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HVDC and Solar in the US Southwest

Peter Hartley

Kenneth Medlock, III

James A. Baker III
Institute for Public Policy
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Key Idea

- Construct a "demonstration project" for new electricity technologies in the US southwest
- Technologies of interest are:
  - Grid-connected photovoltaic solar power
  - HVDC transmission using "nanowire" technology
- Why this location?
  - SW climate is favorable for producing solar electricity
  - Large California and Texas markets are available
  - Market opportunities could allow the project to be built at relatively low cost

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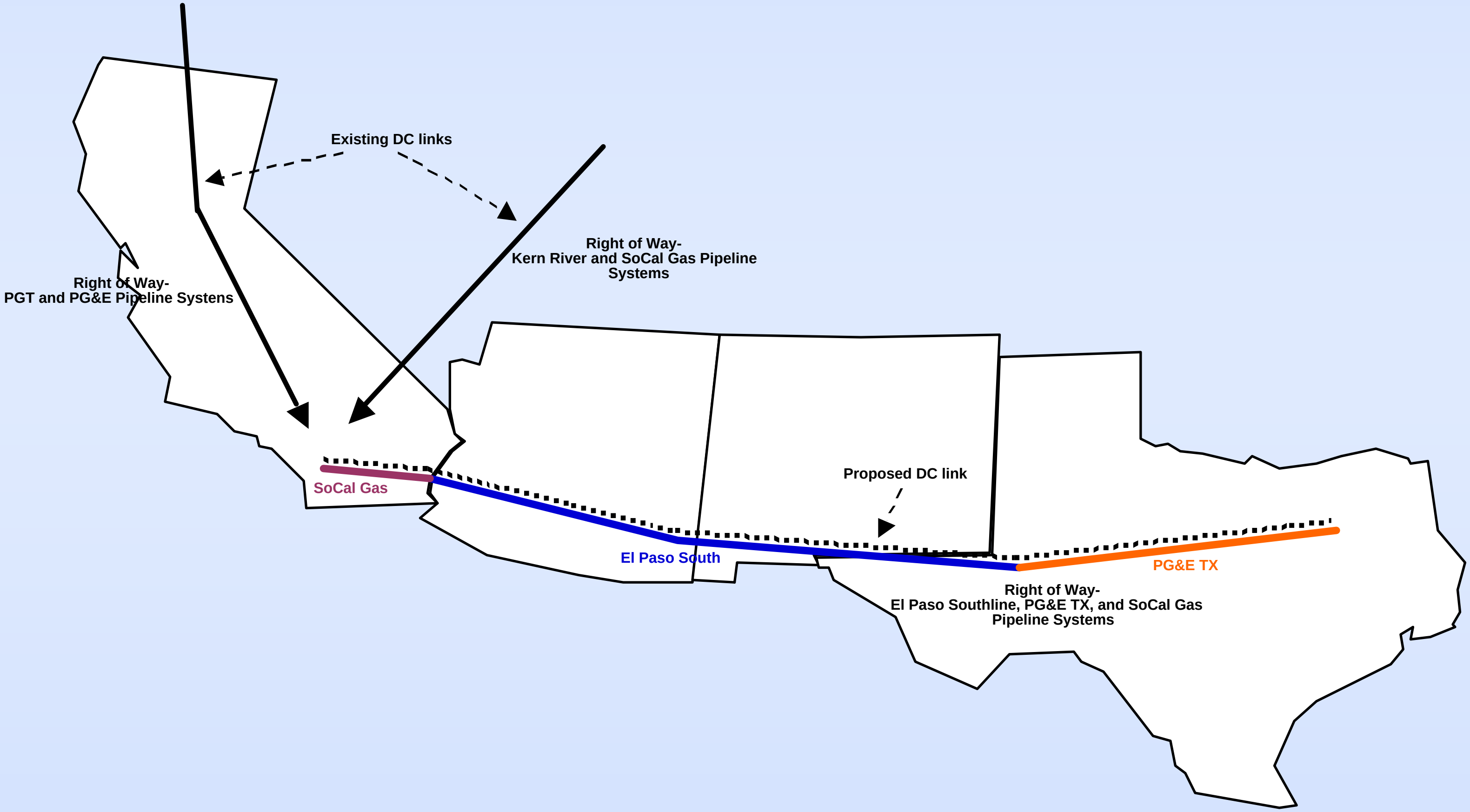
Nanowire project alone

- Expected benefits from connecting the Texas and California electricity grids:
  - ERCOT is only weakly connected to the surrounding North American transmission regions
  - Texas currently has substantial generating capacity relative to the demand
  - California is better connected to surrounding regions but has a smaller reserve plant margin
  - California has access to much better hydroelectricity resources than does Texas
  - Seasonal weather patterns differ in Texas and California
  - TX/CA time difference gives non-coincident daily peaks
    - Other major North American transmission links are N-S
    - TX/CA time difference large relative to the physical distance

Proposed HVDC link route



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Potential nanowire advantages

- First, note that for this project HVDC is the only option
  - Link must be asynchronous
    - Even if not, the long distance favors HVDC over AC
  - If we want to include solar, DC is advantageous
- From current CNL experiments, Single Wall Carbon Nanotubes (SWNT) Quantum Wire may have:
  - 6.3 times better conductivity than standard and proposed composite conductors
  - Near-zero thermal expansion – eliminating sag failure
  - 30% less weight, saving on the cost of tower structures and right-of-way
  - 10 times better tensile strength – allows longer spans, saving tower costs

