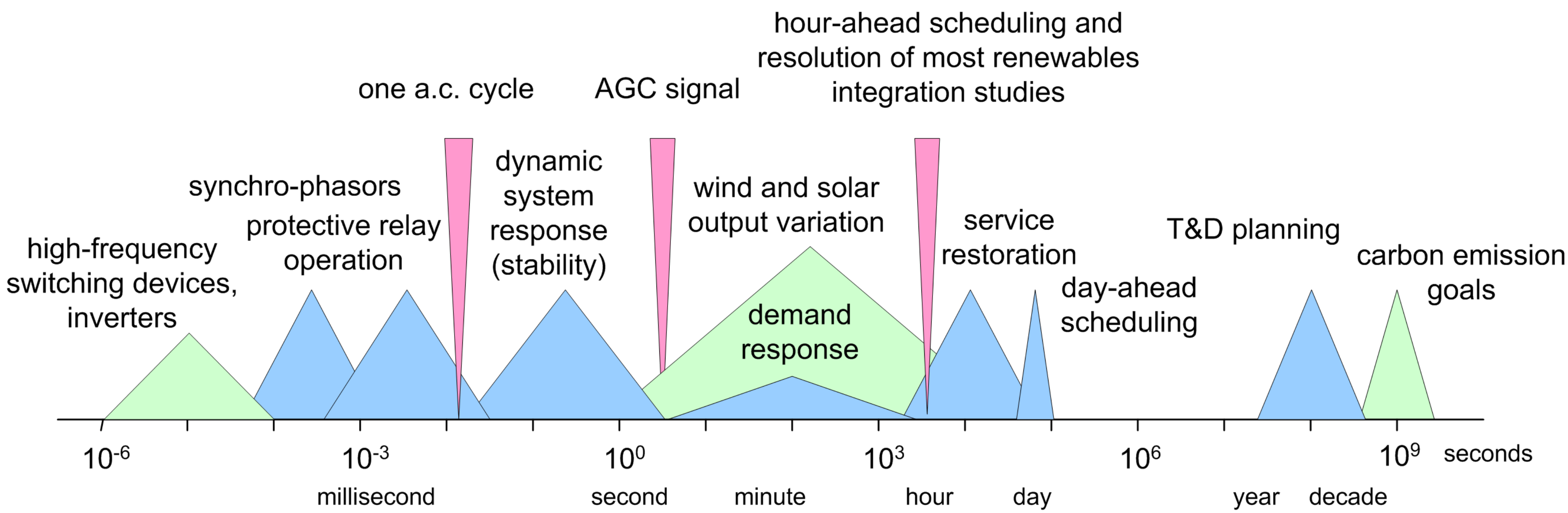
Figure: Real-world price dynamics

Sean Meyn, 2010

Multiple timescale

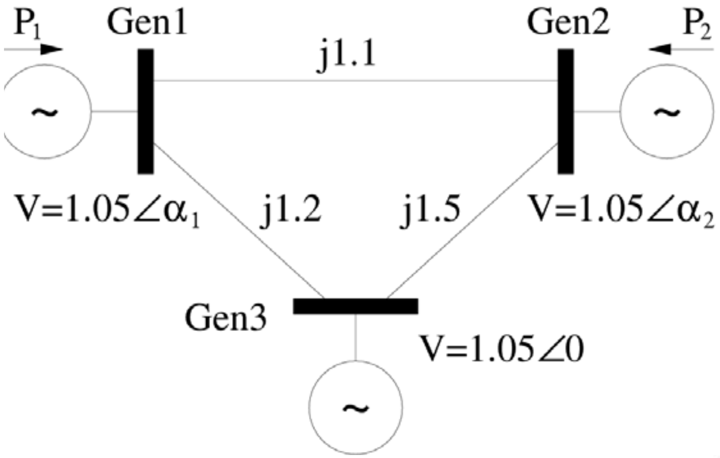
System dynamics and controls at different timescales

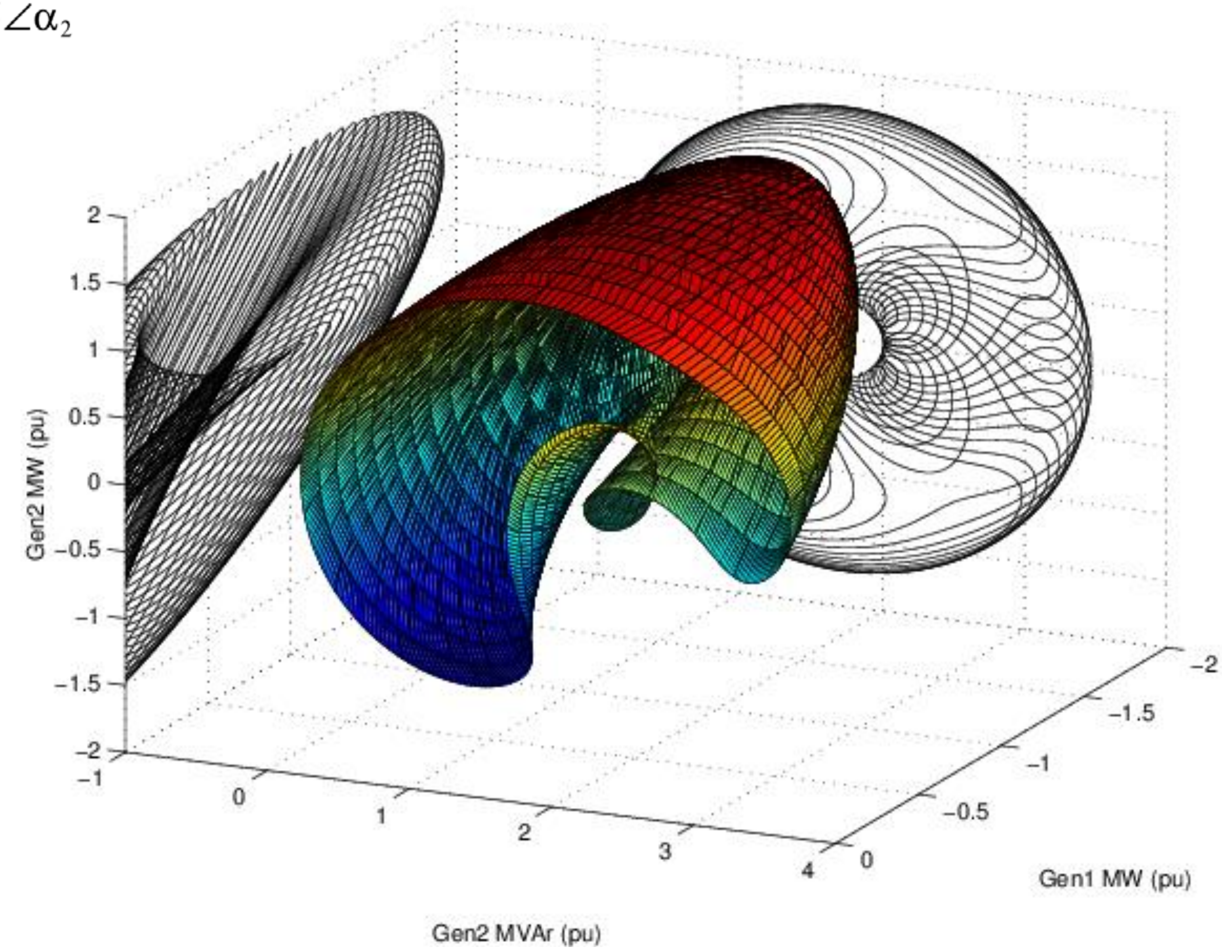
- require different models
- they interact



