ECE 18-879P: Engineering and Economics of Electric Power Systems

Fossil and Renewable Generation Dispatch

Generation Dynamics, Economics, Efficiency and Avoided Emissions

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Unit Dispatch and Duty Cycle

- "Real-life Data" *(Historical/Hourly)*
  - › Fossil Unit Operations (EPA Clean Air Markets)
  - › Regional Power Pool Loads & Prices (NERC Subregions)
  - › Actual or Simulated Renewable Generation
    (using hourly weather data - insolation/windspeed)
- Some interesting dynamics and implications
  - › First: Some background…
    - T&D Losses, Cost of Electric Service vs. Electrical Energy
  - › Second: Fossil dispatch is very "state specific"
  - › Third: Avoiding fossil emissions with renewables
  - › Fourth: "What does it all mean?"

What are T&D Losses in the US?

- A Hard Number to Find…

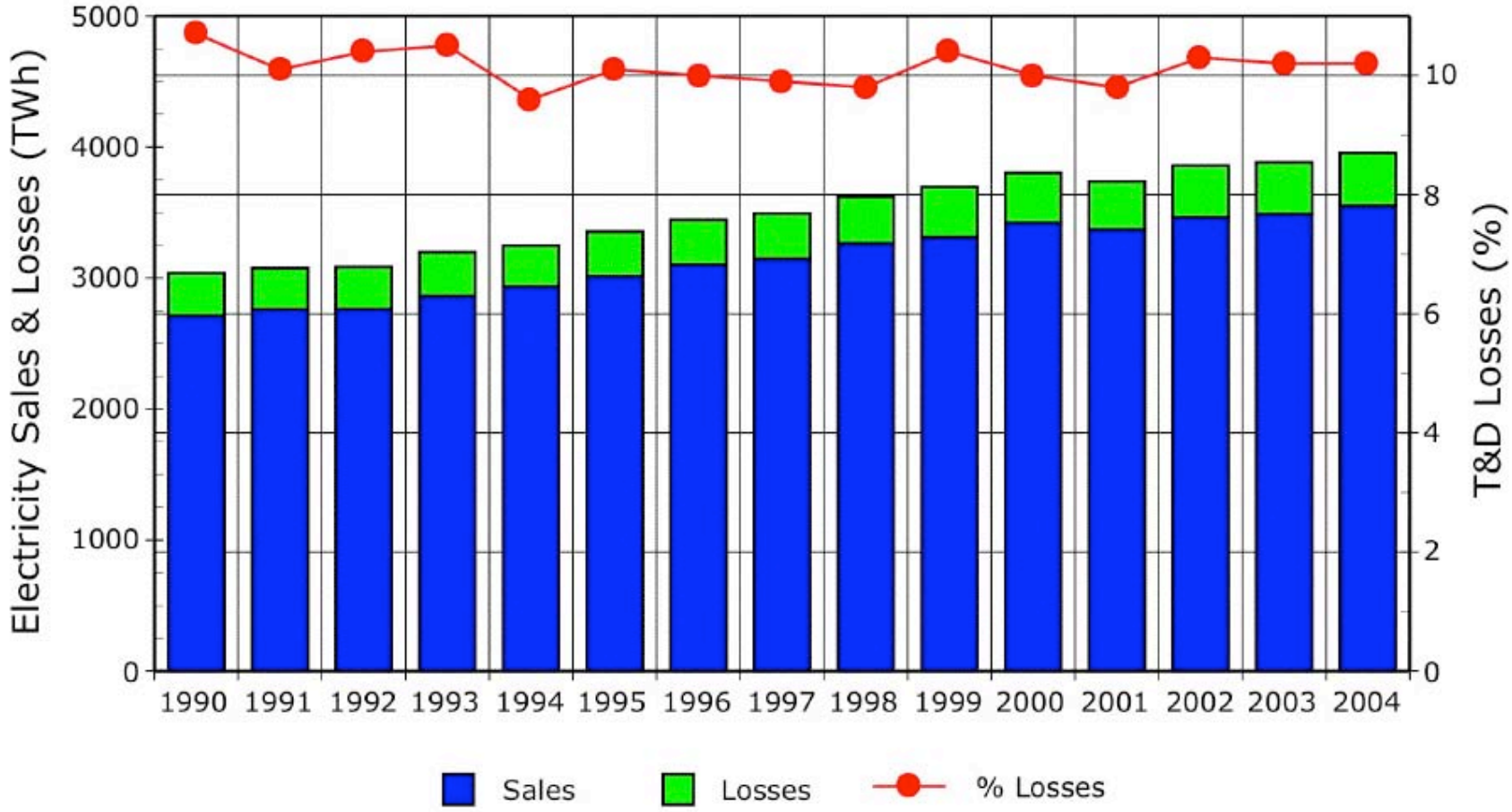
	Electricity Supply, Demand & Losses			
Year	NetGen	Sales	Losses	% Losses
1990	3038.0	2712.6	325.4	10.7
1991	3073.8	2762.0	311.8	10.1
1992	3083.9	2763.4	320.5	10.4
1993	3197.2	2861.5	335.7	10.5
1994	3247.5	2934.6	313.0	9.6
1995	3353.5	3013.3	340.2	10.1
1996	3444.2	3101.1	343.1	10.0
1997	3492.2	3145.6	346.6	9.9
1998	3620.3	3264.2	356.1	9.8
1999	3694.8	3312.1	382.7	10.4
2000	3802.1	3421.4	380.7	10.0
2001	3736.6	3369.8	366.9	9.8
2002	3858.5	3462.5	395.9	10.3
2003	3883.2	3488.2	395.0	10.2
2004	3953.4	3550.5	402.9	10.2
	(TWh)	(TWh)	(TWh)	(%)
			Averages:	10.1

This is a very large amount of energy, fuel, costs & emissions

Source: DOE/EIA Electric Power Monthly-Mar05 Tables 1.1 & 5.1

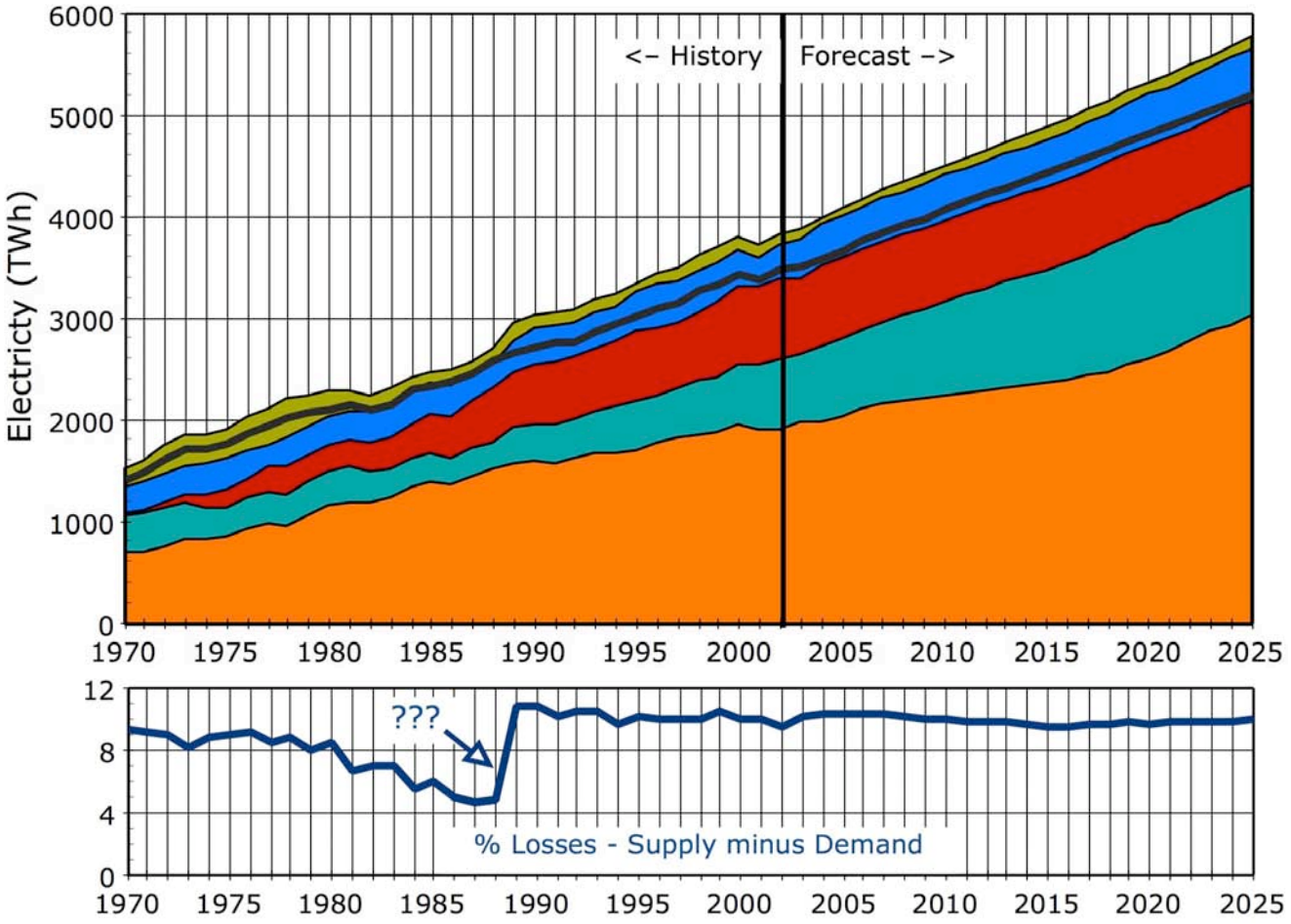
What are T&D Losses in the US?

- A Hard Number to Find…



Where Are We Heading?

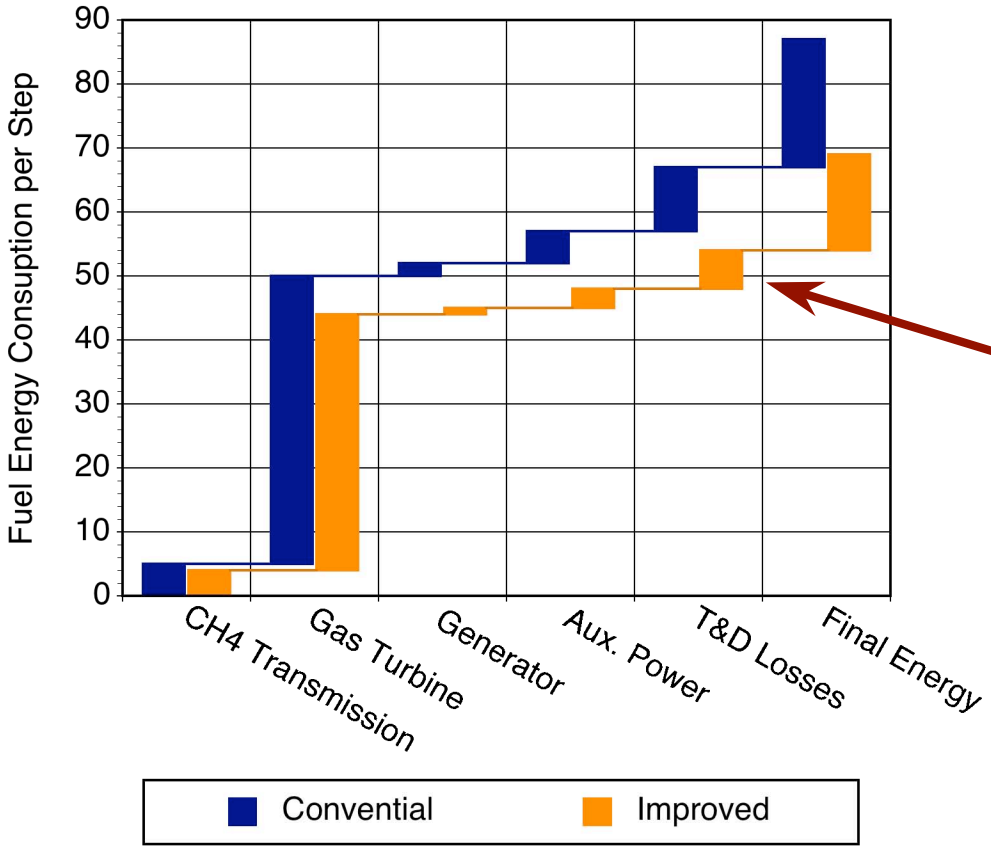
- *The Most Recent US Dept. of Energy Forecast…*



USDOE/EIA Annual Energy Outlook, Jan 2004

Conversion Steps Cost…

- Every "Step" Along the "Supply-Chain" Decreases the Available Energy at the End User.
- Think About Similar Examples Including Hydrogen Vehicles, Biomass Fuel Production, Electronic Equipment etc.

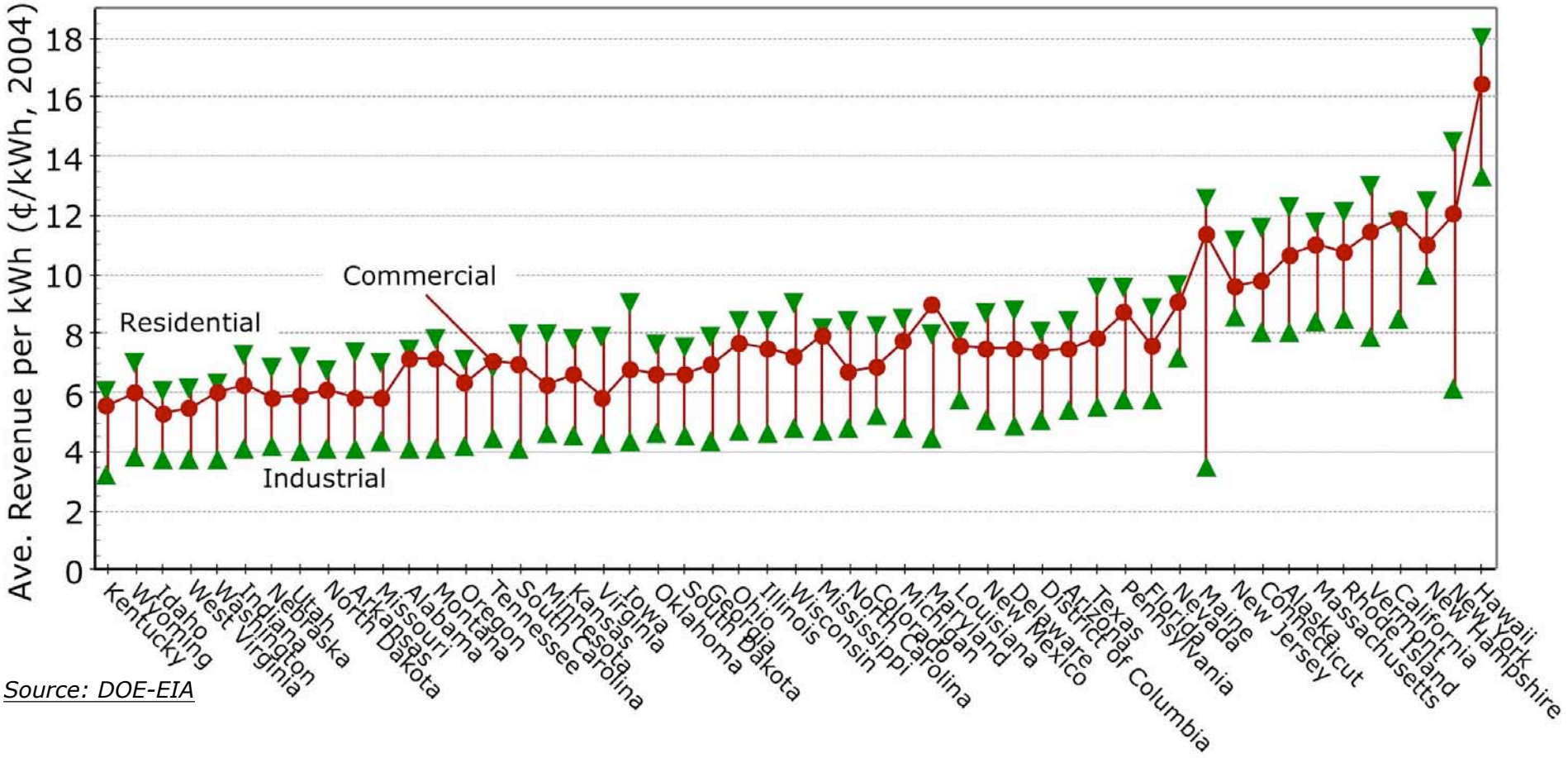


Typical Grid Volatages	Transformer Efficiency Super	Great	Nominal
765.0	99.5	99.0	98.8
500.0	"	"	98.7
▲ 345.0	"	"	**98.6**
▼ 230.0	"	"	**98.5**
161.0	"	"	98.3
138.0	"	"	98.3
▼ 115.0	"	"	**98.2**
▼ 69.0	"	"	**98.0**
46.0	"	"	97.7
▼ 34.5	"	"	**97.5**
25.0	"	"	97.5
▼ 15.0	"	"	**97.0**
7.5	"	"	97.0
▼ 5.0	"	"	**97.0**
(kV)	*(Cumulative Losses – %)*		
	3.4	**6.8**	**14.3**

Source: ACEEE Online Guide to Energy Efficient Commercial Equipment - Distribution Transformers

What Do You Pay for Power?

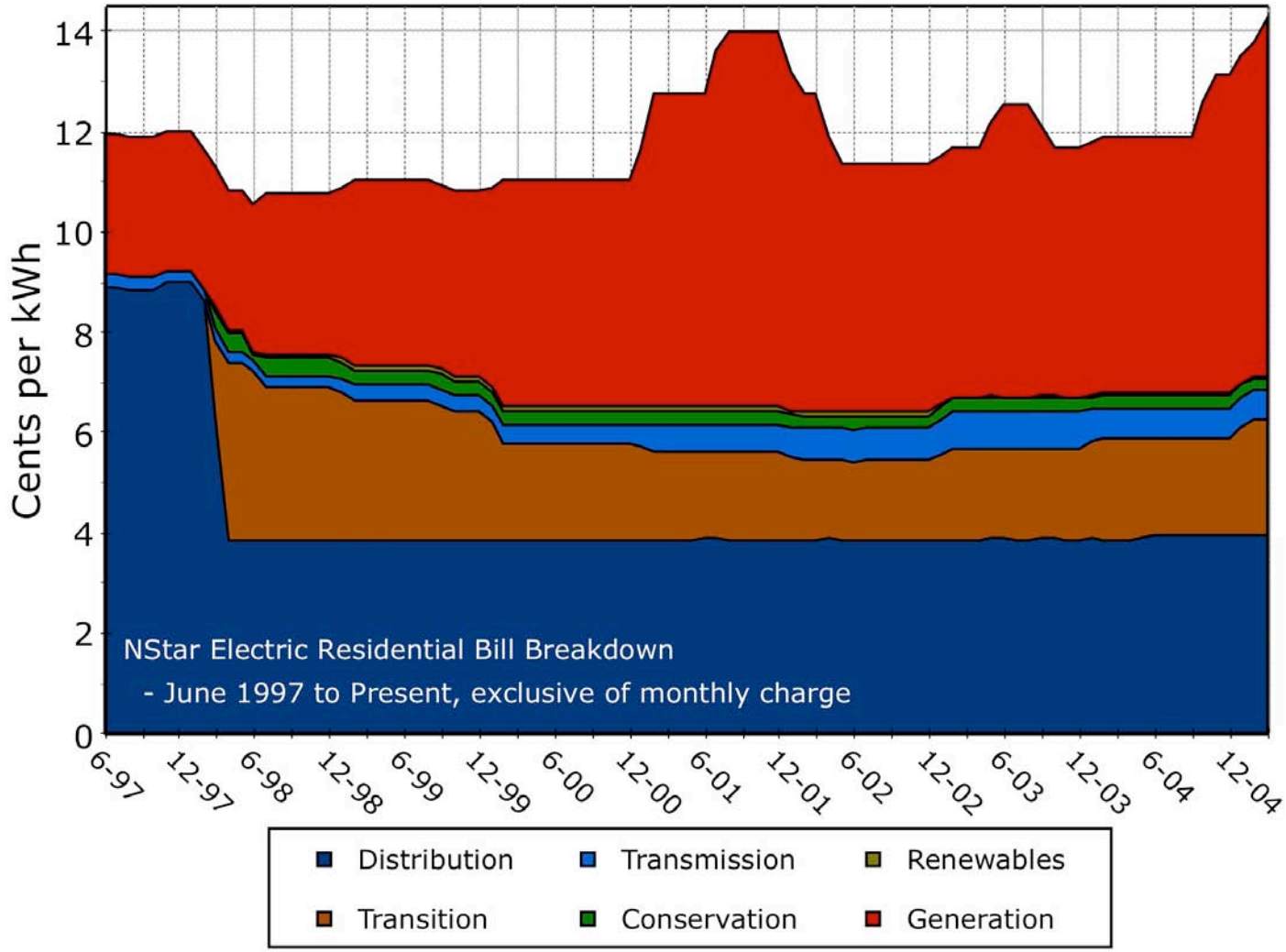
- US "Average Revenue per kWh" (2004)



Source: DOE-EIA

Electricity Costs in Boston

- *NStar Electric Residential Rate Component Costs*



Rotating Equipment Rules!