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The market opportunity

- Ideally, one would build an intertemporal model of the CA and TX electricity markets
  - We can do this with a software platform like *Market Point* from Altos Partners
- For this exercise, we assumed that the outcomes for 2003 were representative of the longer term opportunities
  - Specifically, we collected average hourly wholesale prices in North Texas and Southern California and system loads in each state for all 8760 hours in 2003
    - Sufficiently large price differentials provide arbitrage opportunities that could be exploited with a HVDC link

The market opportunity (continued)

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- The analysis ignores other potential opportunities from providing ancillary services
  - The opportunity to supply ancillary services explains occasional negative energy prices
- An increase in demand in one of the states will drive up prices, while an increase in supply at the other end of the line will drive down prices
  - Take this into account in a simple way by estimating a function relating wholesale prices to system load
  - Although the load also responds to prices, most of it cannot respond in real time
    - Short run price and quantity movements are dominated by shifts in demand along the short run supply curve and movements of the supply curve as a result of component failures, scheduled downtime etc.

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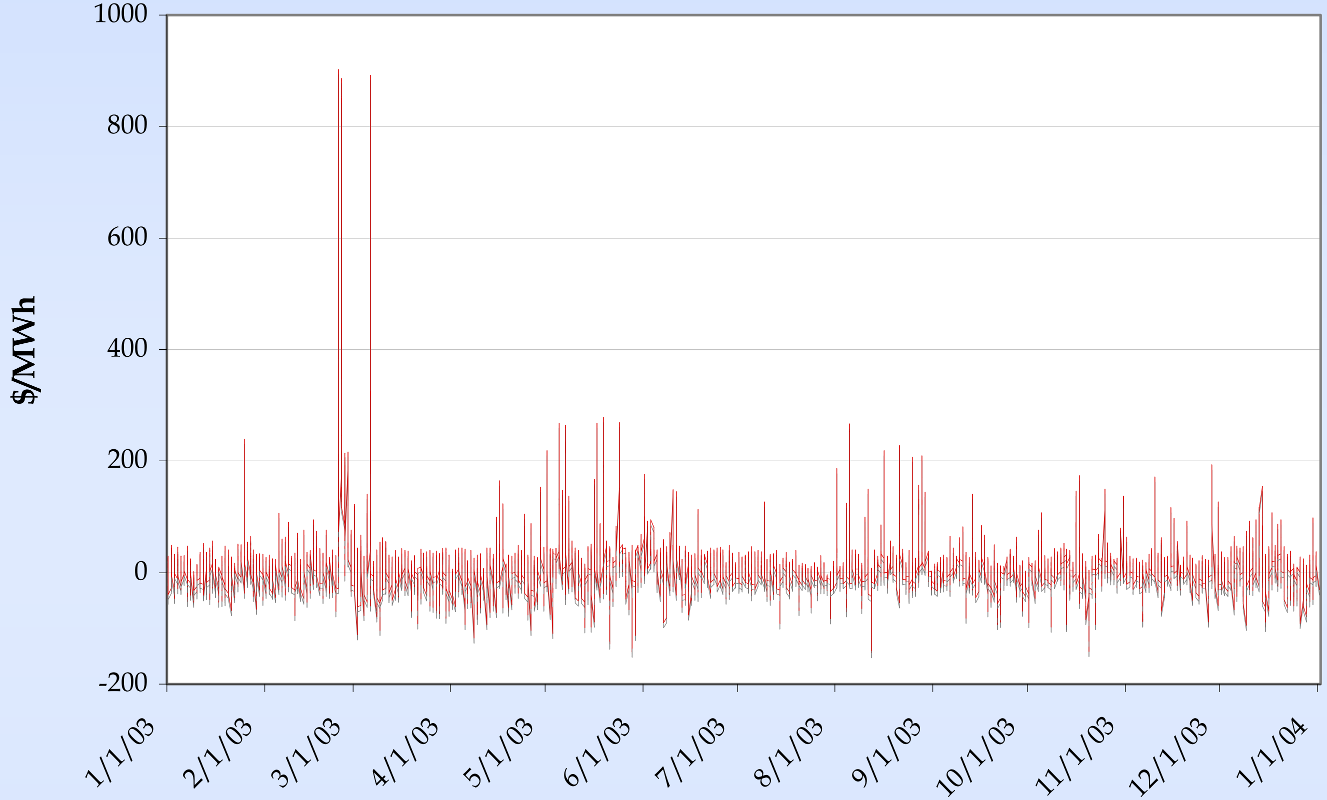
TX-CA price differentials 2003



Mean = $6.21

Minimum = -$143.77

Maximum = $901.93

Standard deviation = 43.42

Skewness = 8.207

Kurtosis = 139.07

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TX Generic prices for Balancing Energy, January 2004

TYPE OF FACILITY	UP ADJUST	DOWN ADJUST
Coal and Lignite	69.91	3.00
Combined Cycle	110.17	29.13
Diesel	145.12	69.90
Gas-Steam	136.38	43.69
Hydro	1048.91	-997.00
Load Acting as a Resource	1051.91	-1000.00
Nuclear	1047.91	-996.00
Qualifying Facility (co-gen)	1049.91	-998.00
Renewable	1050.91	0.00
Simple Cycle	139.29	61.17