Sean Meyn, 2010

Nonconvexity





Ian Hiskens, Michigan

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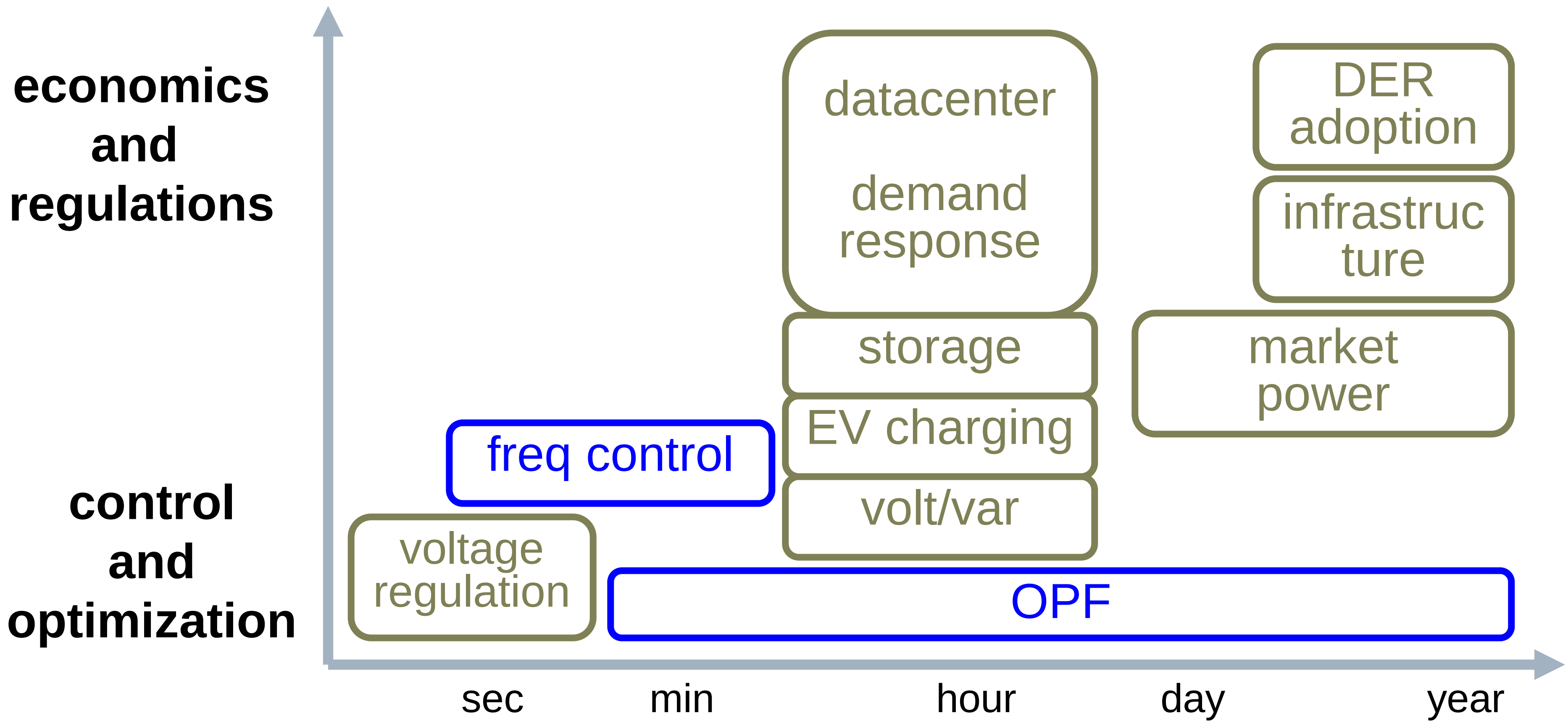
Caltech research

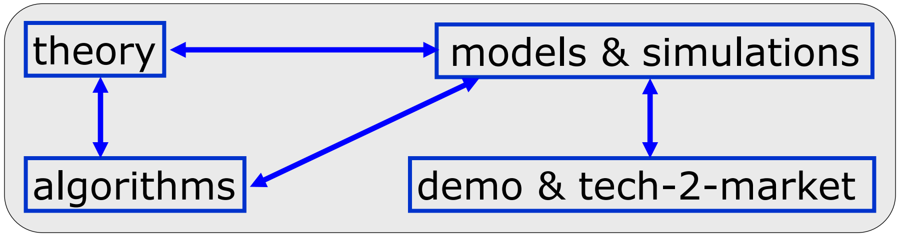


6+ faculty

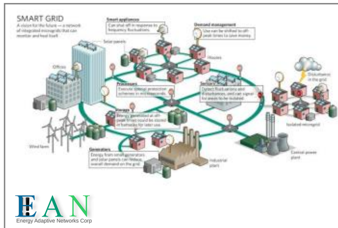
optimal power flow

Distributed Control of Networked DER

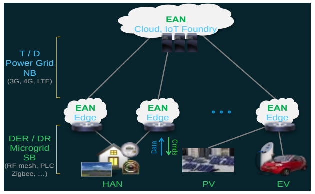
an arpa·e GENI project



Caltech: Profs Chandy, Doyle, **Low (PI)**; Drs. Bunn, Mallada; Students: Agarwal, Cai, Chen, Farivar, Gan, Guo, Matni, Peng, Ren,Tang, You, Zhao
SCE: Auld, Castaneda, Clarke, Gooding, Montoya, Shah, **Sherick (PI)**
Newport/Caltech: DeMartini (advisor)
Alumni: Bose (Cornell), Chen (Colorado), Collins (USC), Gayme (JHU), Lavaei (Columbia), Li (Harvard), Topcu (UPenn), Xu (SUTD)



