A Simple Calculation Procedure for LOLE, LOLH, and EUE, Calculation of Probabilistic Transmission Line Flows, and Study Results for Extreme Renewables in ERCOT

a presentation by EGPreston

to the

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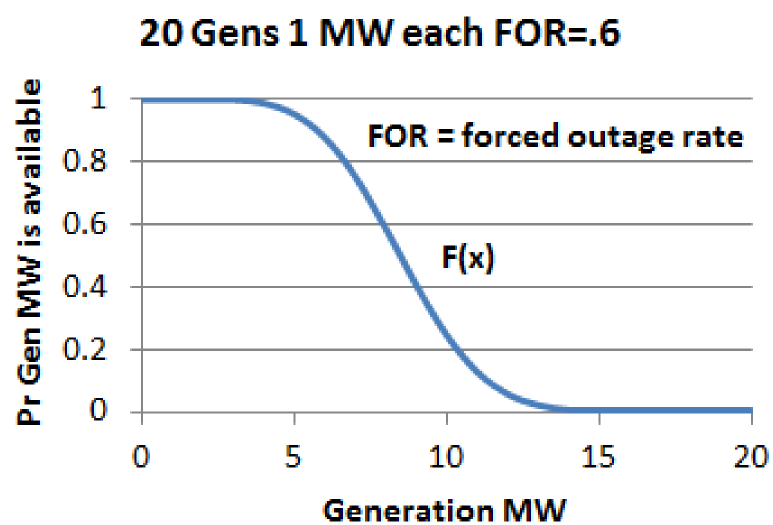
Methodology:

- **Monte Carlo undesirable characteristics learned from experience**
  - ‘Solution’ was slow to converge compared to a direct calculation.
  - Reduced transmission network was hard to create and interpret.
  - Too few transmission constraints were observed to be meaningful.
- **Booth-Baleriaux Recursive Convolution is much faster and more accurate**
  - In France Baleriaux invents a scaling-shifting-adding approx. solution.
  - In Australia Booth shows the Baleriaux method is an exact solution.
  - Recursive convolution BB creates F(x), the cumulative gen distribution.
  - Simple math:

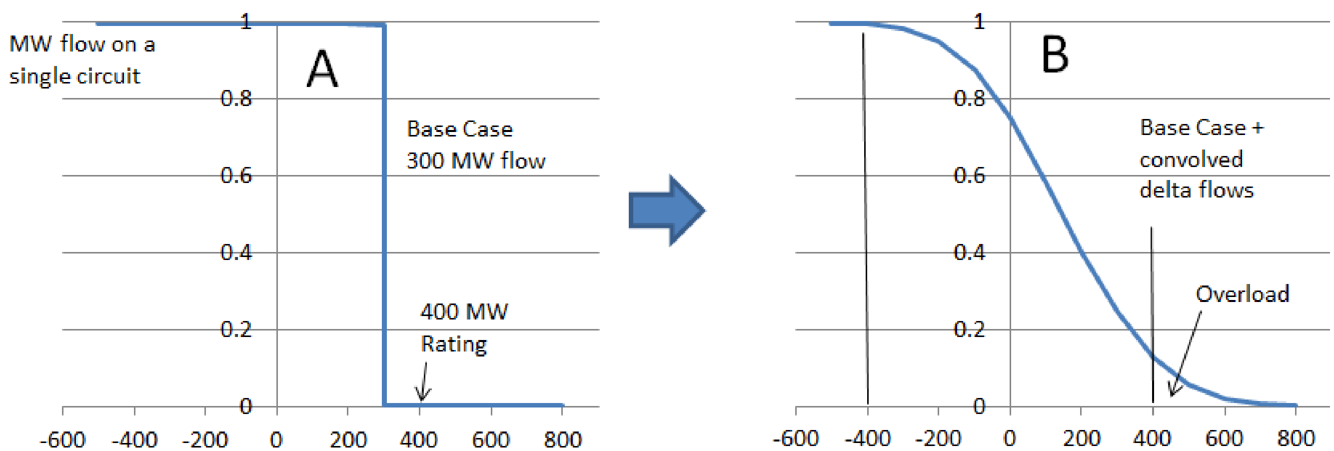
```
   DO 3 J=1, 20    (twenty gens)
   DO 3 I=20,1,-1 (sweep R to L)
3  F(I)=(1.-FOR)*F(I-1)+FOR*F(I)
```

shift ‘up state’ 1 MW to the right



- **Finding LOLP, LOLE, LOLH, and EUE using F(x)**
  - F(x) is only valid for independent generator outages.
  - For demand x MW, LOLP loss of load probability = 1 - F(x).
  - LOLH loss of load hours = sum of all hourly LOLP's in a year (h/y).
  - LOLE loss of load expectation = sum of 365 daily max LOLP's (d/y).
  - EUE expected unserved energy = sum of all LOLP's for each hour for demand 0 MW through the MW demand for that hour (MWh/y).