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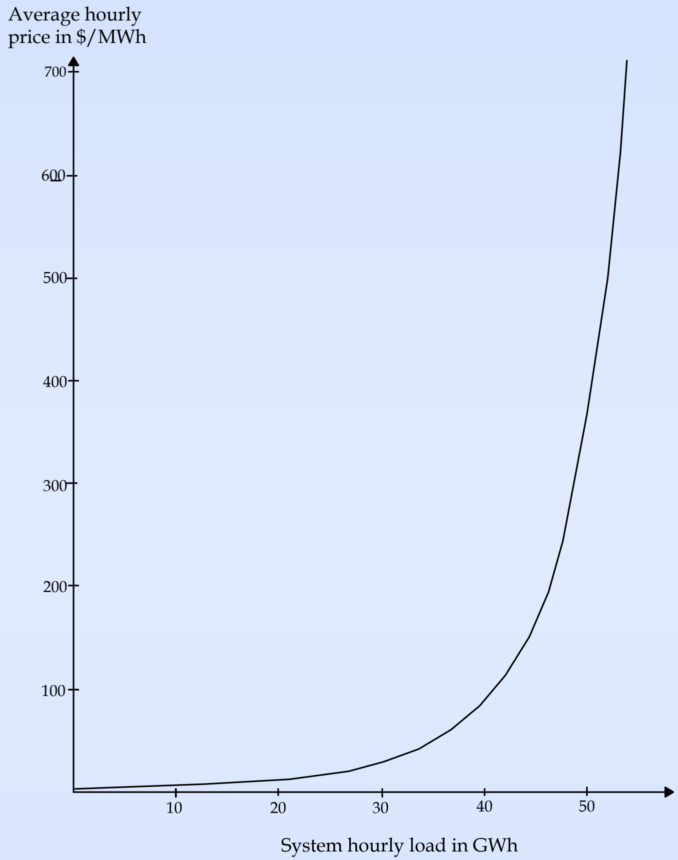
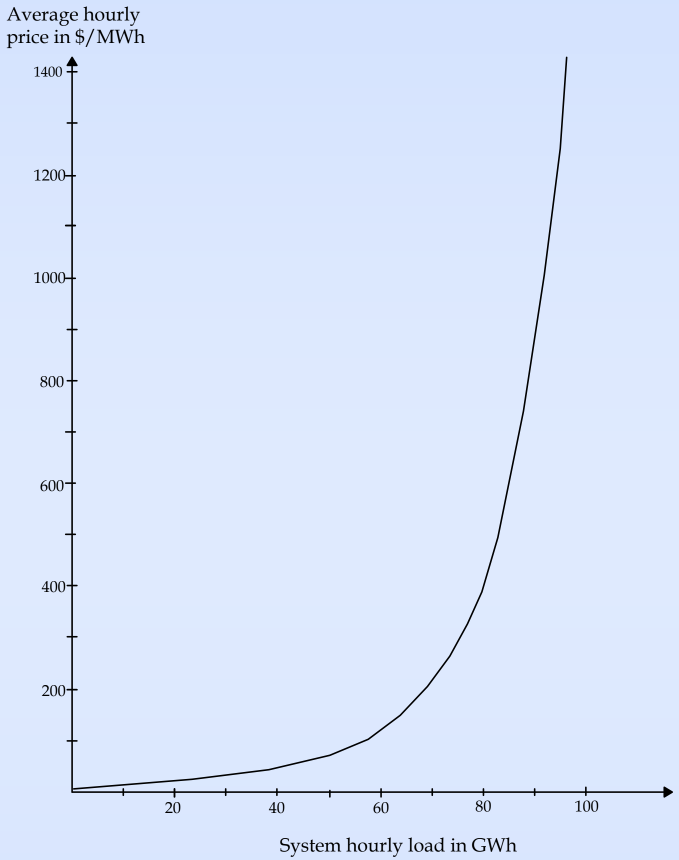
Estimated supply curves





$$\ln p = b_1 b_2^{load}$$

$$\frac{dp}{dload} = p.\ln p.\ln b_2$$

California			*Texas*		
b_1	1.468304	0.0402641	b_1	2.40822	0.0234993
b_2	1.02819	0.0009954	b_2	1.011537	0.0002829
$R^2 = 0.8086$			$R^2 = 0.9568$		

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Estimated arbitrage revenue

- Assume a 1GW capacity line with a length of 2,000 km (Los Angeles to Dallas)
  - A paper by Clerici and Longhi[1] implies losses on an optimized HVDC line with these parameters and using current technology would be ≈ 13%
  - Losses on an optimized SWNT wire may be 1/10th of this (CNL Report) – we assume 1.5%
    - To sell 1GWh, 1.01523 GWh would need to be bought
    - If the current selling price is p_s, and buying price is p_b, assume the new prices will be

$$p_s - \Delta p_s = p_s - p_s . \ln p_s . \ln b_{2s} \text{ and } p_b + \Delta p_b = p_b + p_b . \ln p_b . \ln b_{2b} / 0.985$$