- The Rise of the Turbines

Type of Generation	Combustion Type	Turbine Type				Primay Power	Electrical Conversion
		Gas	Steam	Water	Aero		
◇ **Traditional Boiler**	External		●			Shaft	Generator
◇ **Fluidized Bed Combustion**	External		●			Shaft –	Generator –
Integrated Gasification Combined-Cycle	Both	●	●			Shaft –	Generator –
Combustion Turbine	Internal	●				Shaft	Generator
Combined Cycle	Both	●	●			Shaft	Generator
◇ **Nuclear**			●			Shaft	Generator
Diesel Genset	Internal					Shaft	Generator
Micro-Turbines	Internal	●				Shaft	Generator
Fuel Cells						**Direct**	**Inverter**
Hydropower				●		Shaft	Generator
◇ **Biomass & WTE**	External		●			Shaft	Generator
Windpower					●	Shaft	Generator
Photovoltaics						**Direct**	**Inverter**
◇ **Solar Thermal**			●			Shaft	Generator
◇ **Geothermal**			●			Shaft	Generator
Wave Power		●				Shaft	Generator
Tidal Power				●		Shaft	Generator
◇ **Ocean Thermal**			●			Shaft	Generator

Fossil Unit Operation Modes

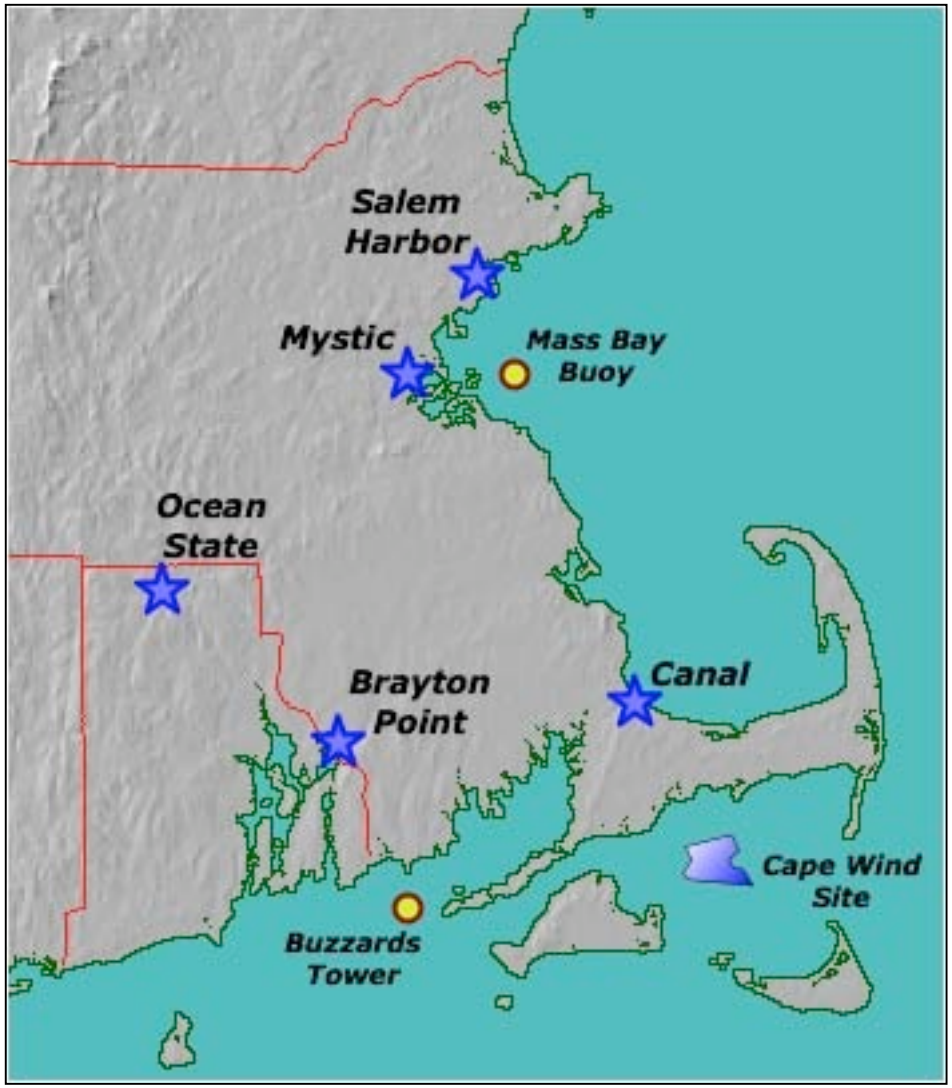
- Generation is generally thought of as "**baseload**," "**intermediate**," or "**peaking**"
- In reality, unit "**dispatch**" is much more complex
- However, several "**Operation Modes**" have been observed by looking at hourly operations.

Operation Mode	***Percent of Net Capacity***
Full Load	● > 90%
Spinning Reserve	≤ 90 % ● > 55 %
Standby	≤ 55 % ● > 5 %
Turning On/Off	≤ 5% ●
Net Capacity = Seasonaly Adjusted Maximum Capacity	

- Even these modes do not, in an of themselves, tell us which units respond to increases in renewable generation, or changes in demand
- These units we call ***Load Shape Following***

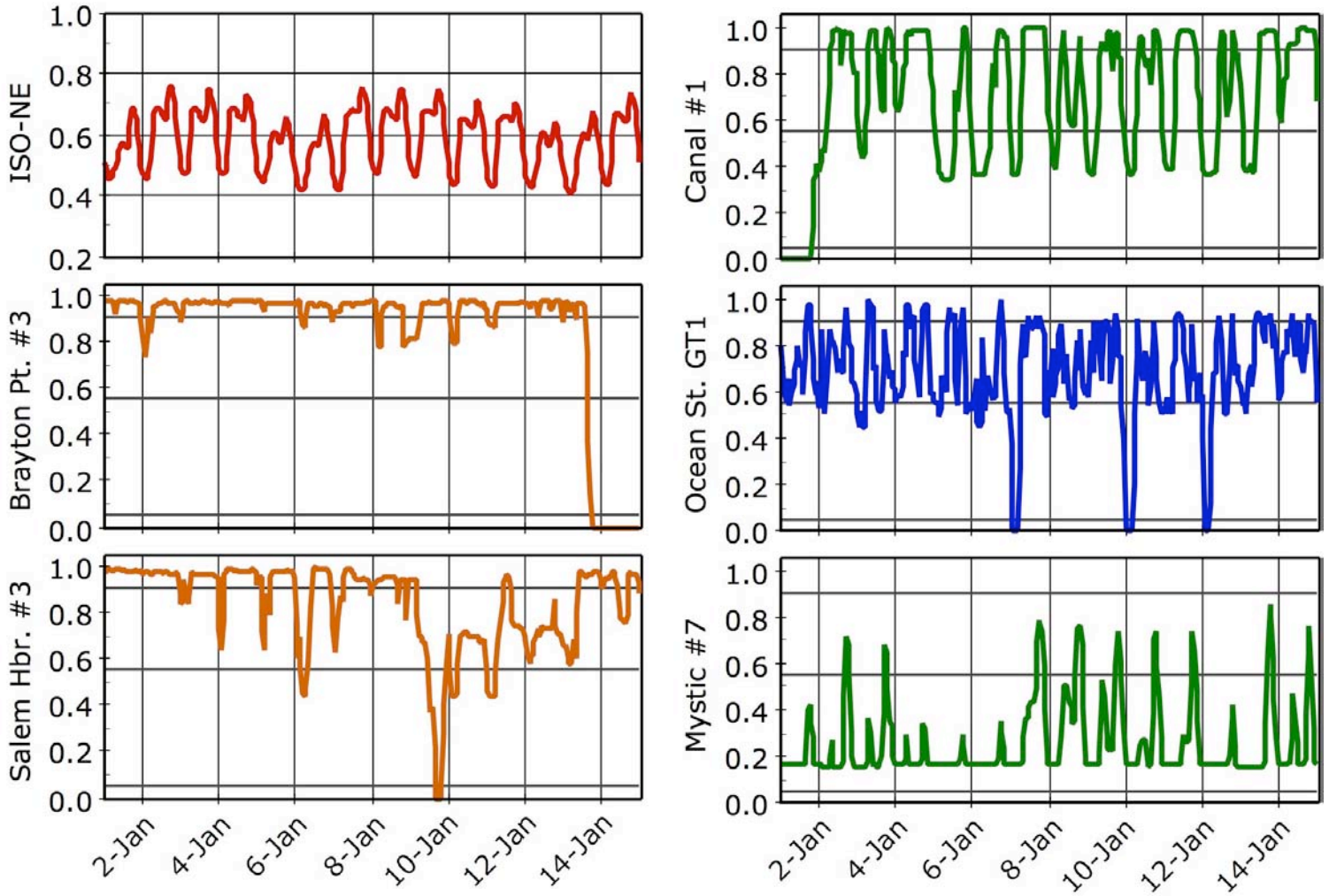
Fossil Dispatch Not So Simple

		Size (MW)		Fuel	Year
Salem Harbor					
1	ST	82	84	Coal	1952
2	ST	80	79	Coal	1952
√ 3	ST	149	150	Coal	1958
4	ST	400	431	Oil	1972
Mystic					
4	ST	95	90	Oil	1957
5	ST	92	91	Oil	1959
6	ST	28	100	Oil	1961
√ 7	ST	555	560	Oil	1975
Canal					
√ 1	ST	559	564	Oil	1968
2	ST	553	562	Oil	1976
Brayton Point					
1	ST	244	255	Coal	1963
2	ST	240	255	Coal	1964
√ 3	ST	612	633	Coal	1969
4	ST	435	446	Oil	1974
Ocean State					
√ GT1/GT2/ST1		271	317	Nat.Gas	1991
GT3/GT4/ST2		272	320	Nat.Gas	1991
		(Summer)	(Winter)		



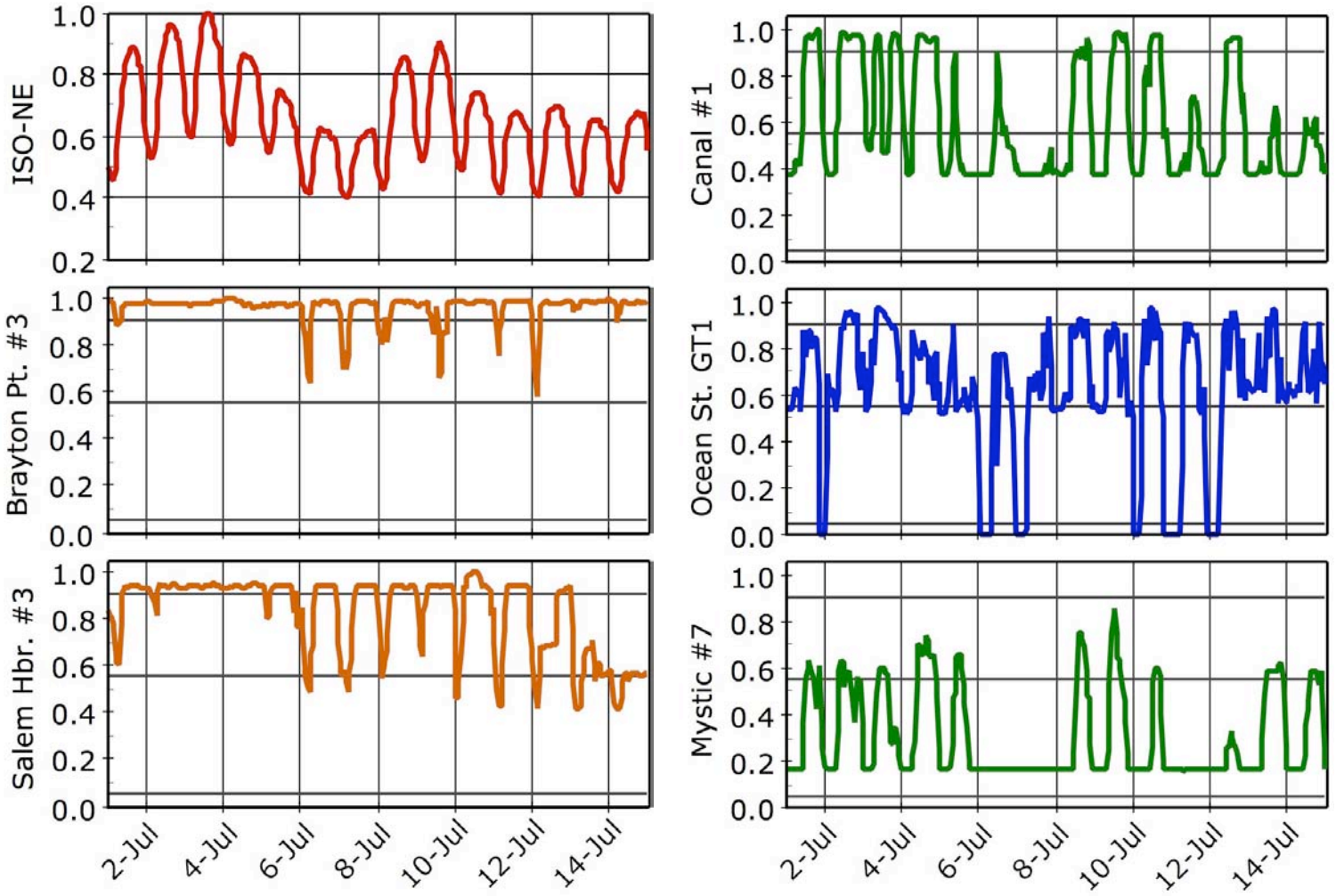
How Do They Really Run?

- Fourteen Days in January 2002



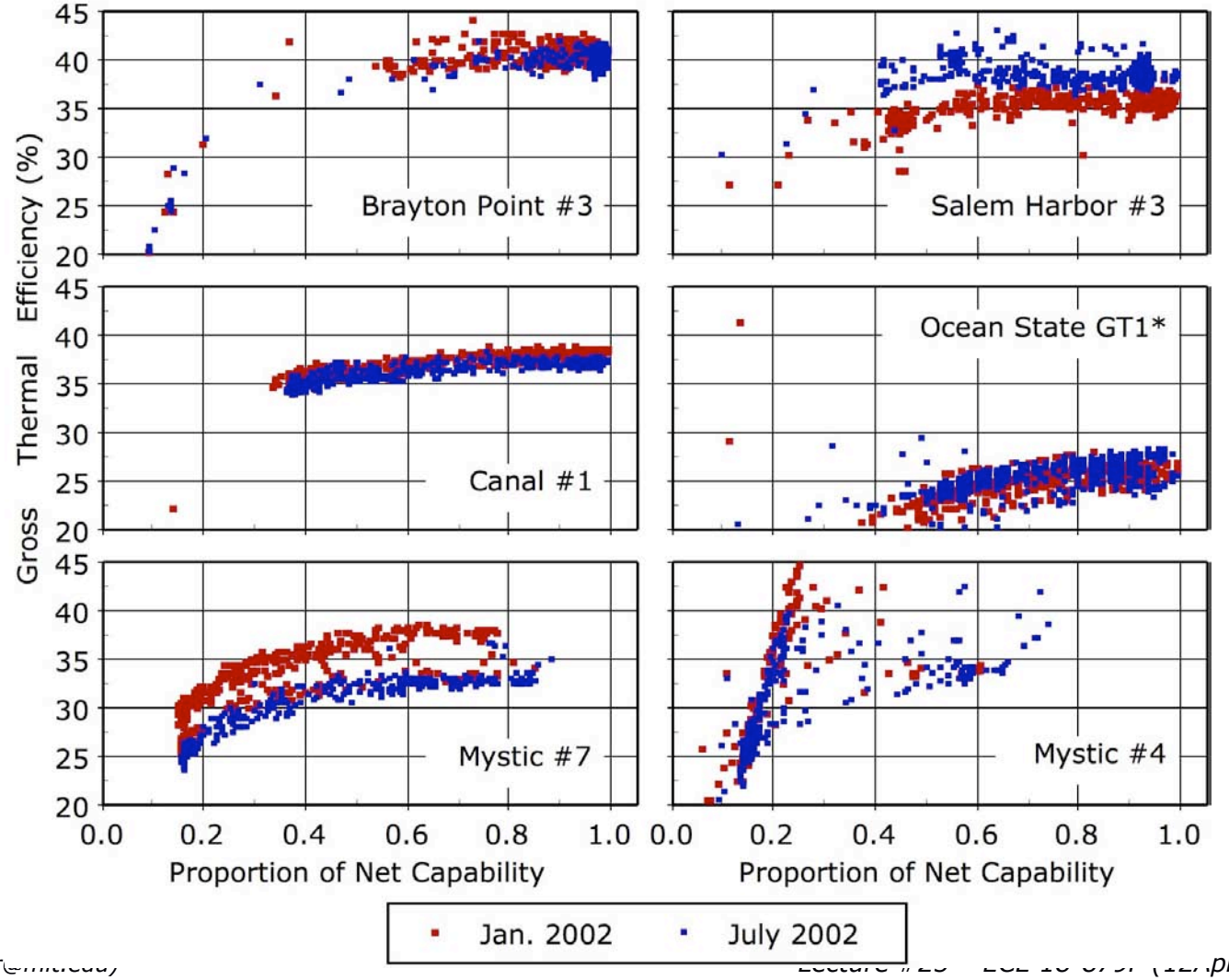
How Do They Really Run?