- EAN analytics and optimization
  DER placement, asset opt, analytics
- EAN enabled control
  DER co-optimization, frequency reg



- Increase(asset(u+liza+on(and(efficiency(
- Improve(power(quality(and(stability(
- Move(data:in:mo+on(analy+cs(to(edge(

Contact: **Michael Enescu**, co-founder CEO, enescu@alumni.caltech.edu

applications and T2M

theory

Convex relaxation of OPF: Theoretical foundation for semi-definite relaxations of power flow

OPF: $\min_V \ \mathrm{tr}(CVV^*)$

s. t. $\underline{s}_j \le \mathrm{tr}(Y_j^* V V^*) \le \bar{s}_j, \quad \underline{v}_j \le |V_j|^2 \le \bar{v}_j$

quadratic in V

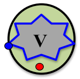
linear in W !

SDP relaxation

$\min_W \ \mathrm{tr}(CW)$

s. t. $\underline{s}_j \le \mathrm{tr}(Y_j^* W) \le \bar{s}_j, \quad \underline{V}_j \le W_{jj} \le \bar{V}_j$

$W \ge 0, \quad \boxed{\mathrm{rank}\ W = 1}$ ignore this (only) nonconvex constr

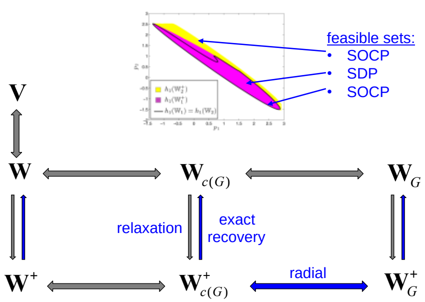


Exact relaxations: Sufficient conditions for recovering global optimum of OPF from relaxations

algorithms

Relaxation algorithms:

- single-phase balanced, multiphase unbalanced
- centralized, distributed

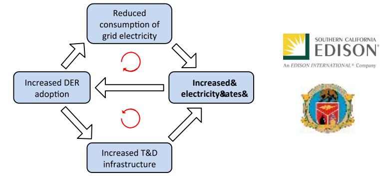


SDP relaxation	Chordal relaxation	SOCP relaxation
• tightest superset	• equivalent superset	• coarsest superset
• max # variables	• much faster for sparse networks	• min # variables
• slowest		• fastest

models

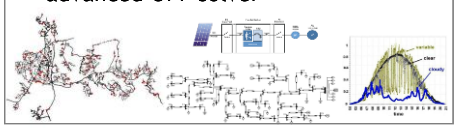
DER adoption model & software

- Sophisticated feedback model
- Cloud service for PV-uptake: http://etechuptake.appspot.com/



volt/var control with renewables

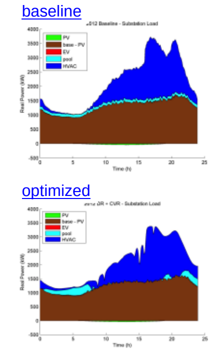
- SCE circuits, DER forecasts
- advanced OPF solver



simulations

Realistic simulations

- SCE feeder model, 2,000 buses
- DER: inverters, HVAC, pool pumps, EV
- Multiphase unbalanced radial



Lead: Prof Mushkin
Undergrads: Chang, Li, Yap, Zhou

Optimal power flow (OPF)

OPF is solved routinely for

- network control & optimization decisions
- market operations & pricing
- at timescales of mins, hours, days, …

Non-convex and hard to solve

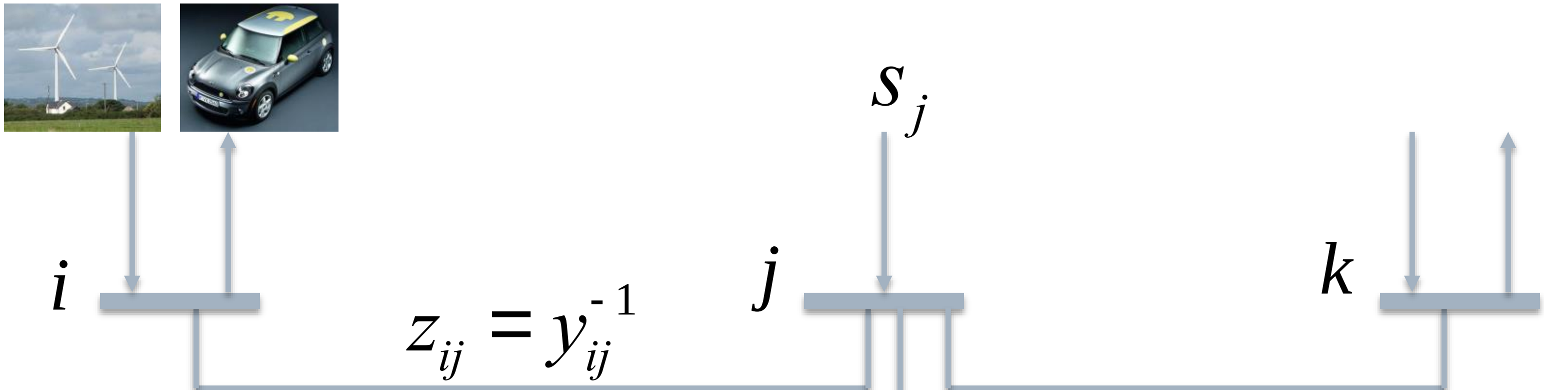
- Huge literature since 1962
- Common practice: DC power flow (LP)
- Also: Newton-Raphson, interior point, …

Optimal power flow (OPF)