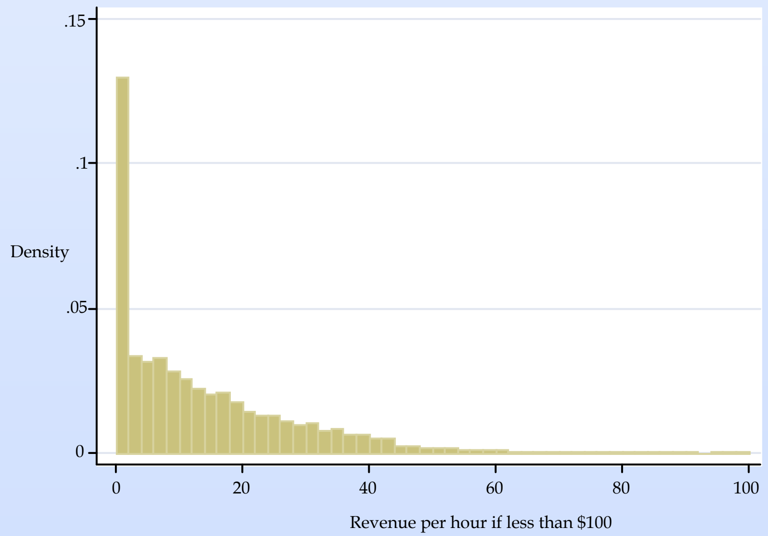
and a 1GW trade would yield

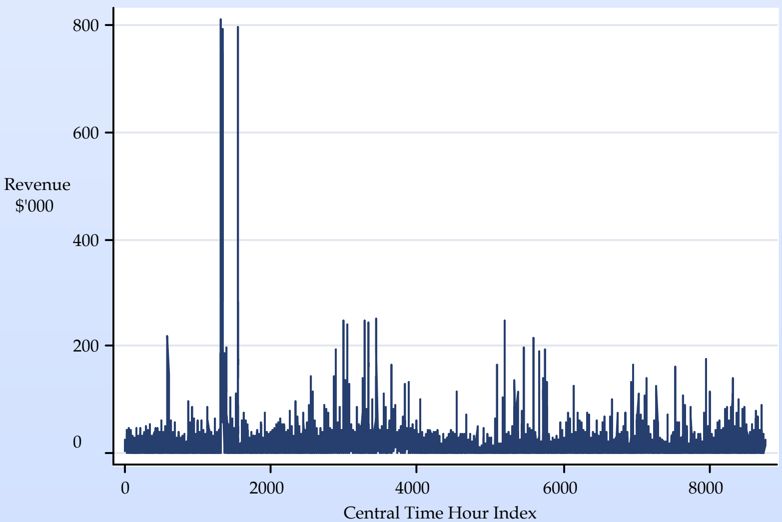
$$Revenue = \left(p_s - \Delta p_s\right) - 1.01523\left(p_b - \Delta p_b\right)$$

1. "Competitive Electricity Transmission as an Alternative to Pipeline Gas Transport for Electricity Delivery", available at http://www.worldenergy.org/wec-geis/publications

Revenue (continued)

- Revenue/hour = $\max(R_{CA \to TX}, R_{TX \to CA}, 0)$
  - $0 for around 19% of hours
  - Mean = $17,174, standard deviation = 33.83, skewness = 11.81, kurtosis = 226.71
- PV of 2003 estimated net revenue @ 6.5% annual discount rate = $146.2 million
  - For a 30-year project, PV = $1,909 million





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Time series properties of revenue

Variable	*Coefficient*	*Std. Error*
Central Time Hour ending		
0200	-0.610	0.709
0300	-0.473	0.888
0400	-2.539	1.015
0500	-4.403	0.870
0600	-3.025	0.928
0700	-3.323	1.043
0800	-1.847	0.949
0900	0.420	0.966
1000	0.159	0.920
1100	-4.006	0.855
1200	-7.436	0.852
1300	-9.982	0.863
1400	-10.300	0.898
1500	-9.518	0.889
1600	-6.388	0.955
1700	-7.088	0.843
1800	-8.179	0.824
1900	-4.436	0.945
2000	-2.834	0.988
2100	-4.118	0.788
2200	-6.478	0.822
2300	-7.715	0.639
2400	-6.455	0.516

Variable	*Coefficient*	*Std. Error*
Central Time Day and Month		
Mon	-2.878	0.7340
Tue	-1.066	0.905
Wed	-0.416	0.864
Thu	-1.974	0.843
Fri	-2.338	0.864
Sat	-0.377	0.761
Feb	-3.007	1.454
Mar	0.367	1.325
Apr	2.166	1.469
May	5.648	1.308
Jun	2.358	1.443
Jul	-4.455	1.739
Aug	-9.645	1.372
Sep	-1.216	1.580
Oct	-0.861	1.453
Nov	-6.033	1.321
Dec	1.802	1.494
Constant	20.847	1.317

Variable	*Coefficient*	*Std. Error*
Error term model: $(1-\rho_1 L-\rho_2 L^2-\rho_{24} L^{24})(y_t - x_t\beta)=\varepsilon_t+\theta\varepsilon_{t-1}$ $\sigma_t^2=\gamma_0+\gamma_1(\lvert\varepsilon_{t-1}\rvert+\gamma_2\varepsilon_{t-1})^2+\delta_1\sigma_{t-1}^2$		
ρ_1	-0.171	0.057
ρ_2	0.401	0.031
ρ_{24}	0.035	0.004
θ	0.708	0.057
γ_0	70.373	1.258
γ_1	0.406	0.021
γ_2	0.663	0.037
δ_1	0.320	0.008