- Fourteen Days in July 2002



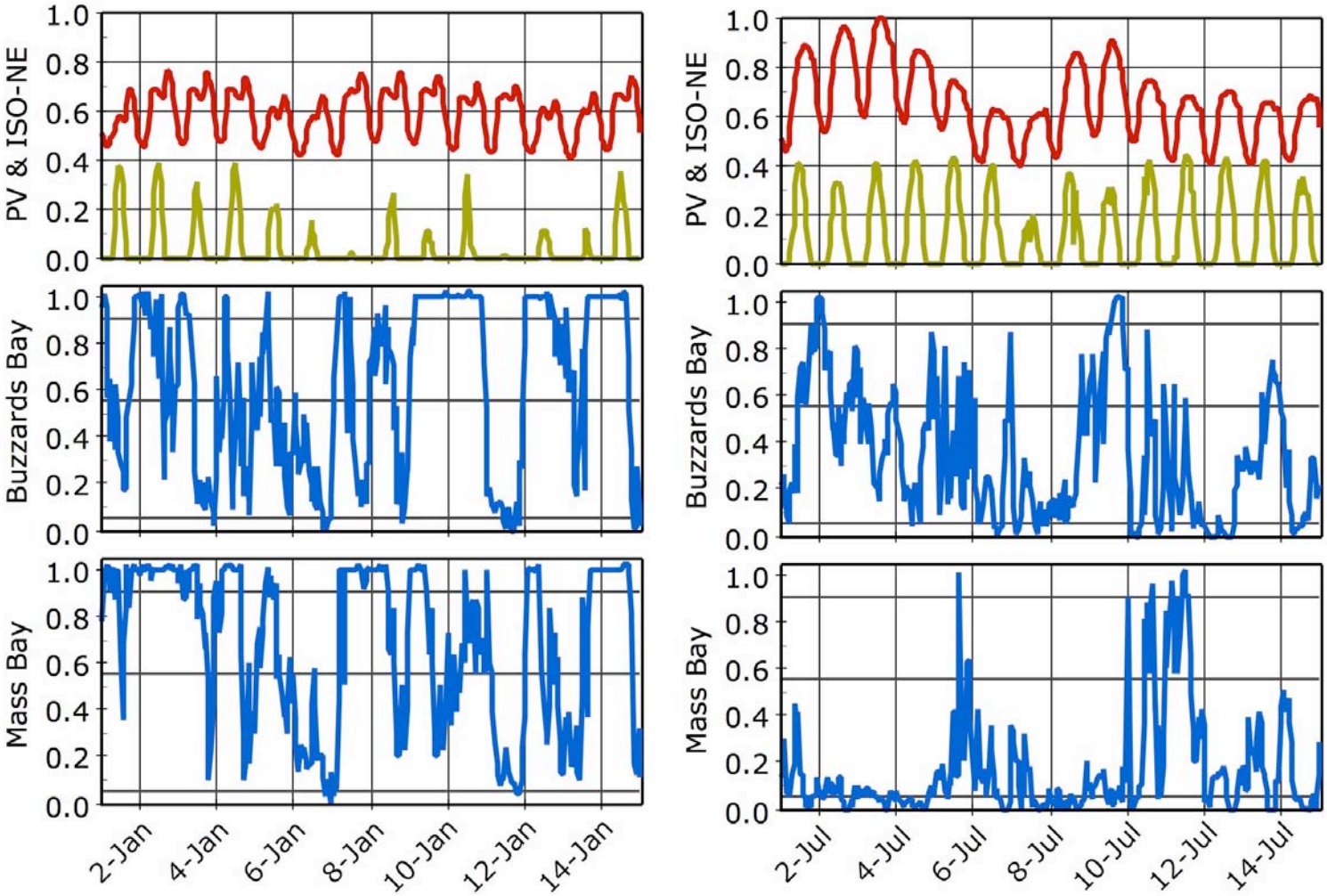
Hidden Efficiency Penalties…

- All Hours in January & July 2002



How Do Renewables Run?

- Fourteen Days in January & July

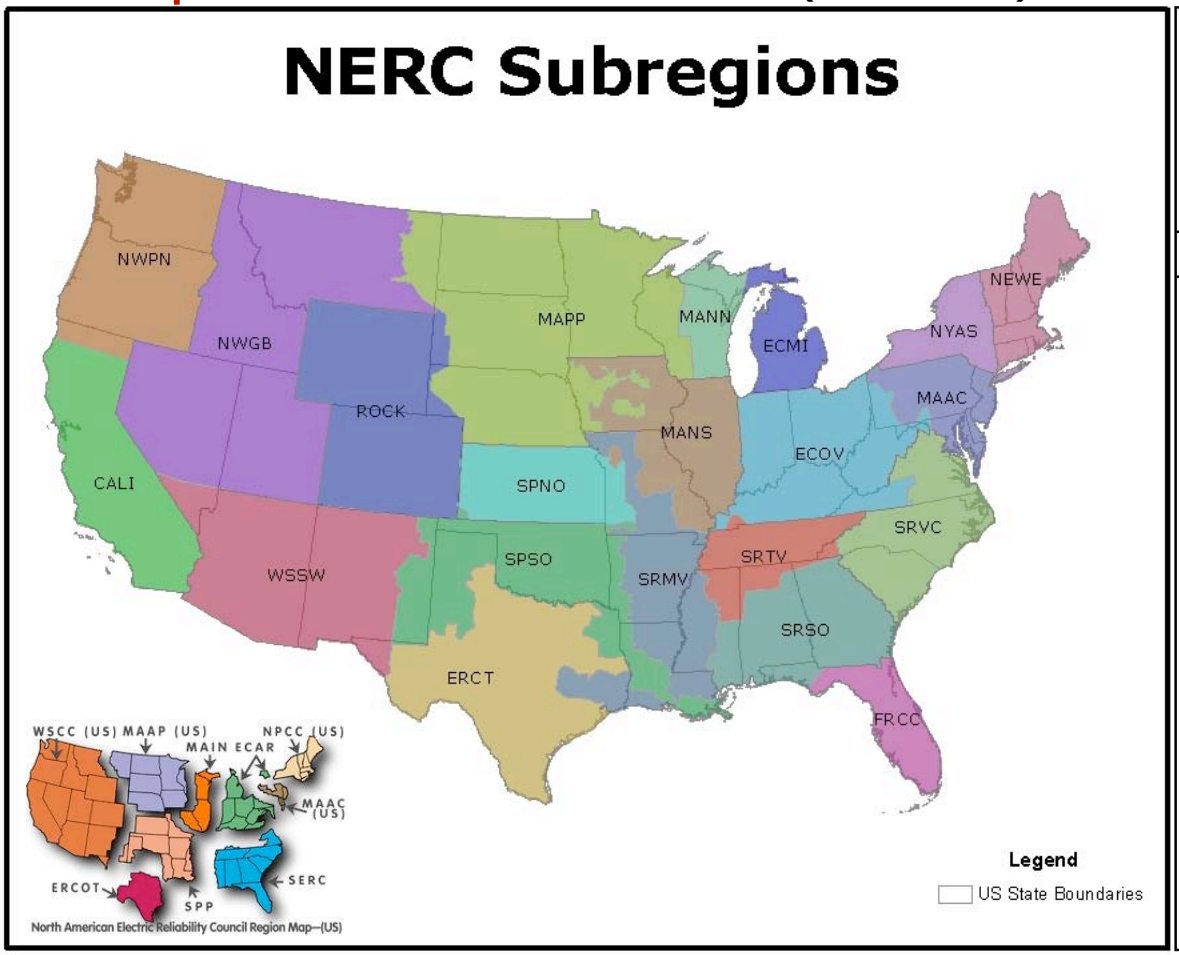


Avoidable Emissions & PV

- How ***much/many emissions*** are avoided from photovoltaic generation?
- We know where it is ***sunny***, but where is it ***dirty***?
- Which kWhs from ***which generation*** units will be displaced?
- PV avoided generation depends on…
  - » Amount of sun (plus temperature, wind, clouds)
  - » What generators are "Load Shape Following?"
  - » How does LSF units change by NERC Sub-Region season to season (load, fuel choice)and year to year (generation mix, competition)?

Look at NERC Subregions

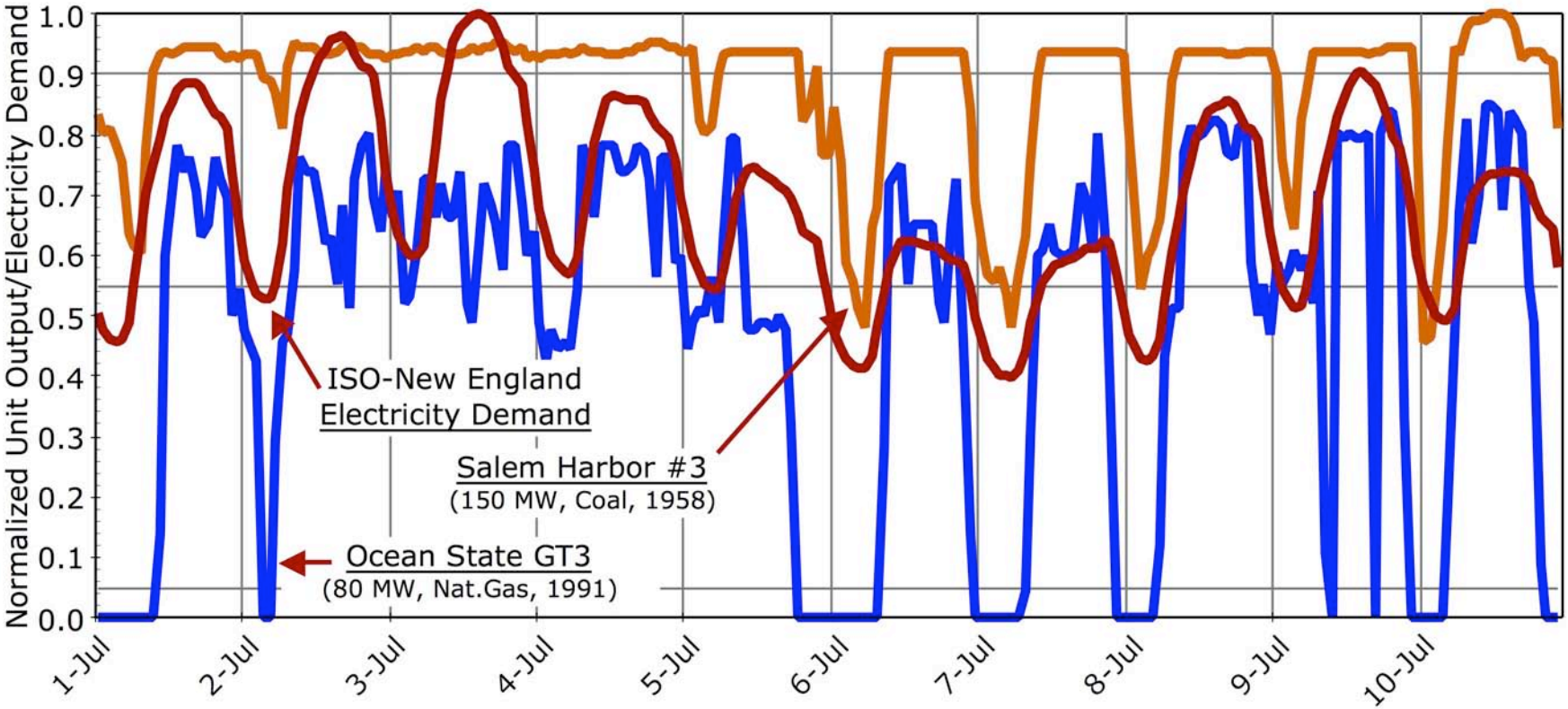
- Better representation of fossil unit dispatch, *including* grid reliability/contingency related "operational modes." (21 vs. 9)



	NSR Code	Region (Descriptive)
(1)	CALI	**California**
(2)	NWPN	**Pacific Northwest**
(3)	NWGB	**Great Basin**
(4)	WSSW	**Southwest**
(5)	ROCK	**Rockies (CO, WY)**
(6)	ERCT	**ERCOT (Texas)**
(7)	MAPP	**Northern Plains**
(8)	SPNO	**Kansas**
(9)	SPSO	**Oklahoma**
(10)	SRMV	**Mississippi Valley**
(11)	SRTV	**Tennessee Valley**
(12)	SRVC	**Virginia-Carolinas**
(13)	SRSO	**Southeast**
(14)	FRCC	**Florida**
(15)	MANN	**Wisconsin**
(16)	MANS	**Illinois**
(17)	ECMI	**Michigan**
(18)	ECOV	**Ohio Valley**
(19)	MACC	**Mid Atlantic (PJM)**
(20)	NYAS	**New York**
(21)	NEWE	**New England**

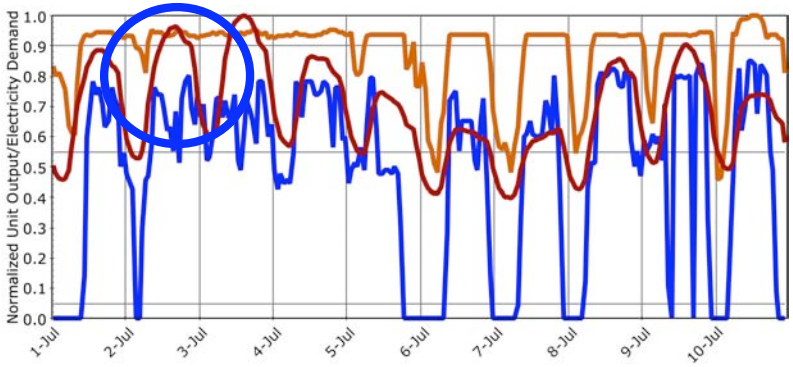
Load Shape Following Logic

- *Identifying LSF Units for Avoided Emissions Calculations*



Example: Peak Demand

- *Representative Northeast Generators*

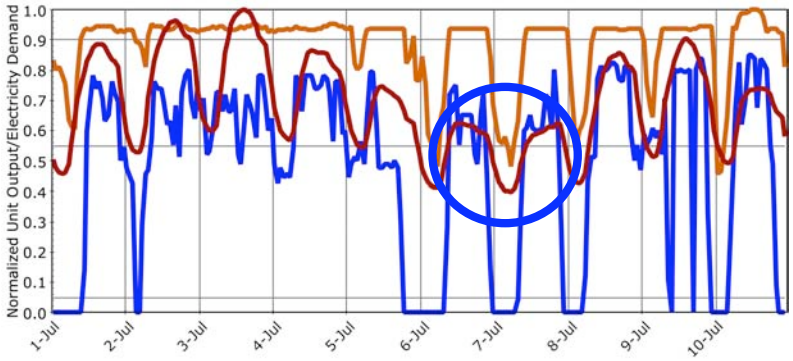


Peak Load Case

LSF Unit	Fuel	Size	Operating Mode	Hourly Output	SO2 Emissions	Δ MW Prev.Hr.	Δ SO2 Emissions
1	Gas	75	**Spinning**	50	0.5	40	0
2	Gas	75	**Spinning**	50	0.5	20	0
3	Oil	350	**Spinning**	250	350	100	140
4	Coal	500	Full Load	475	900	25	47
5	Coal	550	Full Load	525	1400	25	67
		(MW)	**Total:**	1350	2651	210	255
				(MWh)	(kg)	(MWh)	(kg)
			LSF Unweigted Rate:		1.96	**Wgt.Rate:**	**1.21**
					(kg/MWh)		(kg/MWh)

Example: Overnight/Off-Peak

- *Representative Northeast Generators*



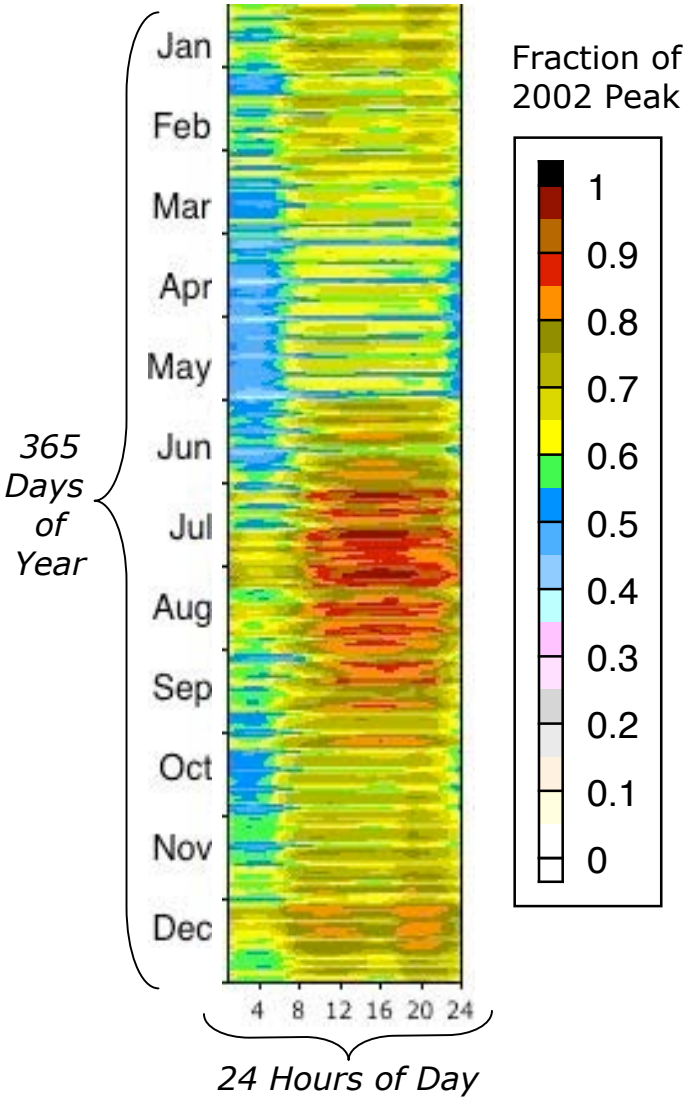
Overnight Case

LSF Unit	Fuel	Size	Operating Mode	Hourly Output	SO2 Emissions	Δ MW Prev.Hr.	Δ SO2 Emissions
1	Gas	75	Off				
2	Gas	75	Off				
3	Oil	350	**Standby**	150	450	25	75
4	Coal	500	**Spinning**	425	1100	25	65
5	Coal	550	**Spinning**	400	1600	75	300
		(MW)	**Total:**	975	3150	125	440
				(MWh)	(kg)	(MWh)	(kg)
			LSF Unweigted Rate:		3.23	**Wgt.Rate:**	**3.52**
					(kg/MWh)		(kg/MWh)

The Role of Resources

- How good is the renewable resource?
- Where (in space and time) is the renewable resource?
- How well does it match your energy service needs (seasonally, daily)?
- What is the "competitive market value" of the energy service?
- An issue of timing…

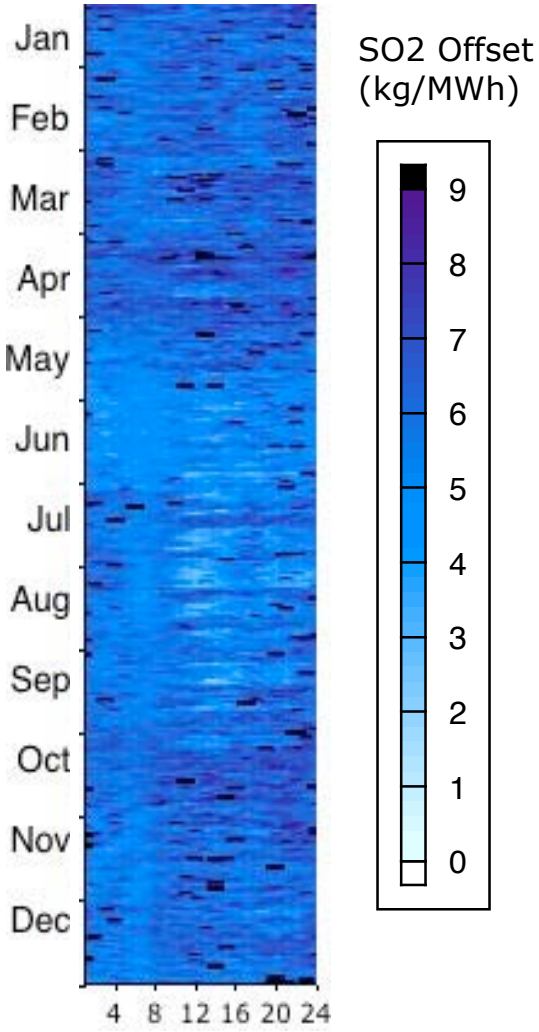
A Year "At a Glance"



Total Load Profiles are normalized to peak subregion demand in 2002

eGrid Fossil Generation Profiles are normalized to peak subregion eGrid generation in 2002.