OPF underlies many applications

- Unit commitment, economic dispatch
- State estimation
- Contingency analysis
- Feeder reconfiguration, topology control
- Placement and sizing of capacitors, storage
- Volt/var control in distribution systems
- Demand response, load control
- Electric vehicle charging
- Market power analysis
- …

Bus injection model



admittance matrix:

$$Y_{ij} := \begin{cases} \sum_{k \sim i} y_{ik} & \text{if } i = j \\ -y_{ij} & \text{if } i \sim j \\ 0 & \text{else} \end{cases}$$

graph G: undirected

Y specifies topology of G and impedances z on lines

Bus injection model

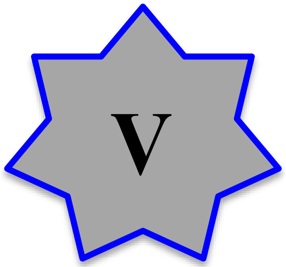
In terms of V:

$$s_j = \mathrm{tr}\left(Y_j^H V V^H\right) \qquad \text{for all } j$$

$$Y_j = Y^H e_j e_j^T$$

Power flow problem:

Given (Y, s) find V



isolated solutions

OPF: bus injection model

min	$\mathrm{tr}\left(CVV^H\right)$	gen cost, power loss
over	(V, s)	
subject to	$\underline{s}_j \le s_j \le \overline{s}_j$	$\underline{V}_j \le \lvert V_j \rvert \le \overline{V}_j$

OPF: bus injection model

min	$\mathrm{tr}\left(CVV^H\right)$	gen cost, power loss
over	$\left(V, s\right)$	
subject to	$\underline{s}_j \le s_j \le \overline{s}_j$	$\underline{V}_j \le \lvert V_j \rvert \le \overline{V}_j$
	$s_j = \mathrm{tr}\left(Y_j^H VV^H\right)$	power flow equation

OPF: bus injection model

$$\min \quad \operatorname{tr} C V V^H$$

$$\text{subject to} \quad \underline{s}_j \le \operatorname{tr}\left(Y_j V V^H\right) \le \bar{s}_j \qquad \underline{v}_j \le |V_j|^2 \le \bar{v}_j$$

nonconvex QCQP
(quad constrained quad program)

Feasible set & SDP

$$\min \quad \mathrm{tr}\, CVV^H$$

$$\text{subject to} \quad \underline{s}_j \;\pounds\; \mathrm{tr}\left(Y_j VV^H\right) \;\pounds\; \bar{s}_j \qquad \underline{v}_j \;\pounds\; |V_j|^2 \;\pounds\; \bar{v}_j$$

quadratic in V
linear in W

Equivalent problem:

$$\min \quad \mathrm{tr}\, CW$$

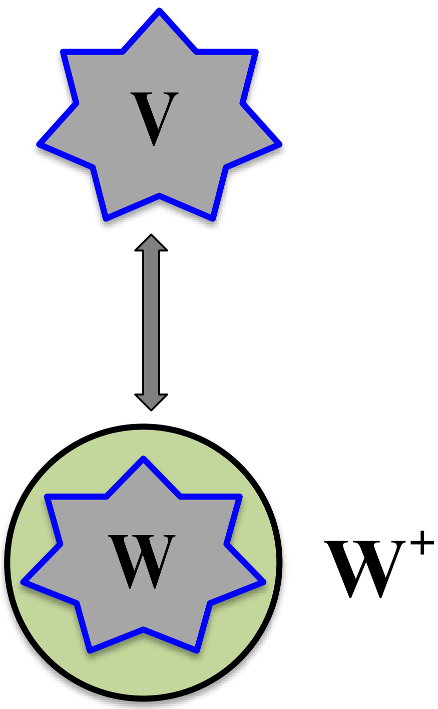
$$\text{subject to} \quad \underline{s}_j \pounds \mathrm{tr}\left(Y_j W\right) \pounds \bar{s}_j \qquad \underline{v}_i \pounds W_{ii} \pounds \bar{v}_i$$

$$W\ ^3\ 0, \quad \mathrm{rank}\, W = 1$$

convex in W
except this constraint

Equivalent feasible sets

$\mathbf{V} := \{ V : \underline{\text{quadratic}} \text{ constraints} \}$



QCQP: *n* variables

SDP: n^2 vars !

$\mathbf{W} := \{ W : \underline{\text{linear}} \text{ constraints} \} \cap \{ W \geq 0 \ \sout{\text{rank-1}} \}$

idea: $W = VV^H$

Equivalent feasible sets

$$\mathbf{W}_G := \left\{ W_G : \underline{\text{linear}} \text{ constraints } \right\}$$

$$\text{idea: } W_G = \left(VV^H \text{ only on } G \right)$$

$$\mathbf{W} := \left\{ W : \underline{\text{linear}} \text{ constraints } \right\} \cap \left\{ W \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } W = VV^H$$

Equivalent feasible sets

$$\mathbf{W}_G := \left\{ W_G : \underline{\text{linear}} \text{ constraints} \right\} \bigcap \left\{ \begin{matrix} W(j,k) \geq 0 \text{ rank-1}, \\ \text{cycle cond on } \angle W_{jk} \end{matrix} \right\}$$

$$\text{idea: } W_G = \left(VV^H \text{ only on } G \right)$$

$$\mathbf{W} := \left\{ W : \underline{\text{linear}} \text{ constraints} \right\} \bigcap \left\{ W \geq 0 \text{ rank-1} \right\}$$