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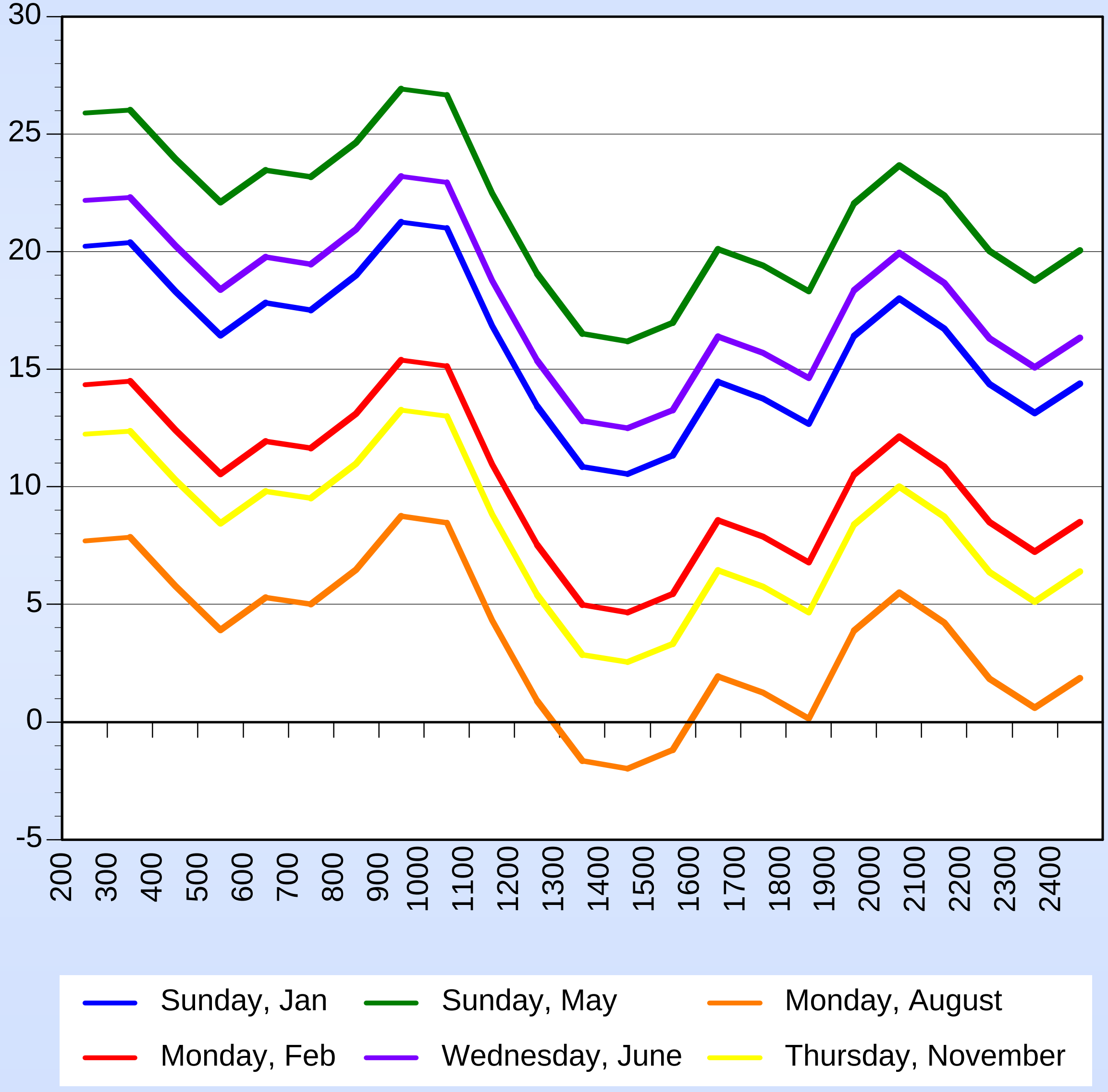
Example expected revenue profiles



Conventional HVDC revenue

- With higher resistance loss, to sell the same power, more needs to be bought
  - This also drives up the buying price

$$Revenue = p_s\left(1 - \ln p_s . \ln b_{2s}\right) - p_b\left(1 - \ln p_b . \ln b_{2b} / 0.87\right) / 0.87$$

    - Get a term involving the losses squared
- Calculate arbitrage revenue for a 13% loss
  - $0 for around 34% of hours
  - Mean = $14,532, standard deviation = 32.97, skewness = 11.93, kurtosis = 230.96
- PV of 2003 estimated net revenue @ 6.5% annual discount rate = $123.7 million
  - For a 30-year project, PV = $1,615 million
- Higher line loss also means line capacity has to be greater in order to *deliver* 1 GW, raising costs