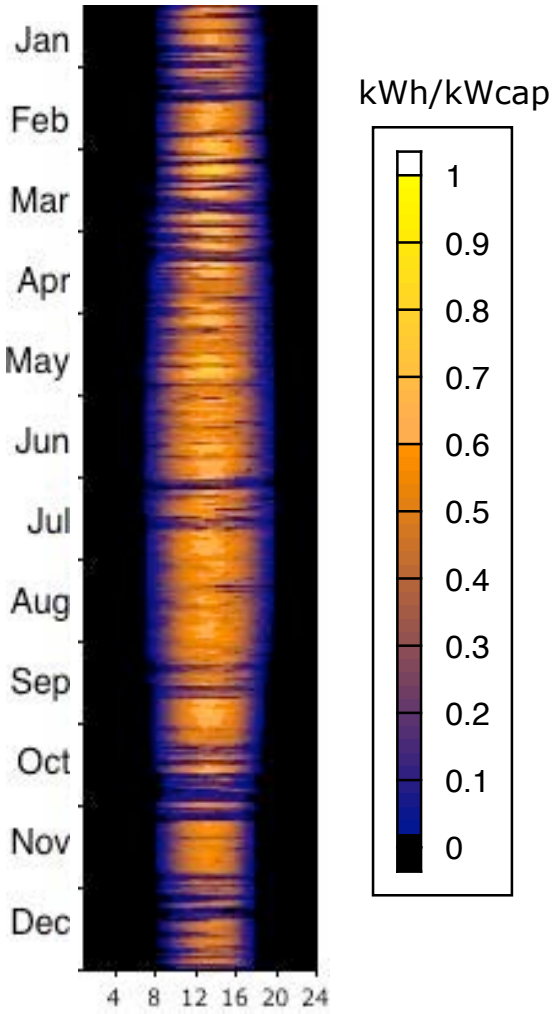
LSF Avoided Emissions Rates



Load Shape Following Emission Rate Profiles represent emissions from 1MWh of load shape following generation in each hour. These are the emissions offset by 1MWh of non-emitting generation applied in each hour of the year.

Units are kg/MWh in each hour.

Generation from Photovoltaics

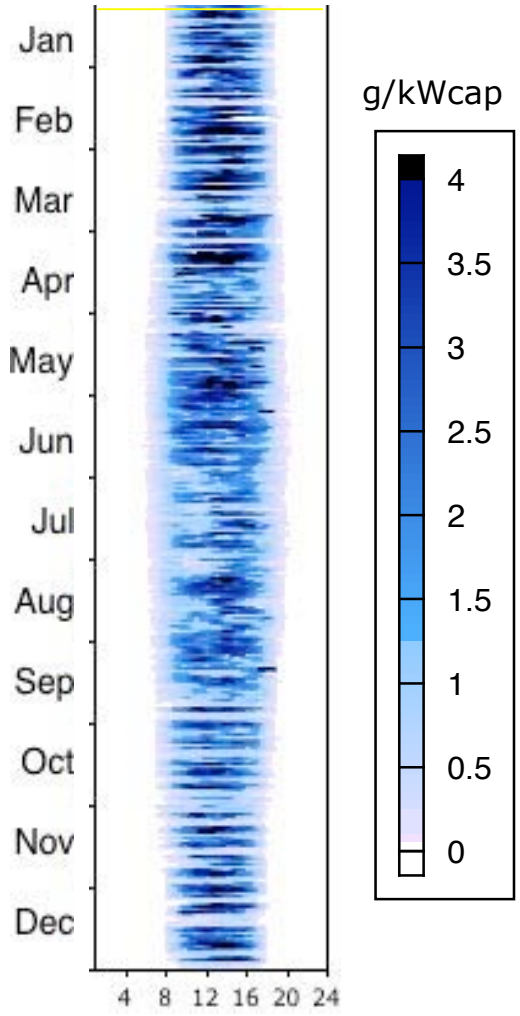


PV Generation Profiles

Show hourly PV generation as a fraction of monitored capacity.

Units are kWh/kWcap in each hour.

Avoided Emissions from PVs



Emissions Offset from PV:
Offsets are the product of hourly PV generation as a fraction of monitored capacity and the hourly load shape following emission rates in the subregion.

Units are g/kWcap in each hour.

Not All kWhs Created Equally

- eGrid kWhs – "Gross" Generation
  - › Less Auxiliary Power Consumption ≈ 2%->12%
- NERC SR Loads – "Busbar" Generation
  - › Less T&D Losses ≈ 10%
- PV kWhs – "Meter" Load

- Auxiliary and T&D Losses Unknown
- So…
  - » Systematically Conservative Avoided Emissions Calculations for ***Monitored*** *PV Sites*
  - » Roughly Right for ***Simulated*** *PV Sites*

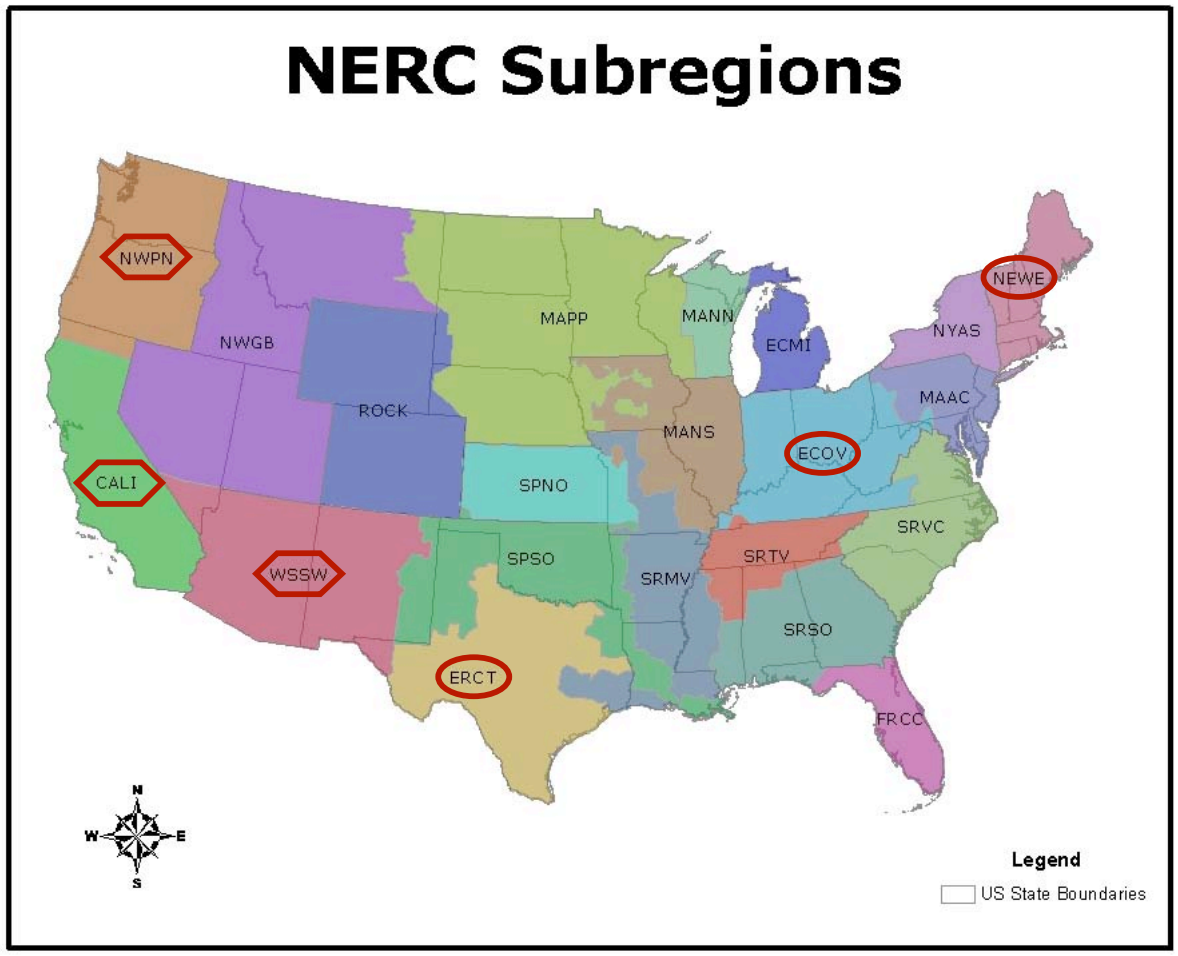
Some Select Subregions

The East

New England (NEWE)
Ohio Valley (ECOV)
Texas (ERCT)

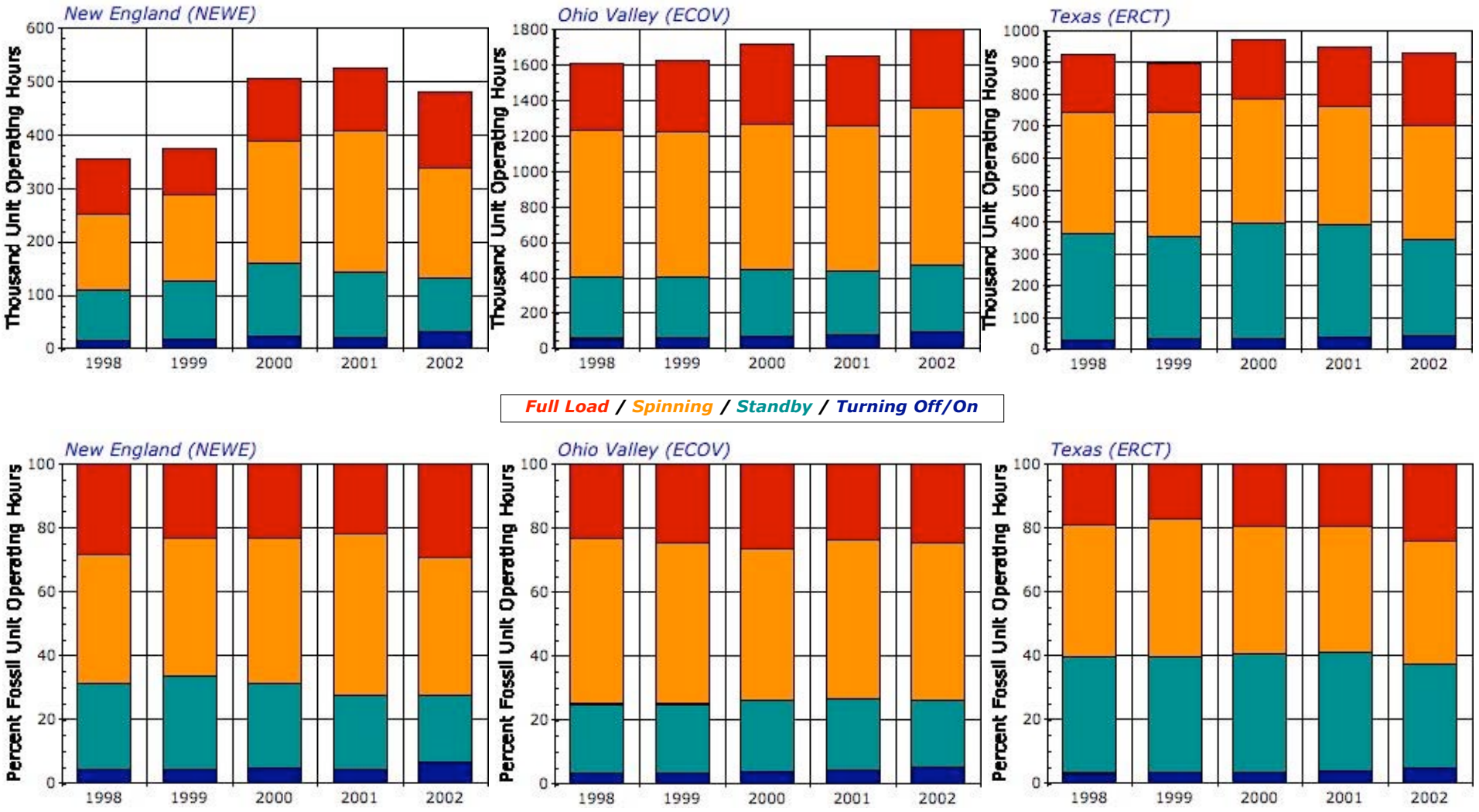
The West

Pacific Northwest (NWPN)
Southwest (WSSW)
California (CALI)



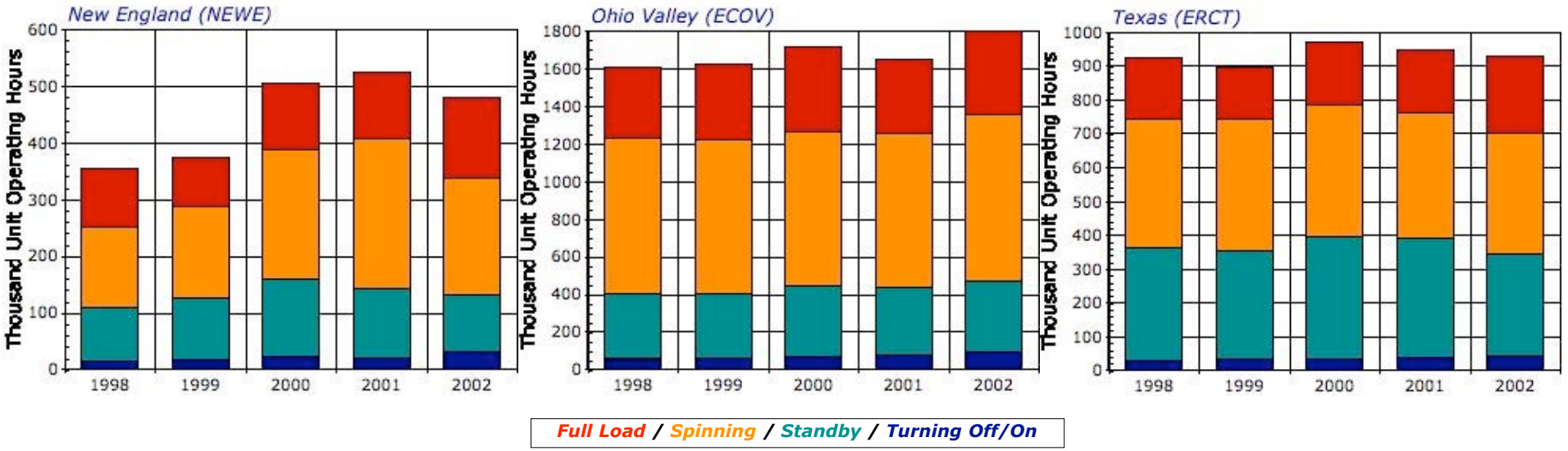
The East: Operating Hours

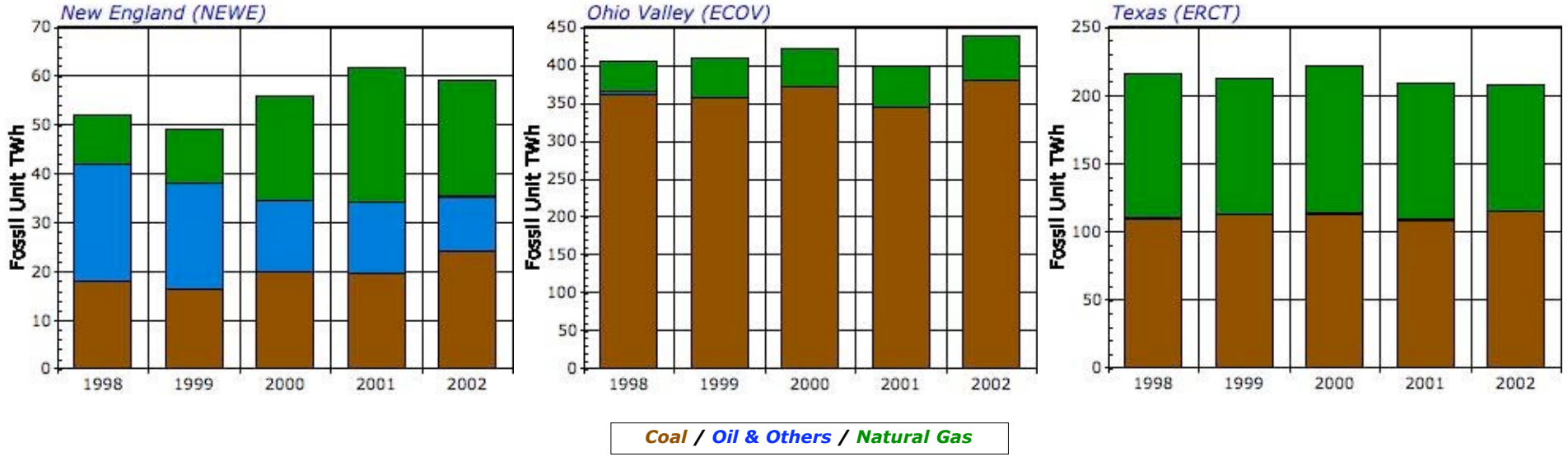
(eGrid Only)



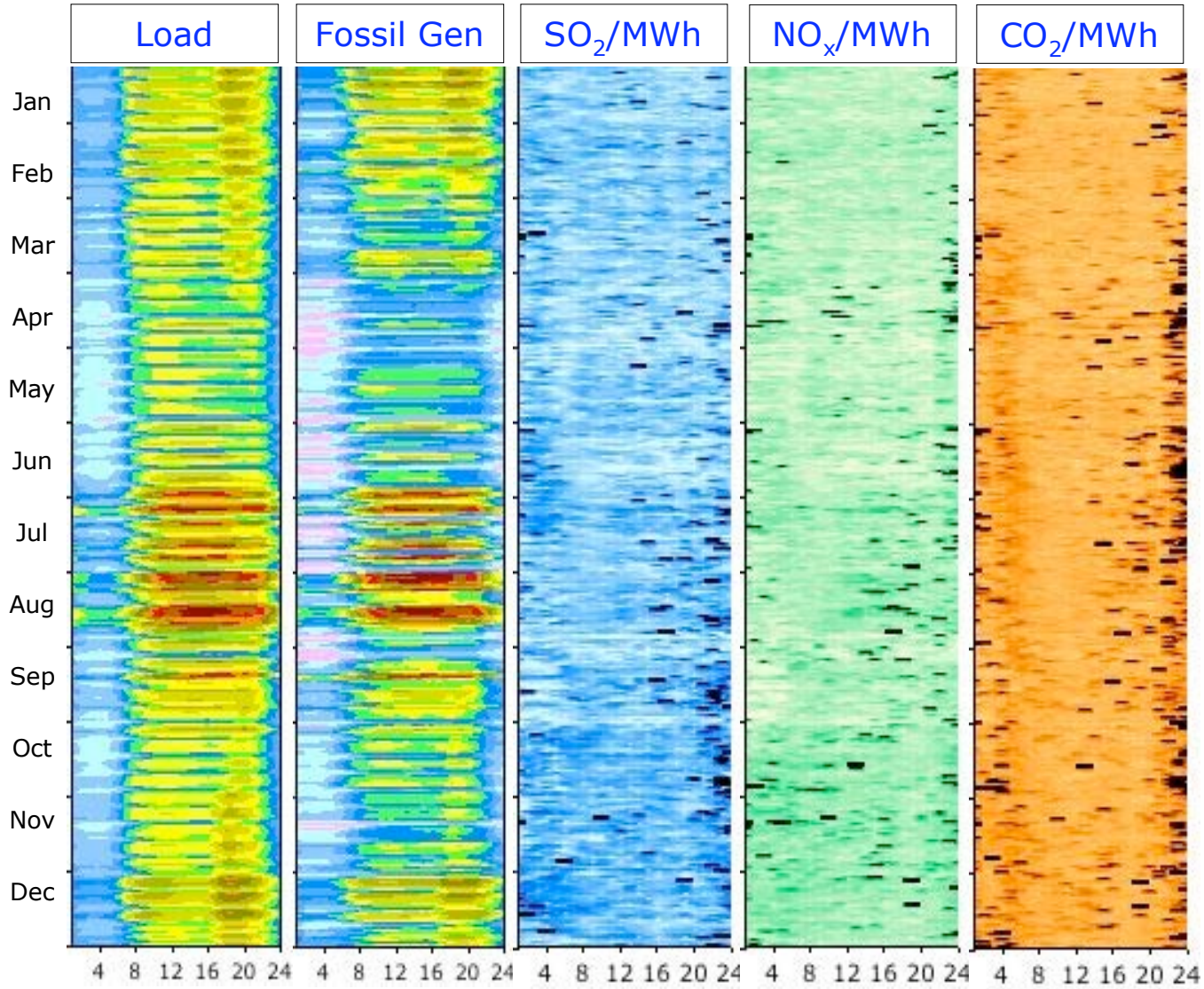
The East: Hours and Energy

(eGrid Only)