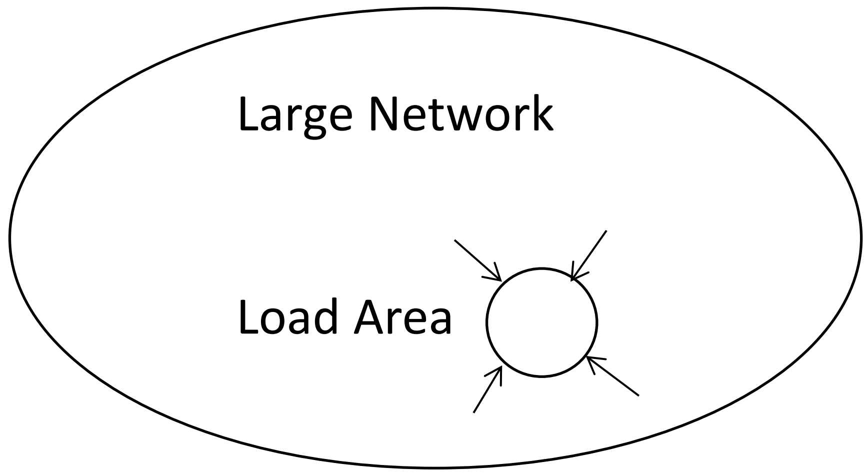
- **Calculating transmission probabilistic distributions**
  - Start with a full network peak demand load flow solution (see A).
  - Increment generators, one at a time, convolve the line flows (see B).



- **Estimating transmission FOR**
  - For a large system with many lines, observe the actual lines outaged at times when all lines should be in service (peak demand period).
  - Record the outages in terms of miles of line, how many lines, and the voltage classes. Record autotransformer outages at these times.
  - After a few years a consistent pattern should emerge in which the numbers of lines out of service at these peak load times is predictable.
  - Adjust the forced outage rates of your model so the model produces what is being observed in the system for total outages by class.

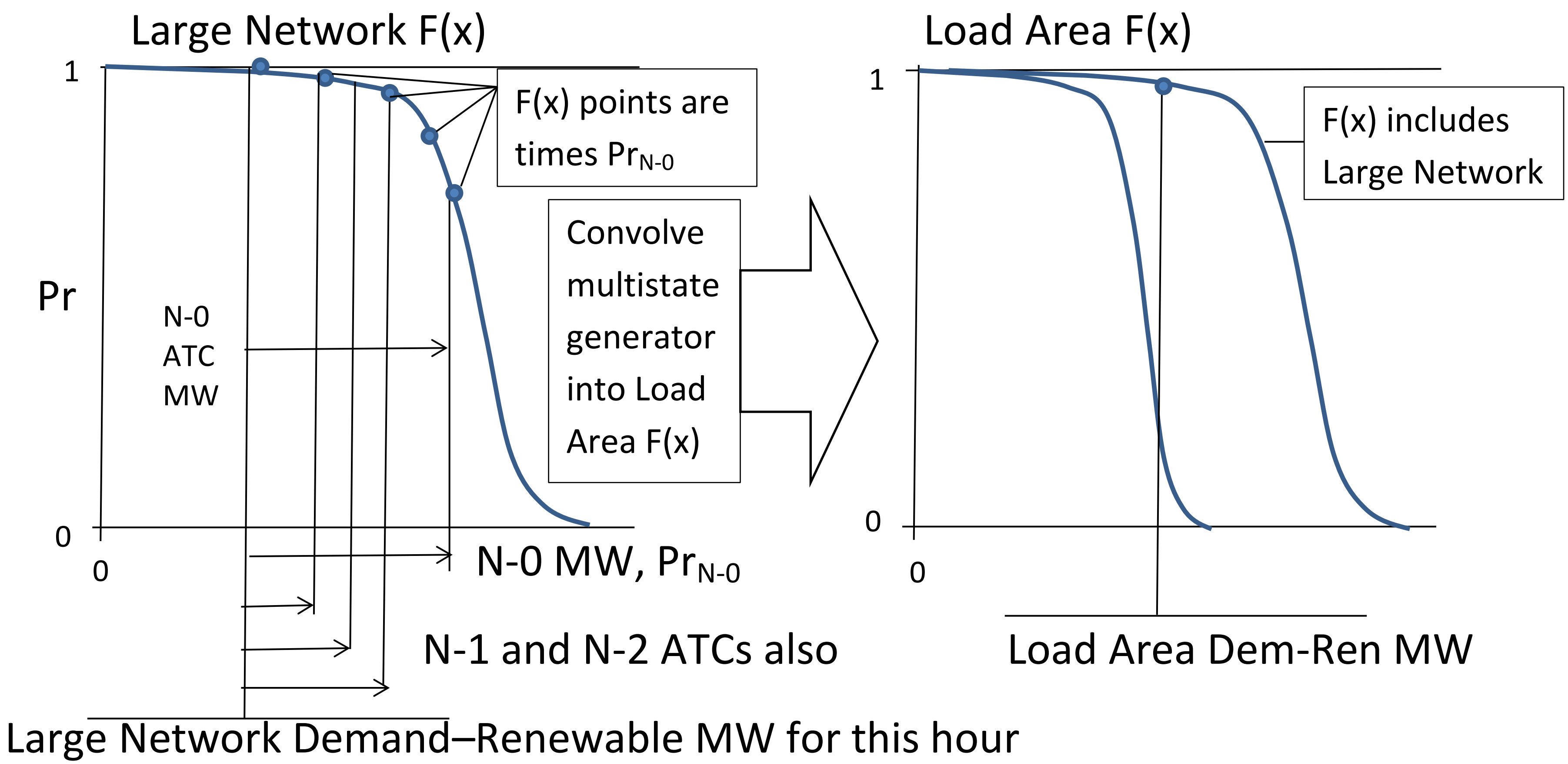
- **Running a combined generation and transmission model**
  - Calculate the F(x) and reliability indices for the no transmission model.
  - Calculate probabilistic line flows for every transmission configuration.
  - N-0, N-1, N-2, etc. transmission configurations must be enumerated.
  - Pr circuit overloads are removed shifting F(x) which increases LOLP's.
  - Recalculate LOLE, LOLH, EUE for new F(x) which includes transmission.
  - See http://www.egpreston.com/bookmod.pdf for more information.