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NPV of HVDC nanowire link

- Cost of converter stations
  - 2 stations at $215 million each
- Conventional HVDC line size = 795 kcmil
  - From figures available[1] at the EIA, we can estimate the cost (excluding right-of-way) at $296,024 per mile, giving a cost of $444 million
  - 10 times higher tensile strength, lesser tendency to sag and 30% less weight of SWNT should allow longer spans, fewer and smaller towers, perhaps reducing line costs 50%
- Ignoring taxes, depreciation and right of way costs, surplus is perhaps $1,900-430-220=$1,250 million

1. From CSA Energy Consultants, "Existing Electric Transmission and Distribution Upgrade Possibilities, "(Arlington, VA, July 18, 1995), available at http://www.eia.doe.gov/cneaf/pubs_html/feat_trans_capacity/table2.html

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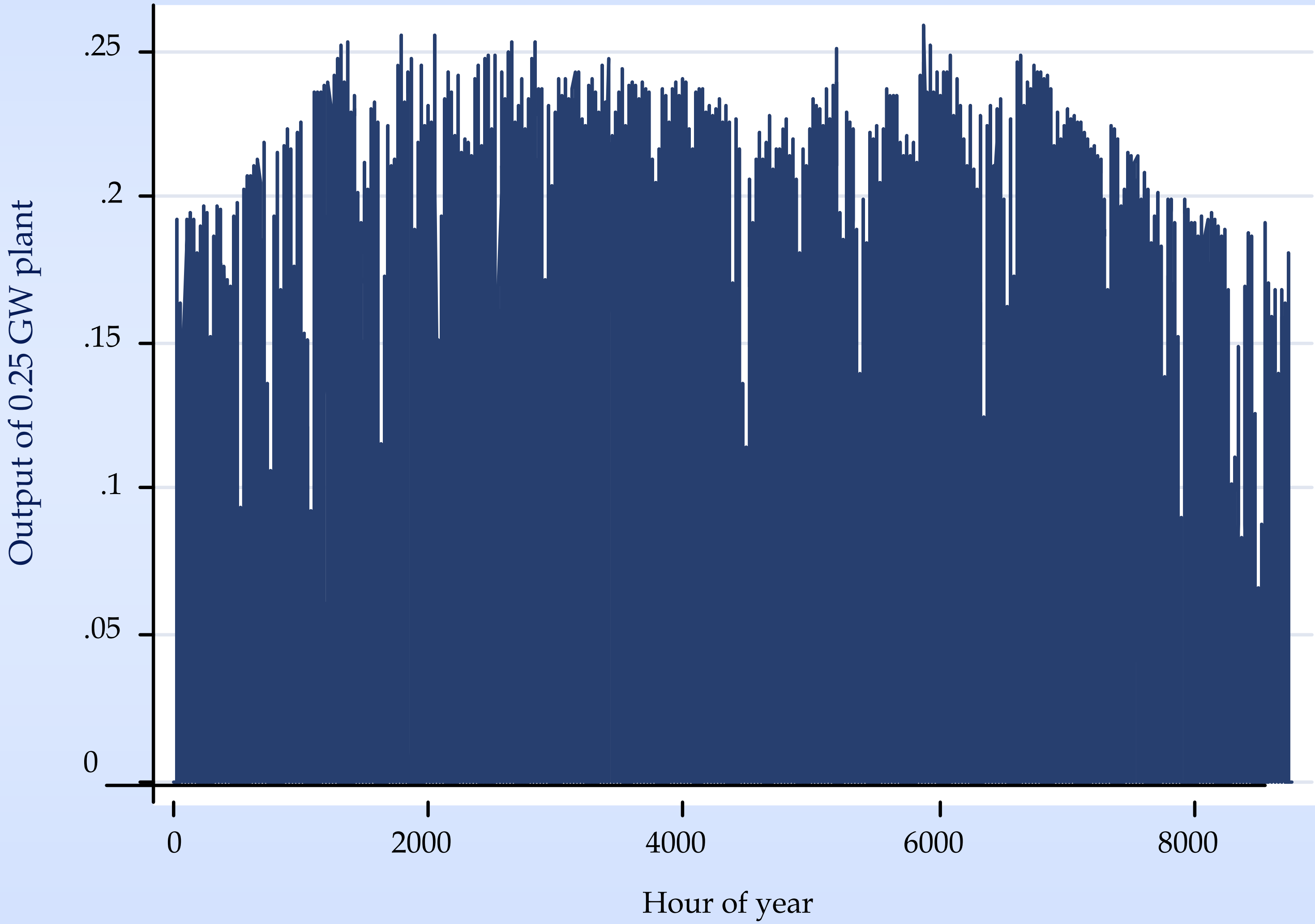
Solar photvoltaic plant

- Arbitrage profits tend to be lowest mid-late afternoon central time
- A solar plant in Arizona would supply additional low cost power at these times
- Take the plant to be in Tucson, AZ and use data from the NREL labs for 1990 to represent output from a plant
- Maximum Wh/m^2 from horizontal panel on surface is ≈ 1,067. We use panels tilted at latitude-15^o with maximum Wh/m^2 ≈ 1,102.5
- For illustrative purposes, we assume the plant has 250 MW capacity and panels have 10% efficiency
  - Assume 250,000/(0.1x1.1025) = 2.268 million m^2 of panels

Simulated output using 1990 data



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Modified revenue calculations