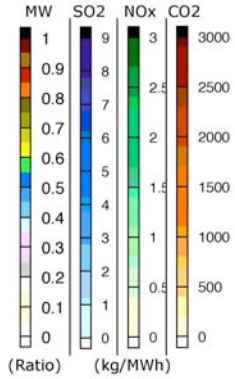
New England–by the hour



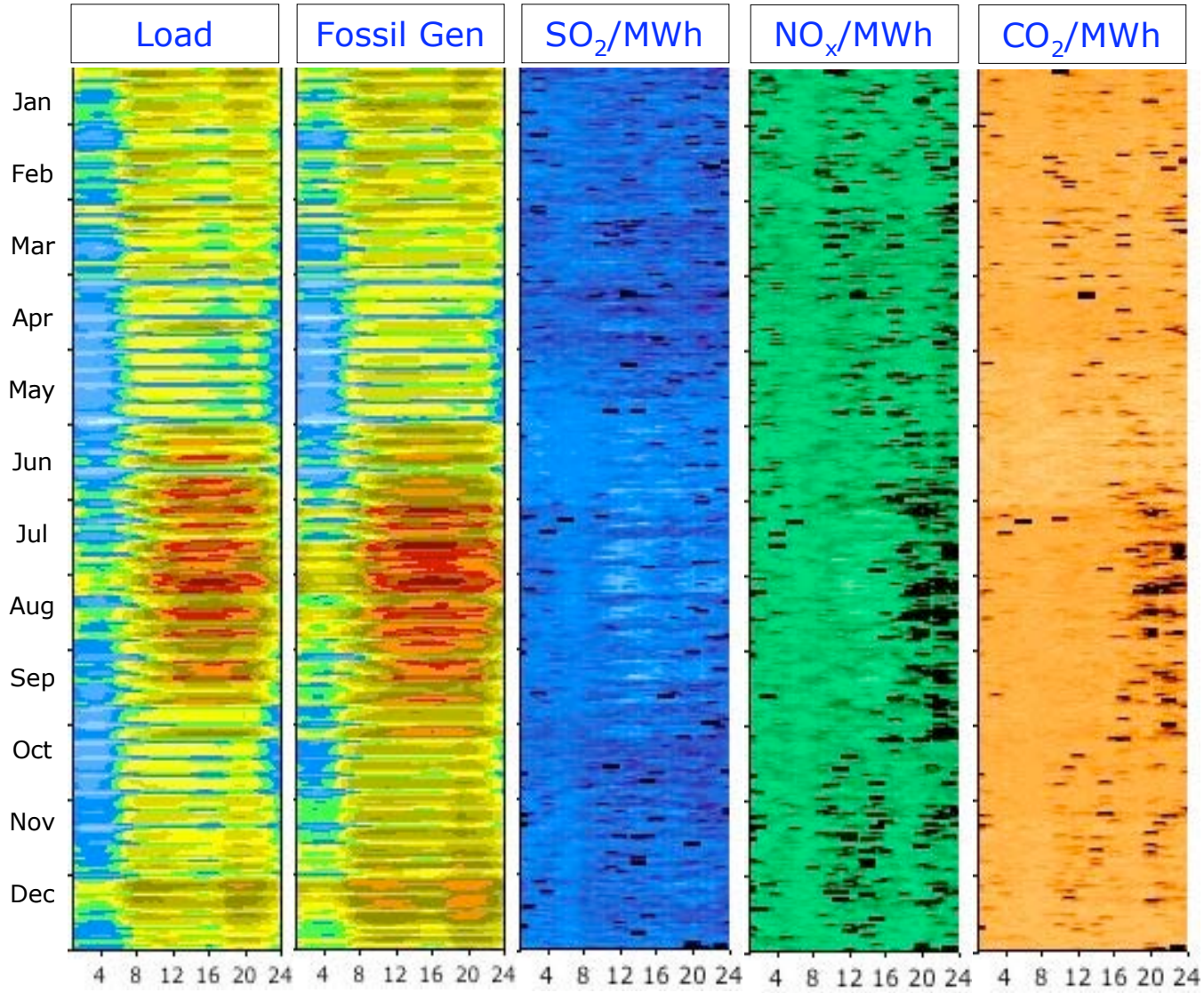
New England
(NEWE-2002)

- 365 days x 24 Hours
- Total Load/Elec. Demand
- Fossil Generation
  (Normalized to 2002 Peak Load)

+ Fossil emissions rates (kg/MWh) are for weighted "Load Shape Following" generating for that hour.



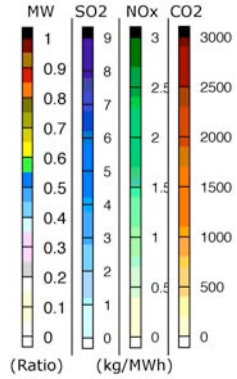
Ohio Valley–by the hour



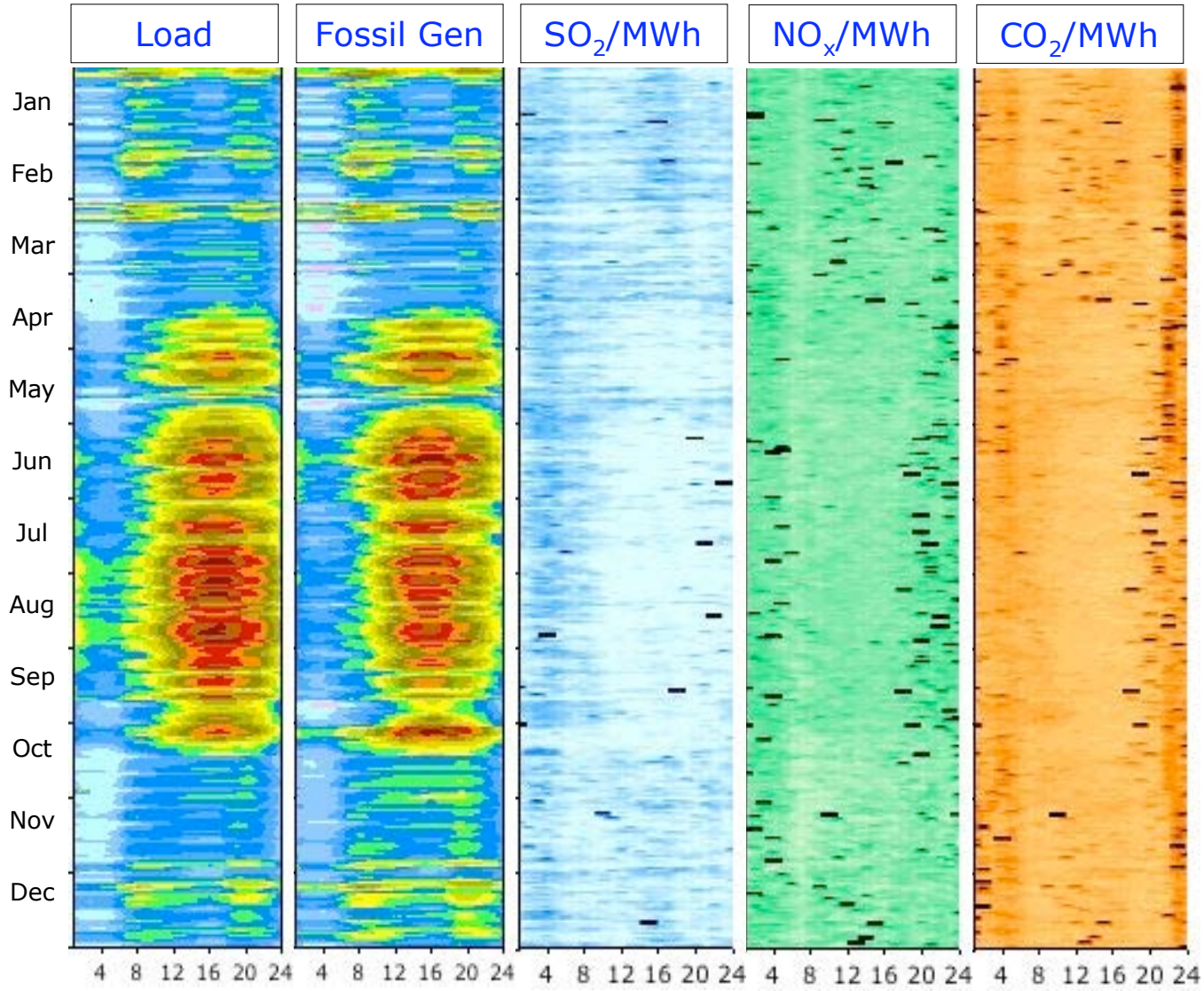
Ohio Valley
(ECOV-2002)

- 365 days x 24 Hours
- Total Load/Elec. Demand
- Fossil Generation
  (Normalized to 2002 Peak Load)

+ Fossil emissions rates (kg/MWh) are for weighted "Load Shape Following" generating for that hour.



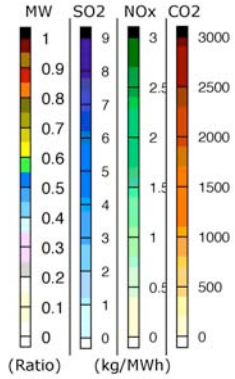
Texas–by the hour



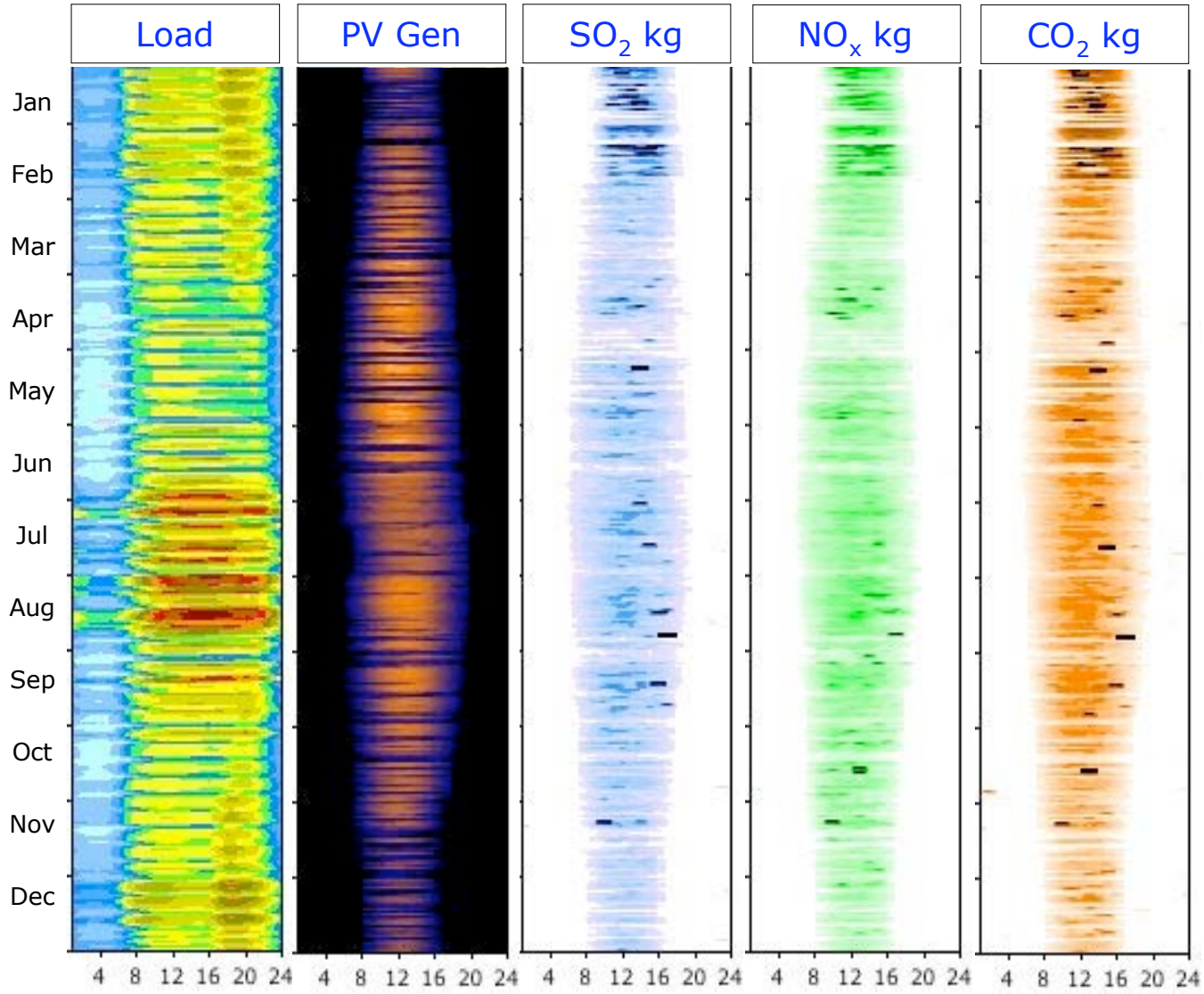
Texas
(ERCT-2002)

- 365 days x 24 Hours
- Total Load/Elec. Demand
- Fossil Generation
  (Normalized to 2002 Peak Load)

+ Fossil emissions rates (kg/MWh) are for weighted "Load Shape Following" generating for that hour.



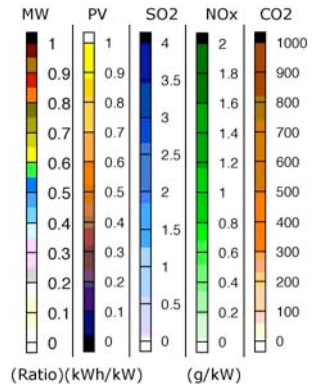
New England–PV by the hour



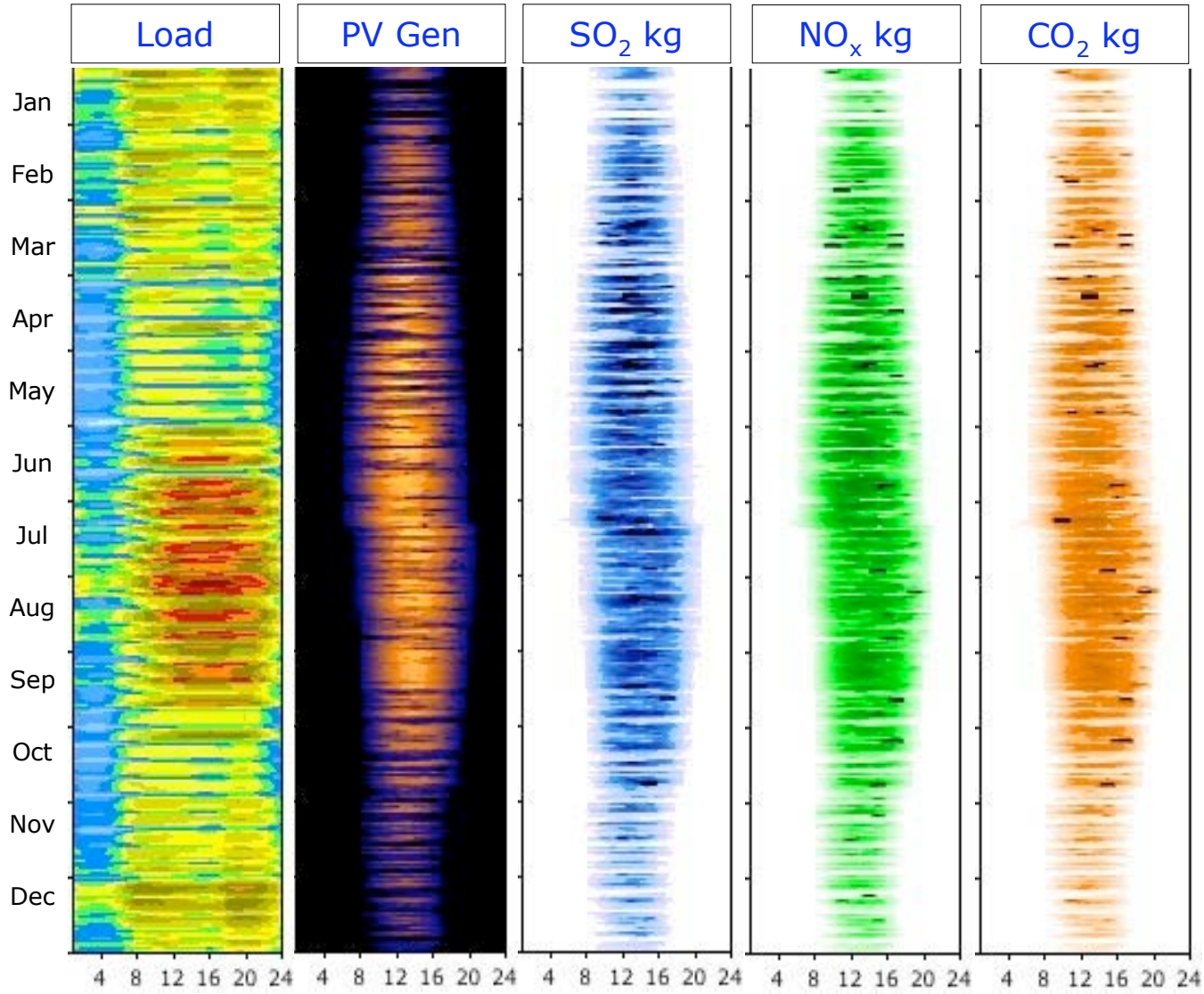
New England
(NEWE-2002)

- 365 days x 24 Hours
- Total Load/Elec. Demand
- PV Generation
  (**Monitored** Systems, normalized to 1 kW of installed PV capacity)

+ Avoided LSF fossil emissions from PV generation (kg per hour)



Ohio Valley–PV by the hour



Ohio Valley
(ECOV-2002)