- **Two area transmission model is elementary (i.e. LOLE of a load area)**
  - The electrical solution import ATCs are external to LOLE calculations



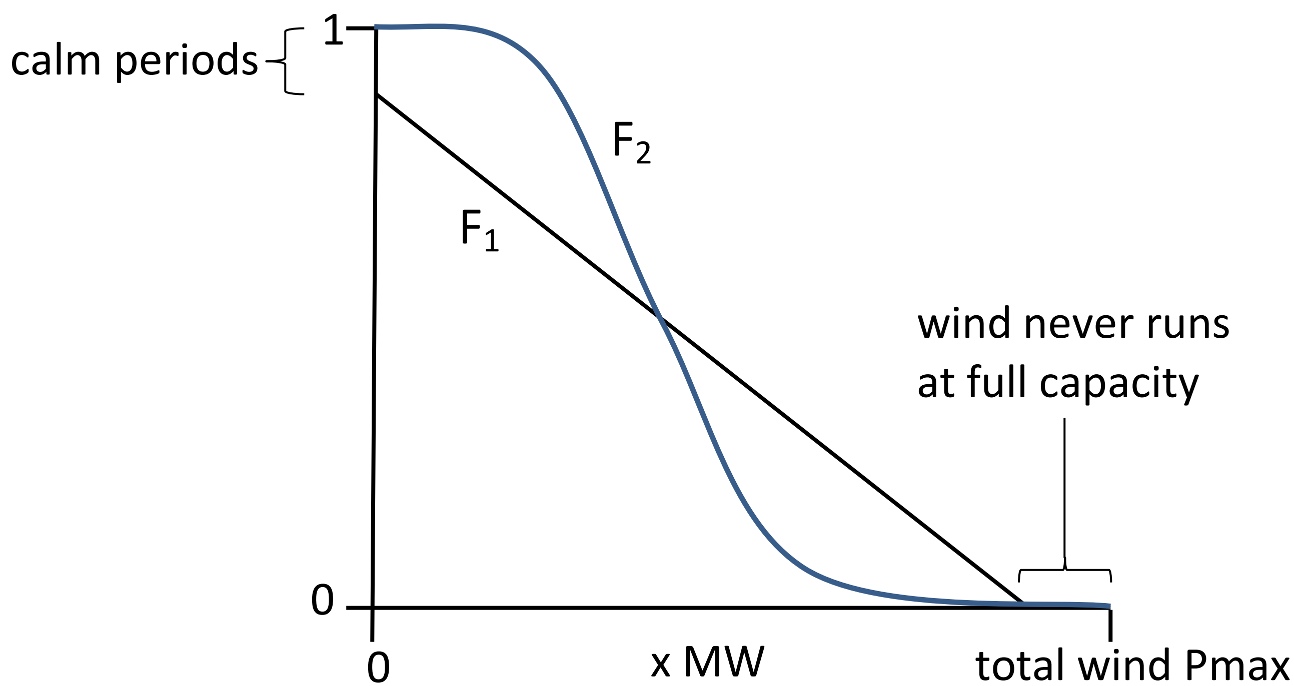
  - Available Transfer Capability MW imports are from load flow cases
  - Probabilities of N-1 and N-2 line outage states are estimated
  - Set the N-0 (no lines out) state to $1 - \sum$ line outage state probabilities
  - Calculate the generation F(x) of the large and small areas separately
  - Continue with steps on the next page….