- Assume the losses from AZ to CA are 0.5016% and from AZ to TX are 1.0033%
- For a solar plant output of *s* MW, to sell 1 MW in California we now need purchase only (1/0.994984-*s*)/0.989967 in Texas
- Conversely, to sell 1 MW in Texas, we need to purchase (1/0.989967-*s*)/0.994984 in CA
- Further, if there is no arbitrage trade but positive solar output, the solar power can still be sold
- Again assume prices adjust to the purchases and sales as assumed above

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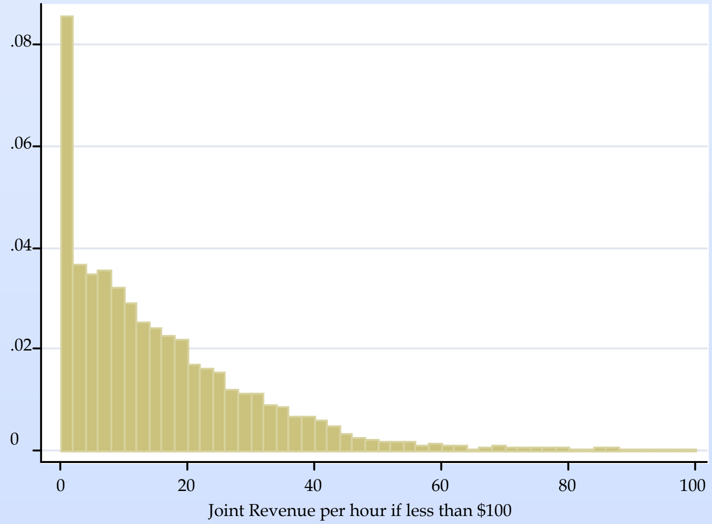
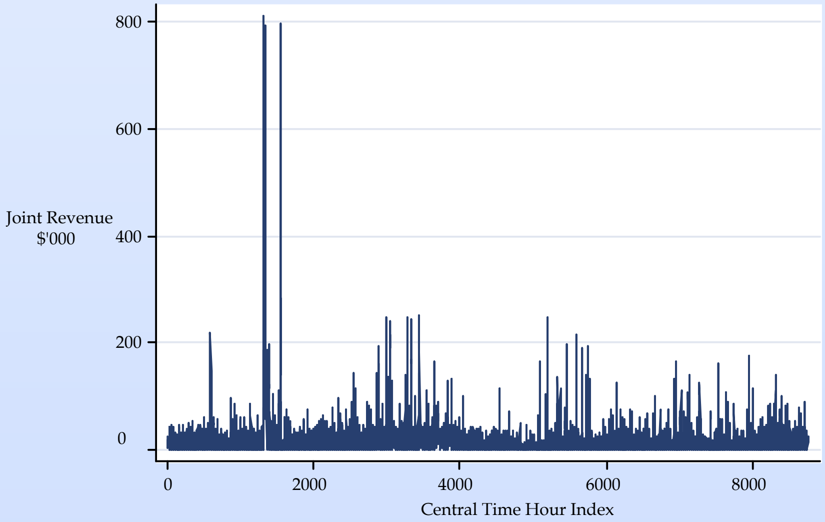
Revenue with solar

- Solar can be used even when arbitrage between the states is unprofitable
  - Now revenue is $0 for around 8.6% of hours
  - Mean = $19,007, standard deviation = 34.32607, skewness = 11.74, kurtosis = 223.07





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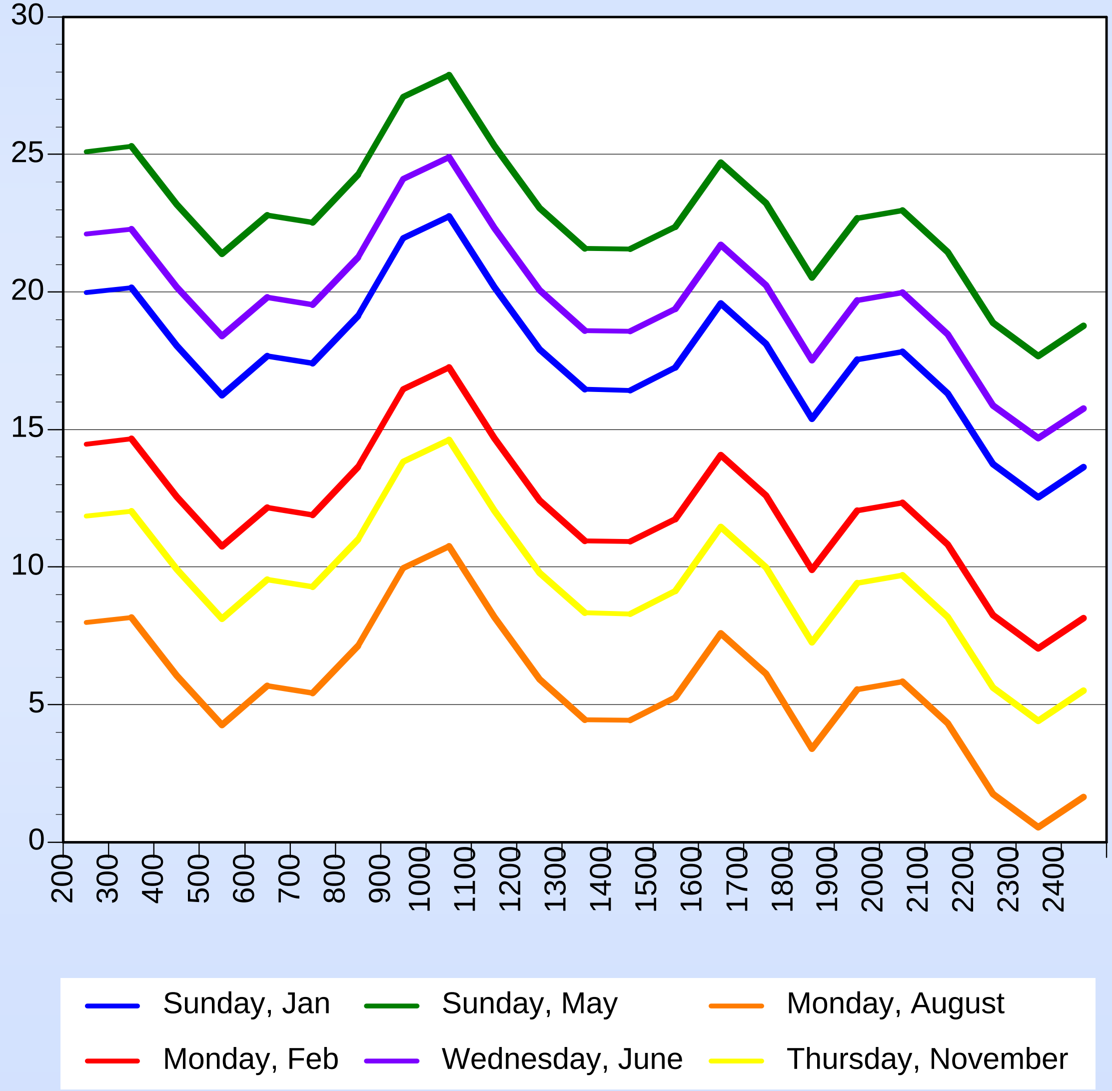
Time series properties - joint revenue