$$\text{idea: } W = VV^H$$

Equivalent feasible sets

Theorem: $\mathbf{V} \circ \mathbf{W} \circ \mathbf{W}_G$

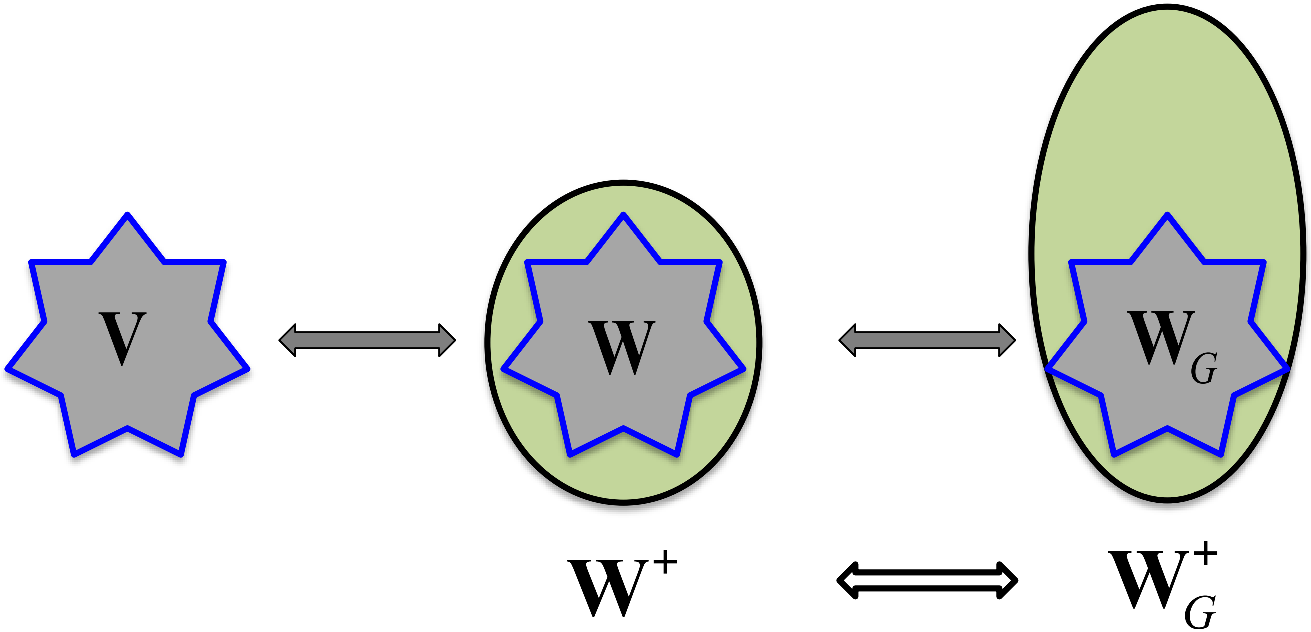
Bose, Low, Chandy Allerton 2012
Bose, Low, Teeraratkul, Hassibi TAC2014

Equivalent feasible sets

$$\mathbf{W}_G := \left\{ W_G : \underline{\text{linear}} \text{ constraints} \right\} \cap \left\{ \begin{array}{l} W(j,k) \geq 0 \ \text{~~rank-1~~}, \\ \text{~~cycle cond on } \angle W_{jk}\text{~~} \end{array} \right\}$$

$$\mathbf{W} := \left\{ W : \underline{\text{linear}} \text{ constraints} \right\} \cap \left\{ W \geq 0 \ \text{~~rank-1~~} \right\}$$

Relaxations

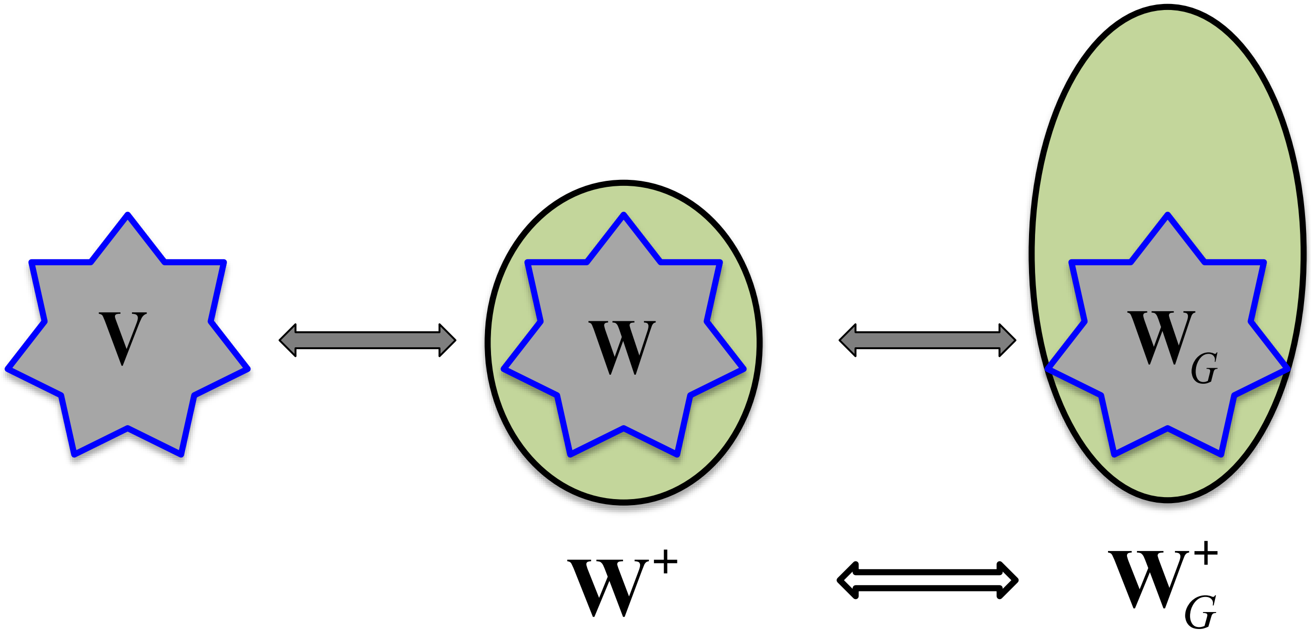


Theorem

- Radial G : $\mathbf{V} \subseteq \mathbf{W}^{+} @ \mathbf{W}_{G}^{+}$
- Mesh G : $\mathbf{V} \subseteq \mathbf{W}^{+} \subseteq \mathbf{W}_{G}^{+}$

Bose, Low, Chandy Allerton 2012
Bose, Low, Teeraratkul, Hassibi TAC2014

Relaxations



Theorem

- Radial G : $\mathbf{V} \subseteq \mathbf{W}^+ @ \mathbf{W}_G^+$
- Mesh G : $\mathbf{V} \subseteq \mathbf{W}^+ \subseteq \mathbf{W}_G^+$

For radial networks: always solve SOCP !