- 365 days x 24 Hours
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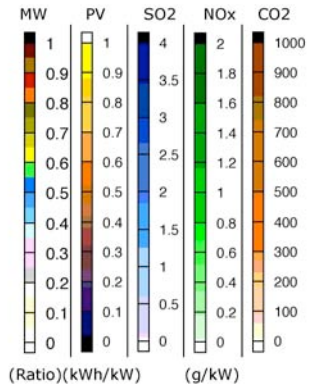
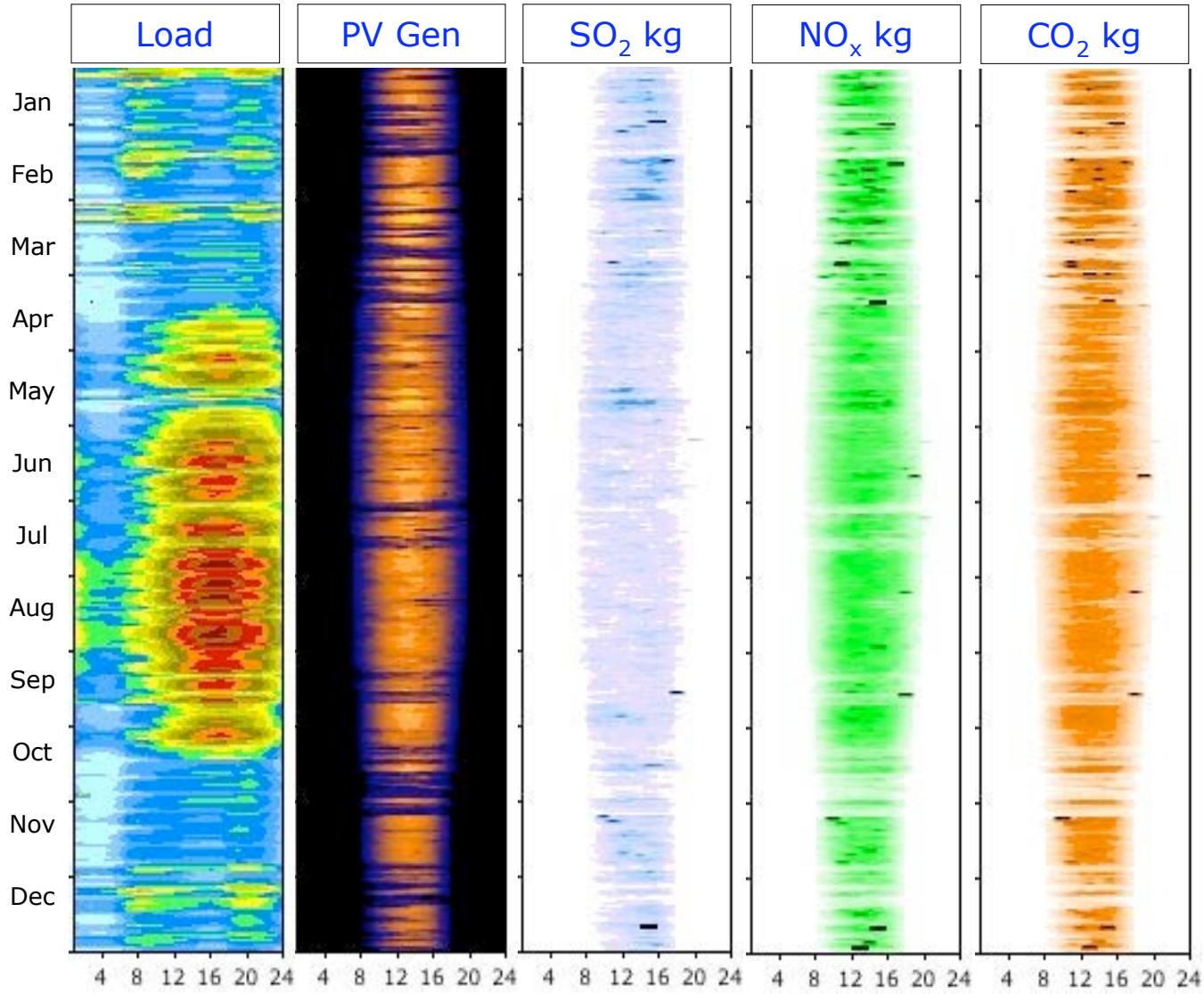
+ Avoided LSF fossil emissions from PV generation (kg per hour)



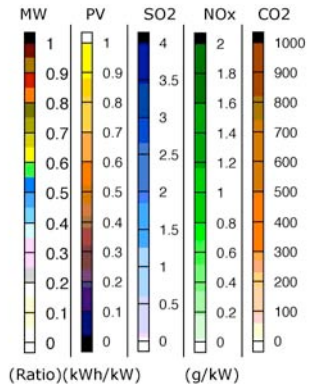
Texas–PV by the hour



Texas
(ERCT-2002)

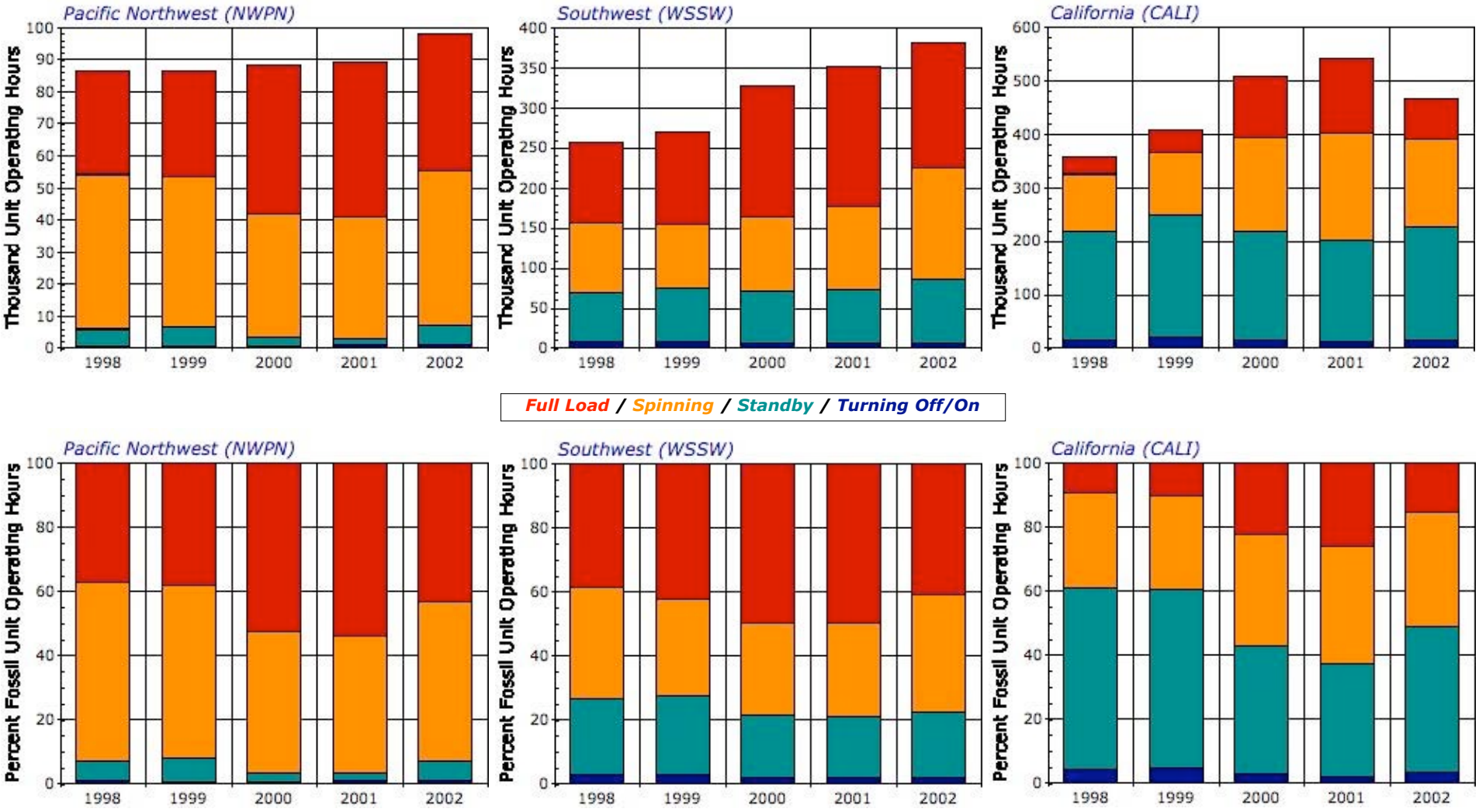
- 365 days x 24 Hours
- Total Load/Elec. Demand
- PV Generation
  (**Monitored** Systems, normalized to 1 kW of installed PV capacity)

+ Avoided LSF fossil emissions from PV generation (kg per hour)



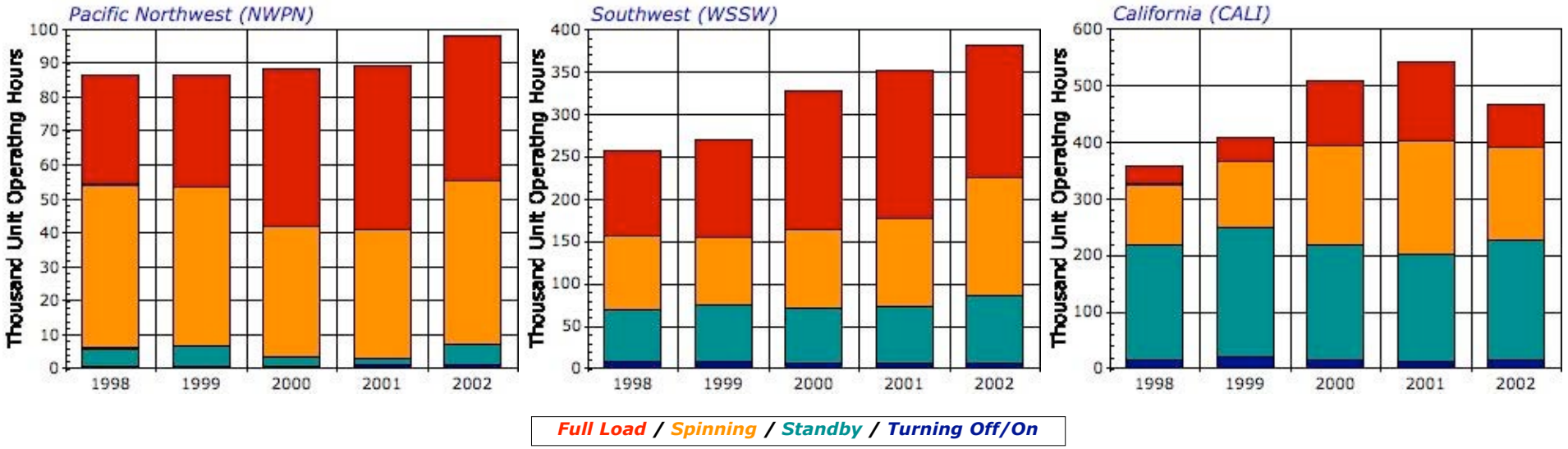
The West: Hours and Energy

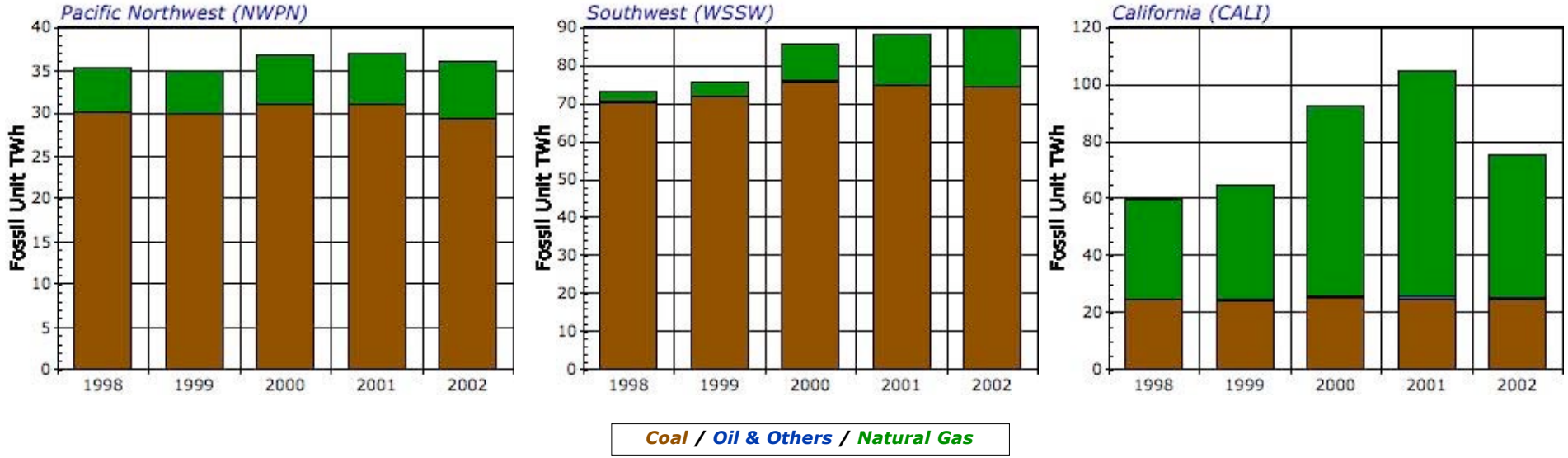
(eGrid Only)



The West: Hours and Energy

(eGrid Only)

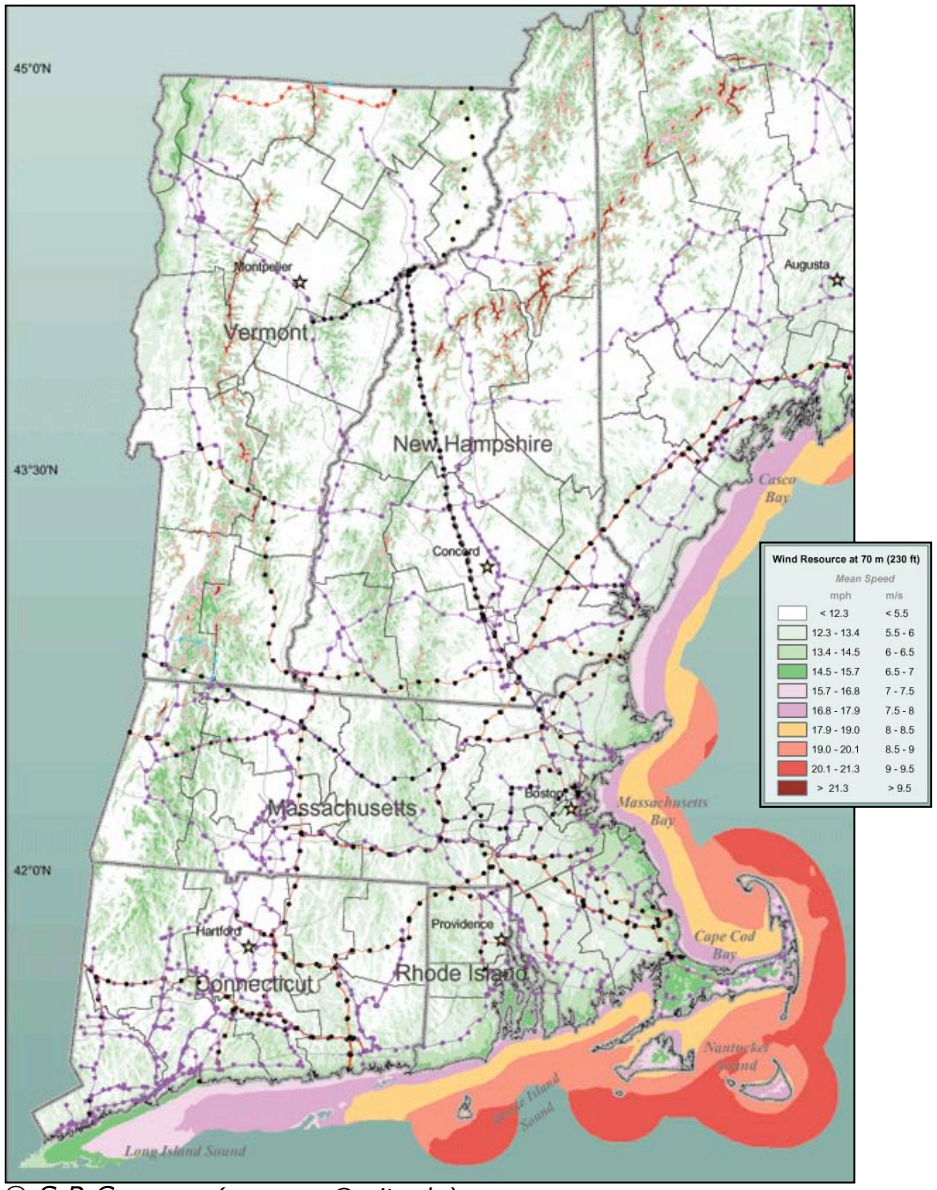




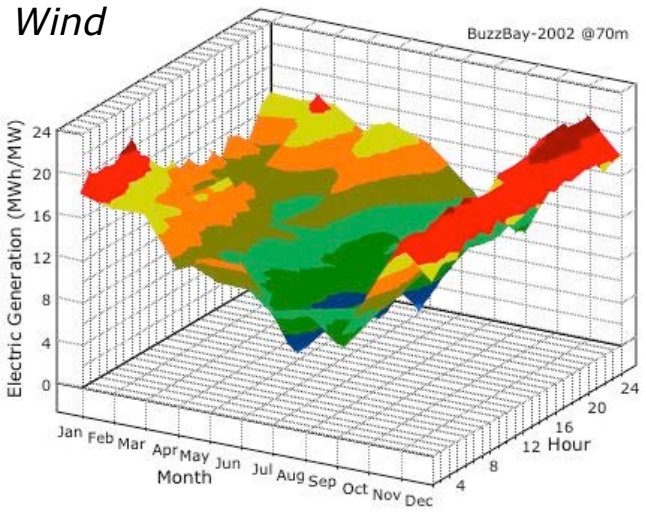
Implications/Opportunities

- What about other Renewables?
  - Windpower (Onshore/Offshore)
  - Hydropower (Integrated/Deferred)
  - Sustainable Biomass
- What about Energy Conservation?
  - Can We "Target" DSM for Emissions Reductions?
  - Should Certain Appliances Be Pushed? (Heat Pumps over Air Conditioners?)
- What Role Distributed Generation?
- What Role T&D & Energy Storage?