Variable	*Coefficient*	*Std. Error*	*Variable*	*Coefficient*	*Std. Error*	*Variable*	*Coefficient*	*Std. Error*
Central Time Hour ending			Central Time Day and Month			Error term model:		
0200	-0.504	0.676	Mon	-2.858	0.745	$\left(1-\rho_1 L-\rho_2 L^2-\rho_{24} L^{24}\right)\left(y_t-x_t\beta\right)=\varepsilon_t+\theta\varepsilon_{t-1}$		
0300	-0.318	0.875	Tue	-0.665	0.903	$\sigma_t^2=\gamma_0+\gamma_1\left(\lvert\varepsilon_{t-1}\rvert+\gamma_2\varepsilon_{t-1}\right)^2+\delta_1\sigma_{t-1}^2$		
0400	-2.428	1.000	Wed	-0.698	0.853	ρ_1	1.491	0.021
0500	-4.226	0.878	Thu	-1.951	0.828	ρ_2	-0.519	0.013
0600	-2.809	0.944	Fri	-2.442	0.861	ρ_{24}	0.003	0.001
0700	-3.073	1.056	Sat	-0.364	0.762	θ	-0.942	0.021
0800	-1.351	0.957						
0900	1.484	0.985	Feb	-2.642	1.489	γ_0	73.316	1.285
1000	2.275	0.944	Mar	0.936	1.359	γ_1	0.255	0.090
1100	-0.292	0.874	Apr	2.521	1.477	γ_2	1.057	0.362
1200	-2.555	0.864	May	5.130	1.330	δ_1	0.325	0.008
1300	-4.021	0.883	Jun	2.836	1.405			
1400	-4.051	0.896	Jul	-3.533	1.714			
1500	-3.228	0.883	Aug	-9.137	1.357			
1600	-0.898	0.954	Sep	-1.047	1.582			
1700	-2.368	0.883	Oct	-0.840	1.481			
1800	-5.084	0.845	Nov	-6.176	1.312			
1900	-2.928	0.943	Dec	1.161	1.486			
2000	-2.639	1.002						
2100	-4.157	0.806	Constant	20.478	1.322			
2200	-6.735	0.817						
2300	-7.936	0.668						
2400	-6.845	0.496						

Example expected joint revenue profiles



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Loss on joint project

- PV of 2003 estimated net revenue @ 6.5% annual discount rate = $161.84 million
  - For a 30-year project, PV = $2,113 million
- Difference due to solar = $204 million
- Cost of panels (*First Solar* thin film)
  - 2.268 million m^2 @ $85/$m^2$ = $192.78 million
  - Balance of system @ $35/$m^2$ = $79.38 million
- Remaining costs
  - Land @ $10m^2$ per $4m^2$ of cells ≈ 2.2 square miles
  - Annual maintenance costs
  - Tax and depreciation considerations

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Final comments

- HVDC link to arbitrage price differences between CA and TX appears profitable
  - A more complete analysis taking account of likely future investment and load growth is needed before definitive conclusions can be drawn
  - But such a project may allow a test of the SWNT quantum wire concept at little or no net cost
  - Perhaps wind resources from west TX could be linked to the system too
    - These would have a different load profile from solar
- In the short term, subsidizing a small solar plant to connect to the HVDC line could allow for further testing of new technologies
  - Having the HVDC link in place would make it easier to introduce solar when the cost falls