Recap: semidef relaxations

OPF

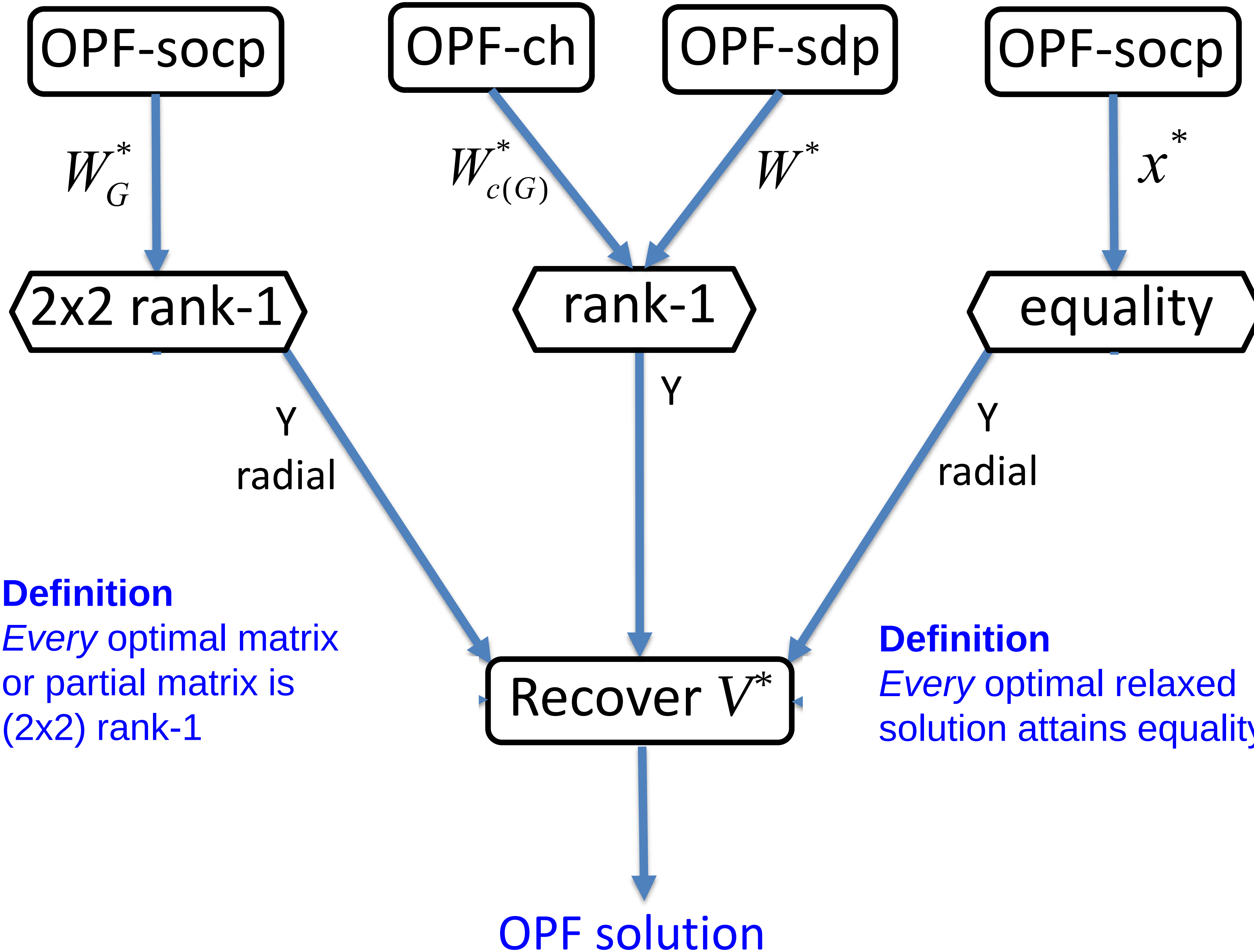
$$\min_{V} \; C(V) \quad \text{subject to} \quad V \;\text{Î}\; \mathbf{V}$$

OPF-sdp:

$$\min_{W} \; C(W_G) \qquad \text{subject to} \quad W \in \mathbb{W}^{+}$$

OPF-socp:

$$\min_{W_G} \; C(W_G) \qquad \text{subject to} \quad W_G \in \mathbb{W}_G^{+}$$



Definition
Every optimal matrix or partial matrix is (2x2) rank-1

Definition
Every optimal relaxed solution attains equality

1. QCQP over tree

QCQP (C, C_k)

$$
\begin{array}{lll}
\text{min} & x^* C x & \\
\text{over} & x \in \mathbf{C}^n & \\
\text{s.t.} & x^* C_k x \leq b_k & k \in K
\end{array}
$$

graph of QCQP

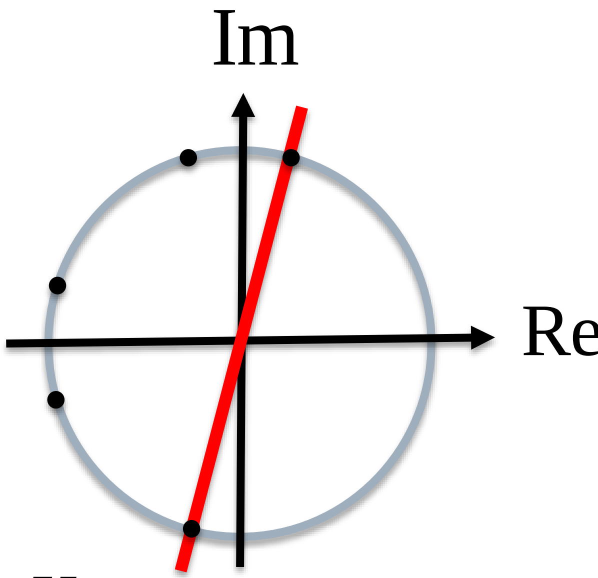
$$G(C, C_k) \text{ has edge } (i,j) \quad \Leftrightarrow$$

$$C_{ij} \neq 0 \ \text{ or } \ [C_k]_{ij} \neq 0 \ \text{ for some } k$$

QCQP over tree

$$G(C, C_k) \text{ is a tree}$$

1. Linear separability



QCQP (C, C_k)

$$\begin{array}{lll} \text{min} & x^* C x & \\ \text{over} & x \in \mathbf{C}^n & \\ \text{s.t.} & x^* C_k x \le b_k & k \in K \end{array}$$