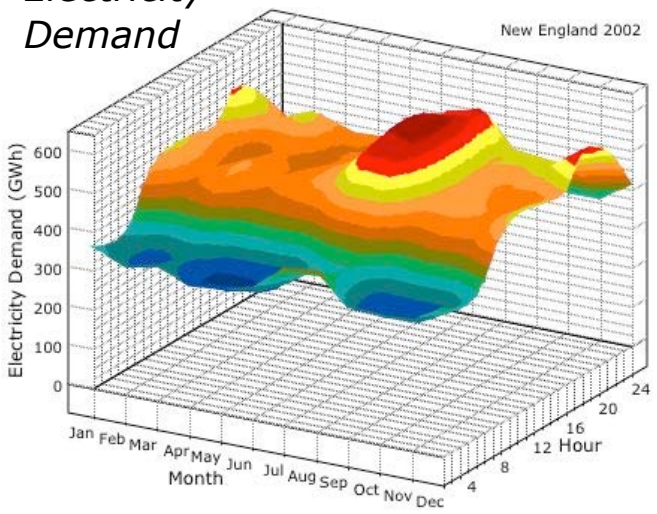
Dynamics in Space and Time



Generation from Wind

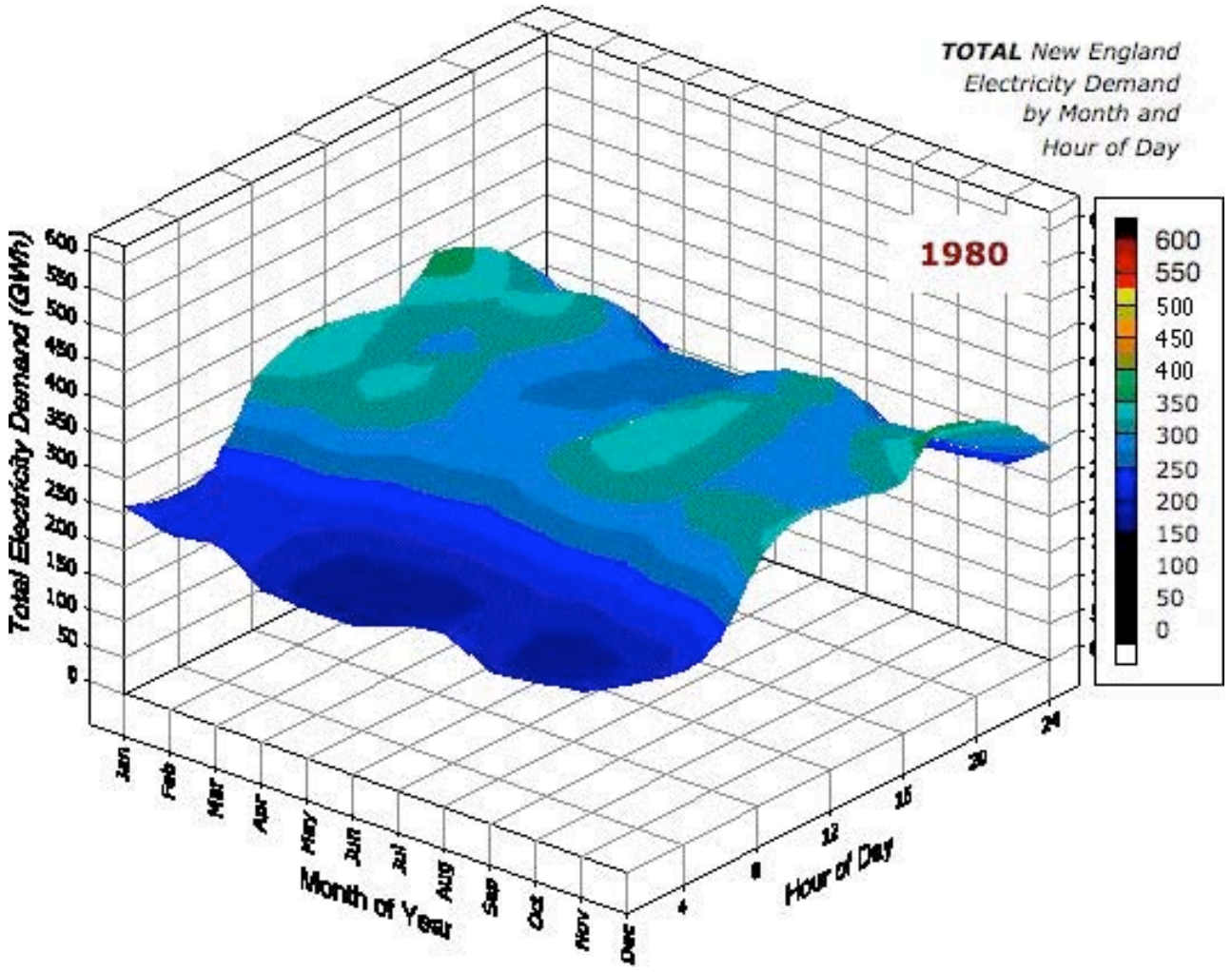


Electricity Demand



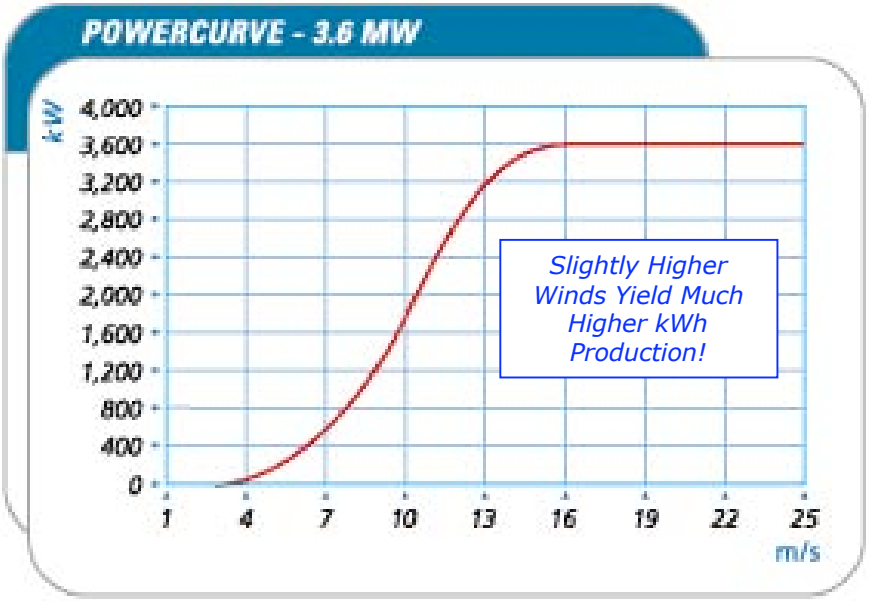
Source: Mass Renewable Energy Trust
TrueWind Solutions

New England Demand

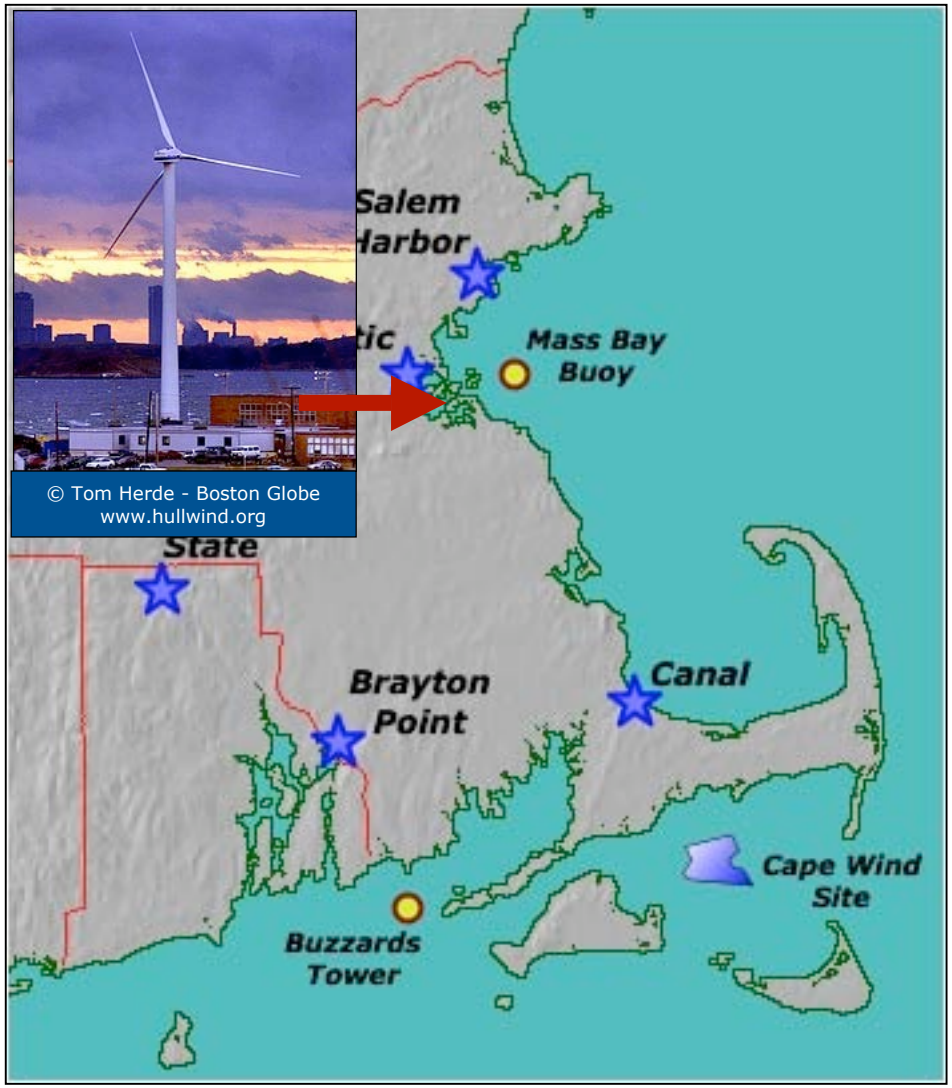


Where & When Is It Windy?

- Look "Near Shore"
  (Data from two NOAA Buoys)
- Near Hull Wind Turbine
- "Near" Cape Wind Site
- How Much?
- How Predictable?



(Source: GE Wind)

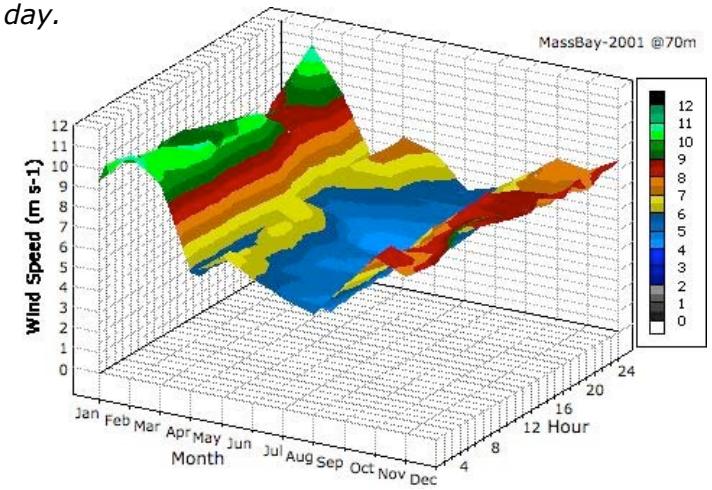


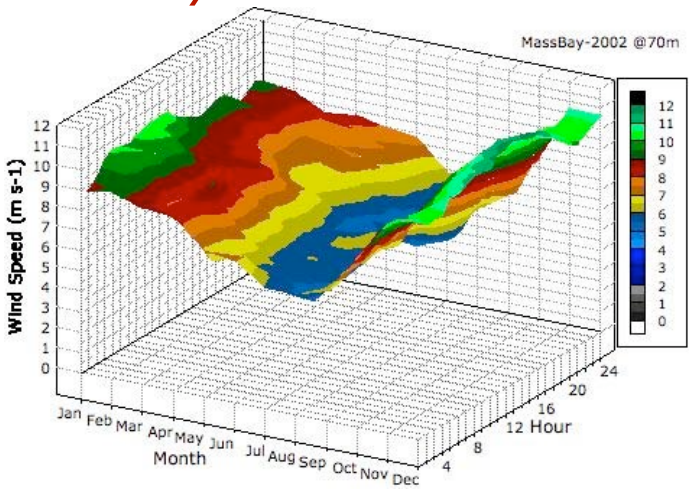
Windspeed by Hour & Month

Average windspeed by month and hour of day.

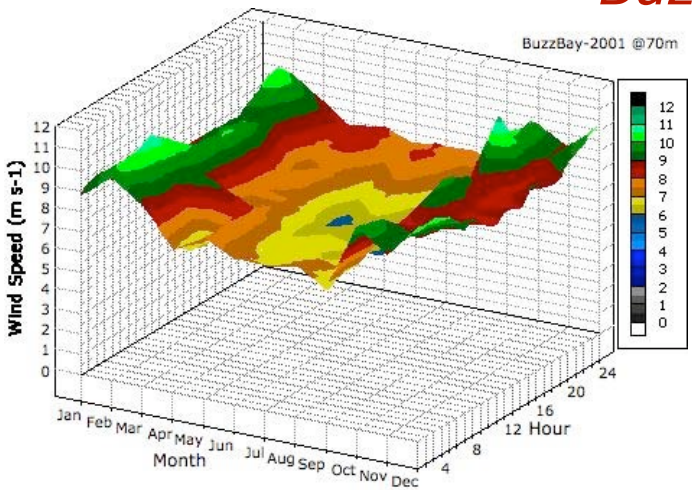
Source Data: NOAA
(Windspeeds Scaled to 70m)

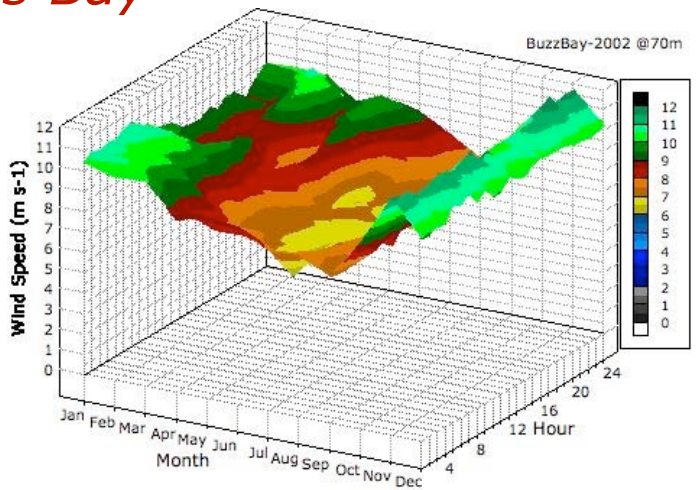
Massachusetts Bay





Buzzards Bay



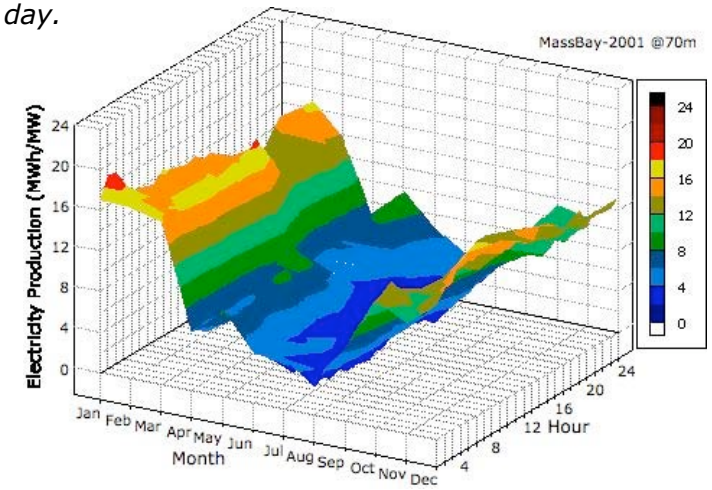


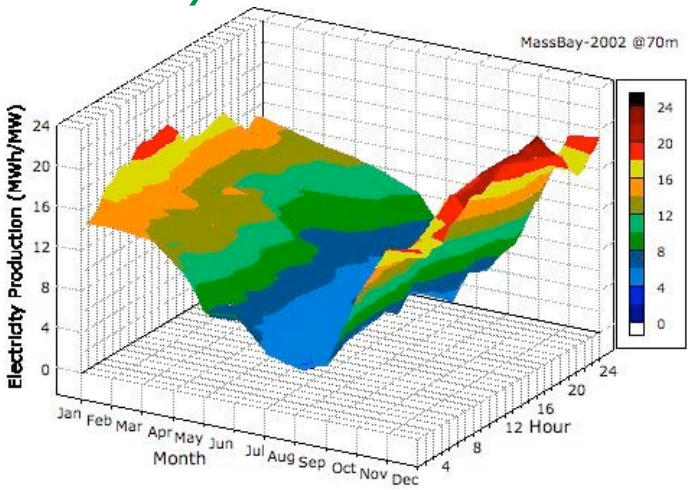
Wind Energy by Hour & Month

Total *Generation by month and hour of day.*

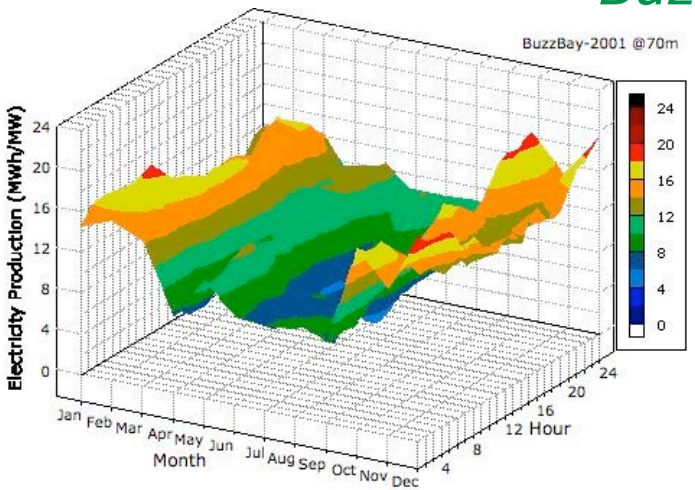
Source Data: NOAA
(Windspeeds Scaled to 70m)

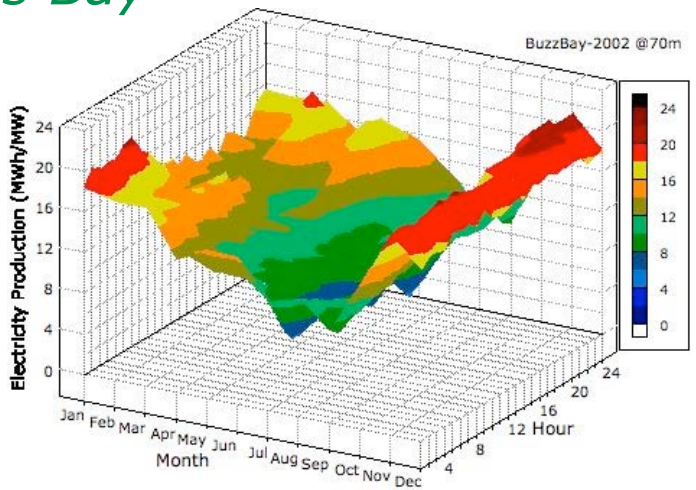
Massachusetts Bay





Buzzards Bay

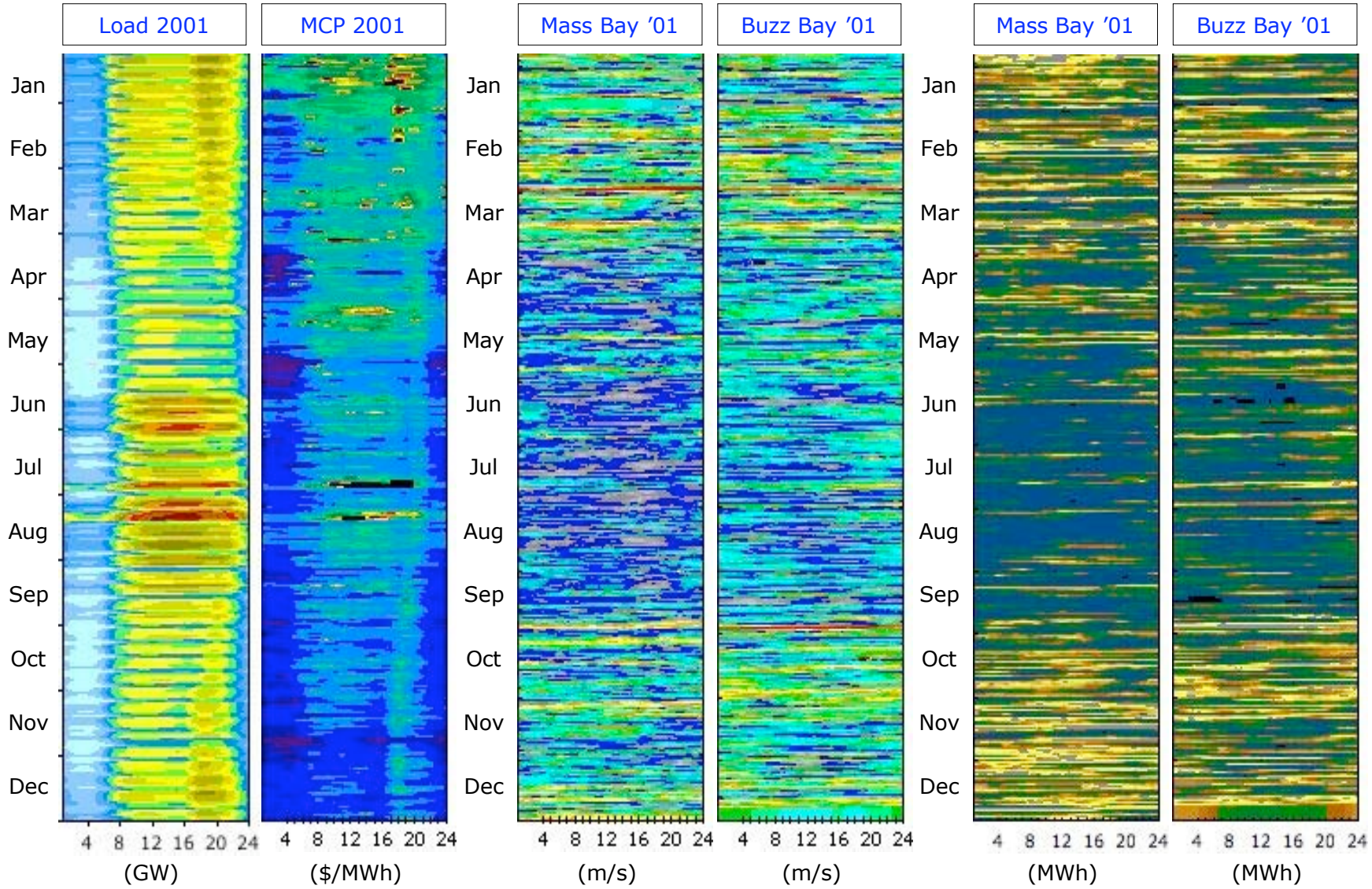




For One MW of Installed Wind Capacity
(@70m using GE Wind 3.6 MW Power Curve)