Key condition

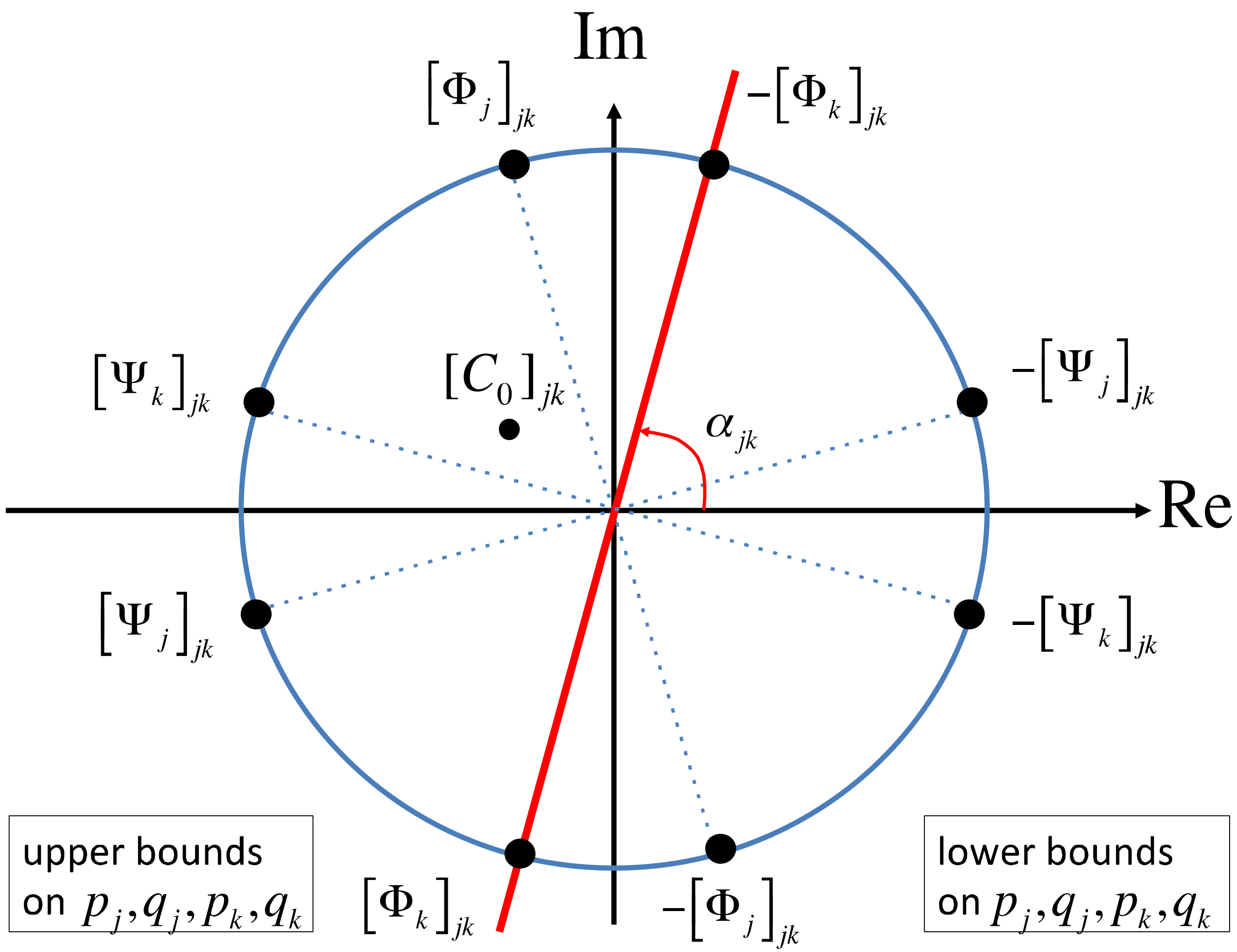
$$i \sim j: \quad \left(C_{ij}, [C_k]_{ij}, \ \forall k\right) \text{ lie on half-plane through } 0$$

Theorem

SOCP relaxation is exact for QCQP over tree

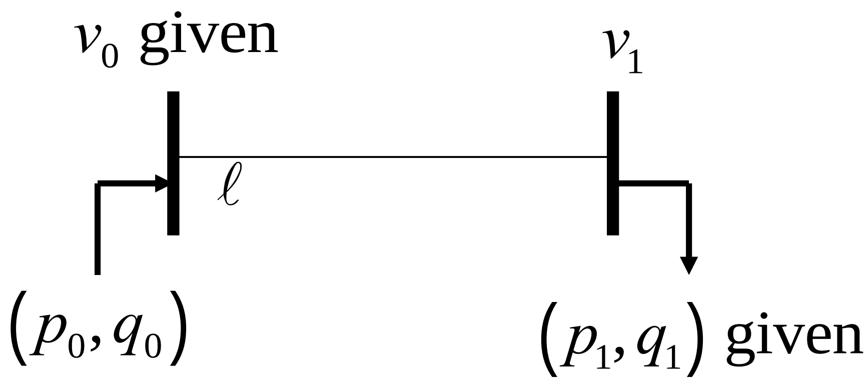
Bose et al 2012
Sojoudi, Lavaei 2013

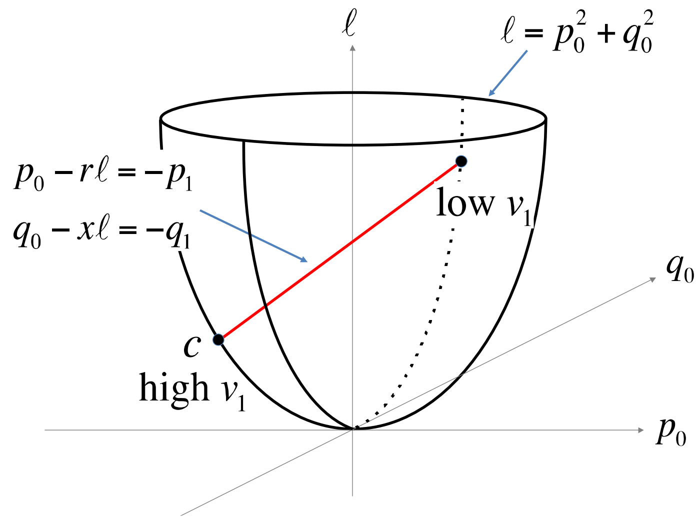
Implication on OPF



Not both lower & upper bounds on real & reactive powers at both ends of a line can be finite

2. Voltage upper bounds

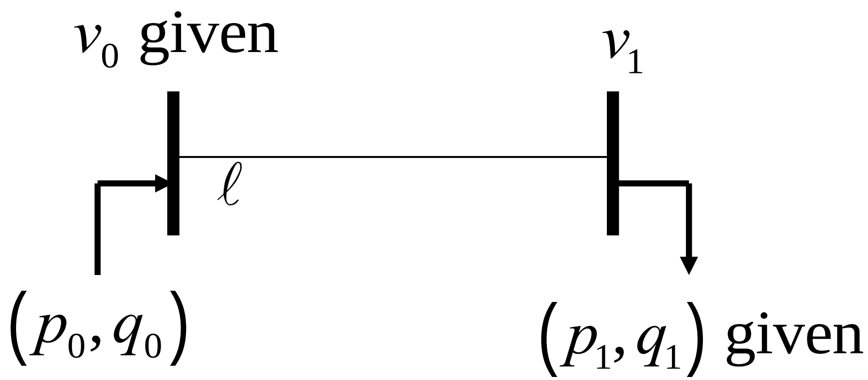


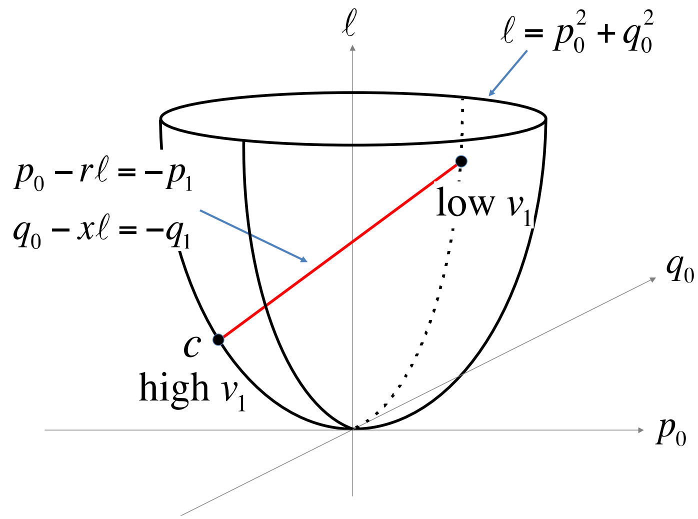


when there is no voltage constraint

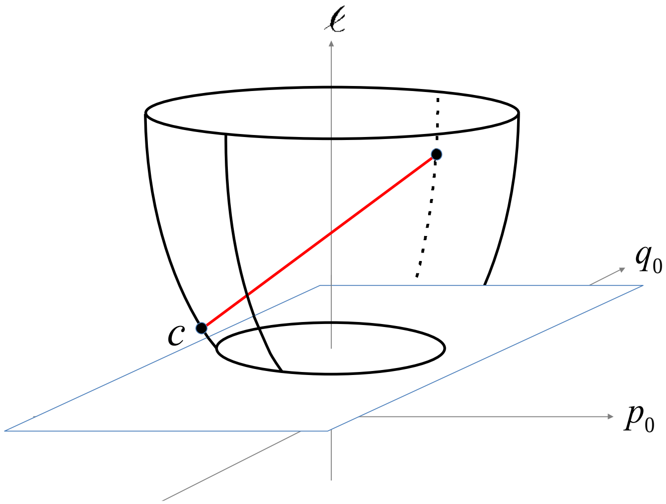
- feasible set : 2 intersection pts
- relaxation: line segment
- exact relaxation: c is optimal

2. Voltage upper bounds

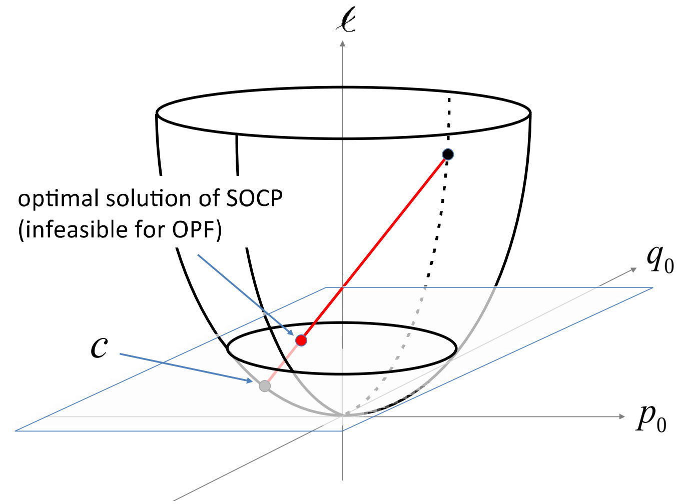




voltage lower bound (upper bound on l) does not affect relaxation



(a) Voltage constraint not binding



(b) Voltage constraint binding

2. Voltage upper bounds

OPF: $\min_{x Î \mathbf{X}} f(x)$ s.t. $\underline{v}$ £ v £ $\overline{v}$, s Î S

SOCP: $\min_{x Î \mathbf{X}^{+}} f(x)$ s.t. $\underline{v}$ £ v £ $\overline{v}$, s Î S

Key condition:

- $L(s)$ £ $\overline{v}$ — voltages if network were lossless
- Jacobian condition — if upward current were reduced then all subsequent powers dec

  $\underline{A}_{i_t} \cdots \underline{A}_{i_{t'}} z_{i_{t'+1}} > 0$ for all $1 \le t \le t' < k$

Theorem

SOCP relaxation is exact for radial networks

Gan, Li, Topcu, Low TAC2014

2. Voltage upper bounds

OPF: $\min_{x \in \mathbf{X}} f(x) \quad \text{s.t.} \quad \underline{v} \le v \le \overline{v}, \quad s \in S$

SOCP: $\min_{x \in \mathbf{X}^+} f(x) \quad \text{s.t.} \quad \underline{v} \le v \le \overline{v}, \quad s \in S$

Key condition:

- $L(s) \le \overline{v}$
- Jacobian condition

  $\underline{A}_{i_t} \cdots \underline{A}_{i_{t'}} z_{i_{t'+1}} > 0$ for all $1 \le t \le t' < k$

satisfied with large margin in IEEE circuits and SCE circuits

Theorem

SOCP relaxation is exact for radial networks

Gan, Li, Topcu, Low TAC2014

OPF: extensions