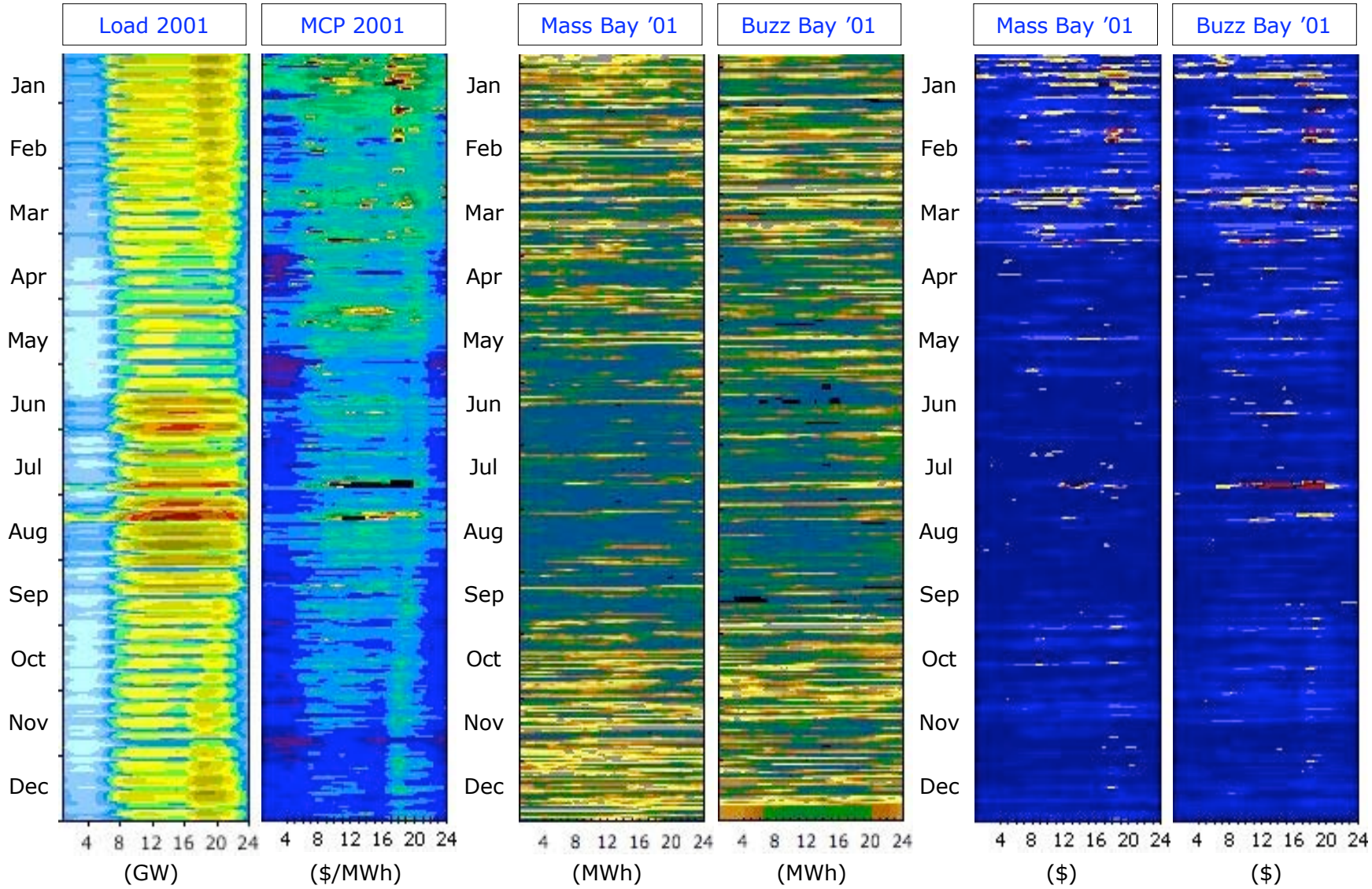
Demand, Price & Revenues '01

Source Data: ISO-NE, NOAA



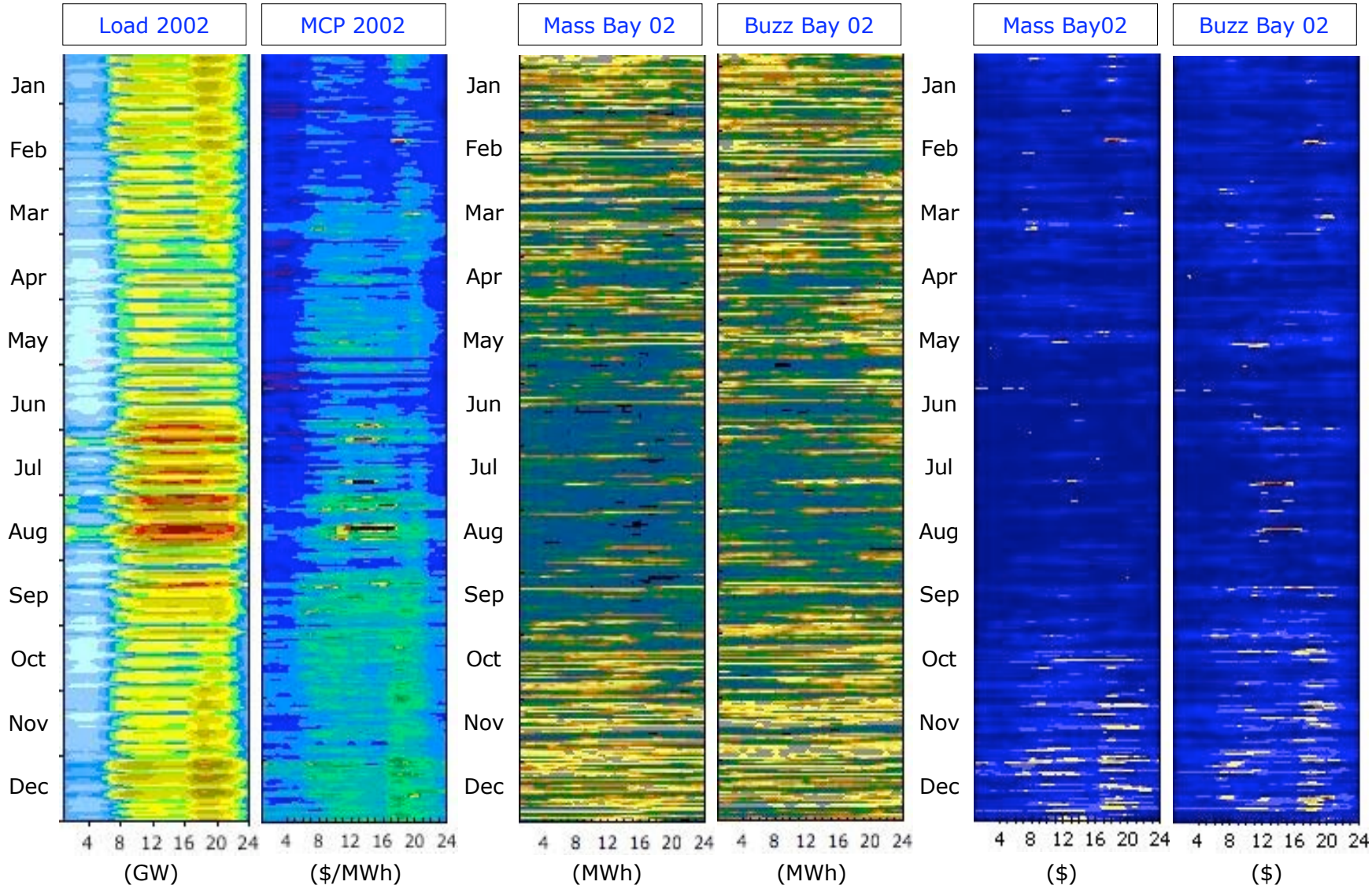
Demand, Price & Revenues '01

Source Data: ISO-NE, NOAA



Demand, Price & Revenues '02

Source Data: ISO-NE, NOAA



Multi-Year Performance

- *Highly Variable in Production, Revenues and Avoided Emissions*

	Mass. Bay 2001	Mass. Bay 2002	Buzzards Bay 2001	Buzzards Bay 2002	Solar PV 2001	Solar PV 2002	
Production & Revenue							
Ave. Windspeed	**7.2**	**7.9** 9.1	**8.2**	**8.9** 8.0			(m/s @ 70m) (Δ% '01 to '02)
Annual Production	**2706**	**3278** 17.5	**3461**	**3973** 12.9	**912**	**851** (7.2)	(MWh / MW) (Δ% '01 to '02)
Capacity Factor	**30.9**	**37.4** 17.5	**39.5**	**45.4** 12.9	**10.4**	**9.7** (7.2)	(%) (Δ% '01 to '02)
Price-Taker Earnings	**107.7**	**115.3** 6.6	**141.0**	**141.7** 0.5	**38.3**	**36.3** (5.6)	(1000 USD / MW) (Δ% '01 to '02)
Ave. Earnings	**3.98**	**3.52** (13.2)	**4.07**	**3.57** (14.2)	**4.20**	**4.26** 1.5	(¢/kWh) (Δ% '01 to '02)
Avoided Emissions – Load Shape Following Methodology							
SO2	**7.0**	**7.2** 1.9	**8.8**	**8.6** (3.4)	**2.2**	**1.7** (26.9)	(tonne) (Δ% '01 to '02)
	2.6	**2.2** (18.9)	**2.6**	**2.2** (18.7)	**2.4**	**2.0** (18.4)	(kg/MWh) (Δ% '01 to '02)
NOx	**2.3**	**2.6** 9.6	**2.9**	**3.0** 4.0	**0.7**	**0.6** (16.4)	(tonne) (Δ% '01 to '02)
	0.9	**0.8** (9.5)	**0.8**	**0.8** (10.2)	**0.8**	**0.8** (8.6)	(kg/MWh) (Δ% '01 to '02)
CO2	**1995**	**2516** 20.7	**2554**	**3045** 16.1	**656**	**630** (4.2)	(tonne) (Δ% '01 to '02)
	737	**768** 4.0	**738**	**767** 3.7	**719**	**740** 2.8	(kg/MWh) (Δ% '01 to '02)

For 1 MW of Installed Renewable Capacity

Variability Matters!

- (Renewable) Resource Variability
  - Wind and Sun (Magnitude and Timing)
  - Rainfall (Hydropower, Biomass)
- Fuel Markets
  - Fuel Prices/Price Differentials (esp. Natural Gas)
  - Infrastructure Investments (Pipelines/Storage/LNG)
- Conventional Generation
  - Nuclear Availability, Hydro Potential
  - Power Market Structure (Capacity Markets, Bid Rules)
  - Power Grid Operations (Reliability/Contingency Practices)
- Energy Demands
  - Demand Growth – Relative to Supply Growth
  - Heating Degree Days/Cooling Degree Days

Dynamic Thinking Required!

- Market Dynamics (including fuels)
- Investment Dynamics
- Operational Dynamics
- Duty Cycle/Driving Cycle Analogies
  - Baseload Nuclear –> Trans-Atlantic Tanker
  - Large Coal –> Freight Train
  - Cycling Coal/Oil –> 18 Wheeler
  - Combustion Turbine –> UPS/FedEx Truck
  - Diesel Genset –> Courier Service (Taxi)

Put That Knowledge to Use…

- On/Off Generation Better than Up/Down Generation?
  - Are a "Bank of Diesels" Better Than One Large Fossil Steam Unit Running Many Hours in Standby?
- Environmental Benefits from Power Grid "Modernization?"
  - Reducing Transmission Bottlenecks May Have (Operational) Environmental Benefits
- Too Much of a "Good" Thing?
  - More "Standby" Operation with Prodigious Renewable? DSM?
- Too Much of a "Bad" Thing?
  - Reducing Standby Generation with Electricity Storage. Good or Bad?

Rethinking Energy Policy

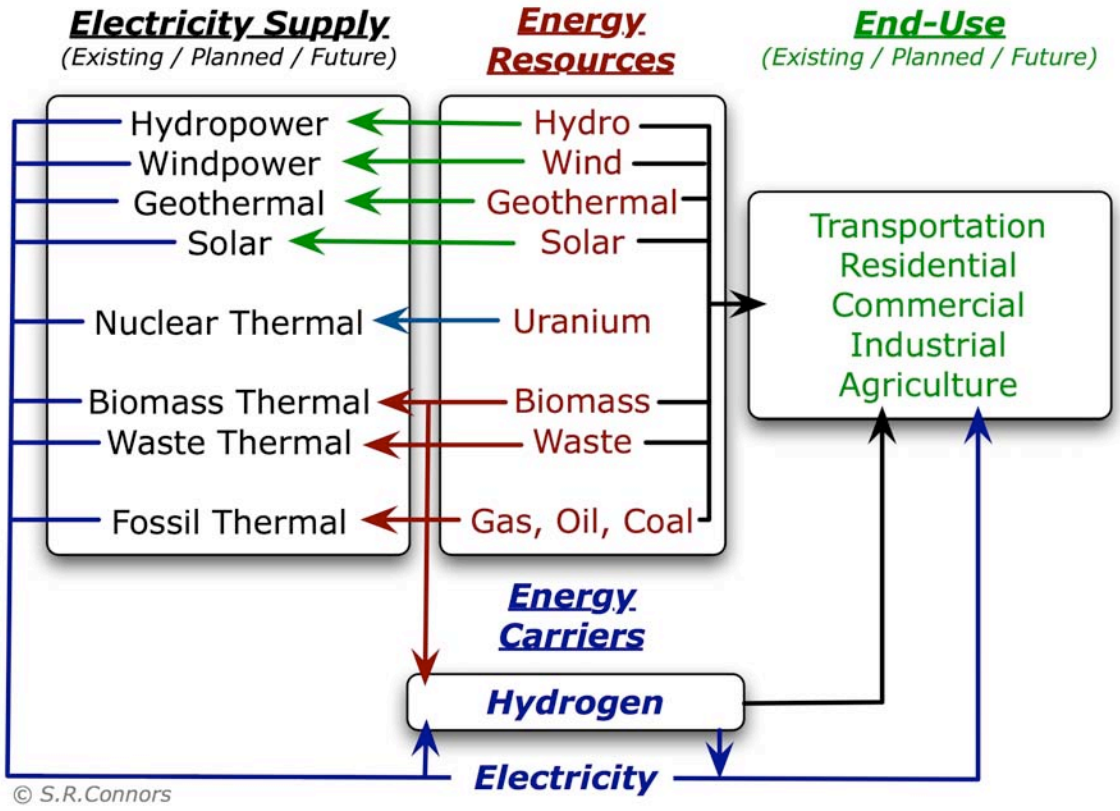
- Regarding Energy "Policies"
  - › Use Policy as an *Adjective*
  - › Policy *Options* to promote/dissuade Specific Technology *Options*
- Infrastructure Management
  - › Technology Development, Deployment, and Use
- What Roles Do Markets Play?
  - › New Products & Services?
  - › Better Signaling Through Prices?
- Three I's: For Infrastructures
  - › Institutions (Industry/Market Structure)
  - › Information (Operations, Planning, Coordination)
  - › Investments (Growth, Replacement, Continuous)

Which Eccentricities?

How Do We Think About Energy Supplies?

- ***Technology Centric?***
  - Renewables, Nuclear, Fuel Cells, HVDC
- ***Resource Centric?***
  - Renewables, Hydrogen Feedstocks, etc. and their dynamics
- ***Utilization Centric?***
  - Energy Services and how to cost-effectively meet them.
- ***Market/Industry Centric?***
  - Operation and investments under various regulations
- ***Environmentally Centric?***
  - Greenhouse gases (Kyoto, emissions trading), land-use, water-use, etc.

Which Focus? How Much Detail?



Lots of Things

- Time and Spatial Distribution of Energy Resources
- Seasonality and Relative Growth of Energy Demands
- Variability & Covariance of Resources & Demands
- Aspects of the Energy Market, Namely Who Owns and Invests in Which Parts
- Trends in Infrastructure Age Growth and Aging
- Greenhouse Gas "Management" and Other Emissions Controls
- What Else?

Broader Lessons/Insights

- The "Utility" of Such Analysis?
  - » More Realistic "Expectations" for Renewables, DSM, etc. (e.g. Duty Cycles)
  - » Better Understanding of Resource, Demand, Economic and Grid Dynamics
  - » Better Targeted - and Therefore More Cost Effective Deployments (Techs & Policy)
- Challenges and Conspiracies?
  - » Variability of Renewable Resources
  - » Role of External Forces (e.g. Nat.Gas Costs, etc.)
  - » T&D Losses, Auxiliary Power Consumption
  - » Compounding vs. Compensating Risks?

Have We Had It Too Easy?

- What Direction Has Our, Should Our Energy Infrastructures Head?

	Centralized	Decentralized
Fuels & Feedstocks	Petroleum, Coal, Natural Gas	Biofuels, Hydrogen, etc.
Generation & Delivery	Central Station, High Voltage Transmission	Windpower, Solar, Distributed Generation, etc.
End-Use	Large Industry	Everything Else!
	Dispatchable	Non-Dispatchable

The Last Slide...

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- What Age Do We Want to Live In?
  - Stone Age / Bronze Age / Iron Age
  - Steel-Industrial Age / Silicon-Information Age

> *"The Stone Age didn't end because they ran out of stones."*
> (Jeroen van der Veer, Shell Oil)

- What Your "Favorite Future?"
  - Non-Carbon - Hydrogen Age? (OHEC)
  - Knowledge Age? (World Wise Web?)

> *"What Gets Measured, Gets Managed"*
> (Sir John Browne, BP)