- **Steps for calculating the load area LOLP of the two area model**
  - The large network ATC and Probability states are treated as a single multi-state generator feeding the load area, recalculated each hour

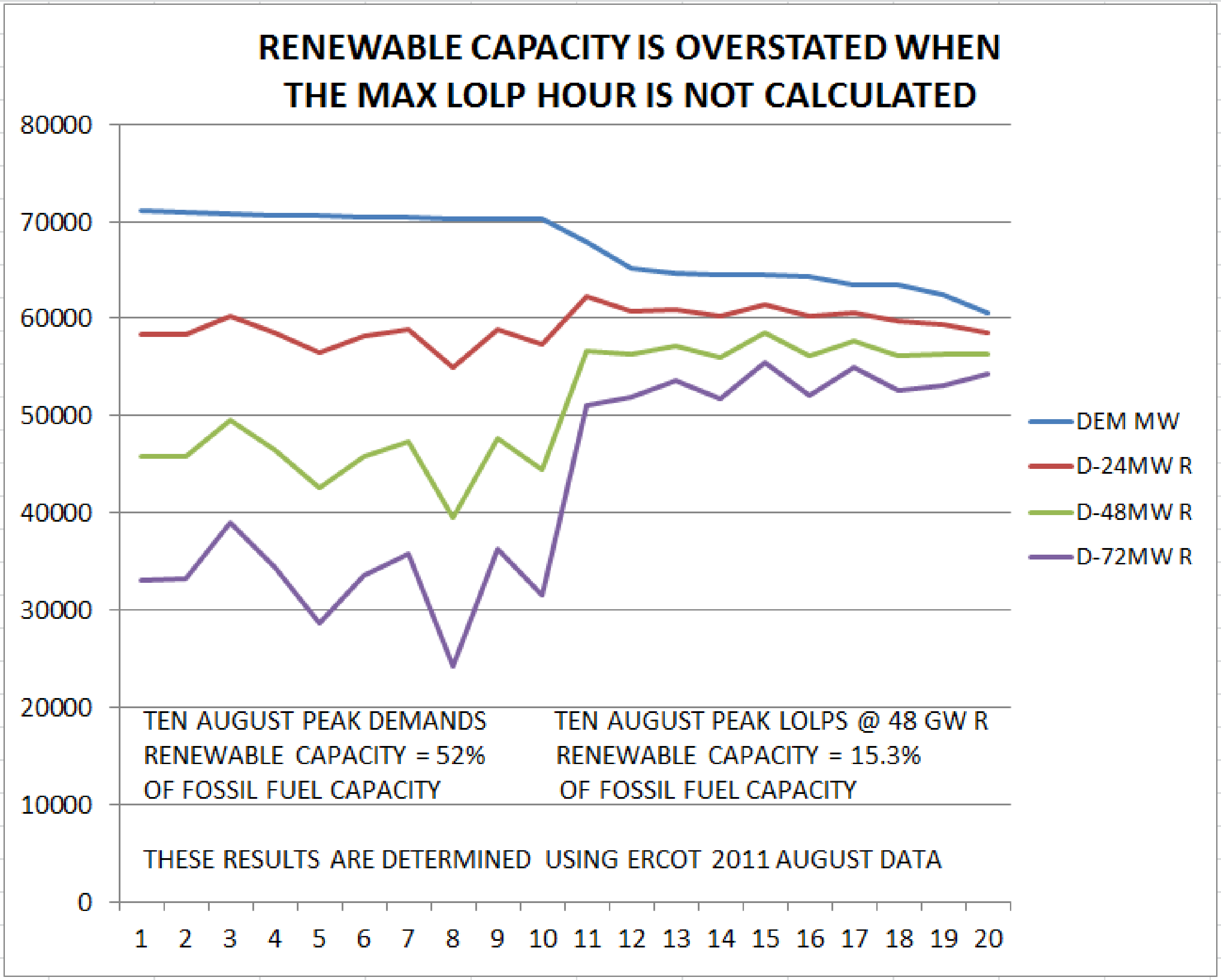


Uncertainties in the modeling of renewables

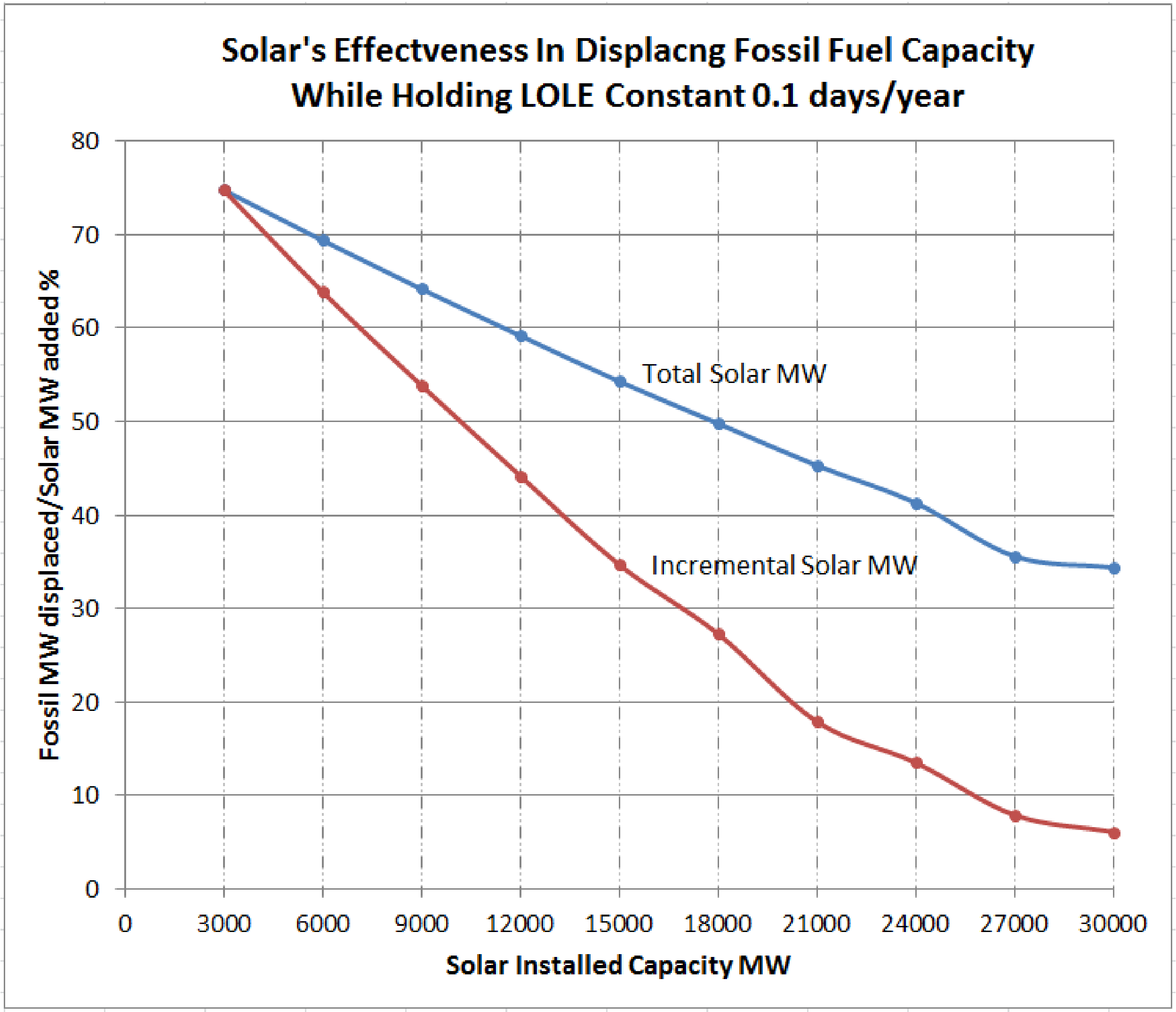
- **Should we treat wind as probabilistic generation or as load reduction?**
  - $F_1(x)$ is approximately the shape of actual wind duration data.
  - $F_2(x)$ = Pr[x MW is available] is from convolved wind generators.
  - Conclusion – a very complex convolution will be needed to obtain F_1 treating wind as generators. Wind as negative load is much simpler.



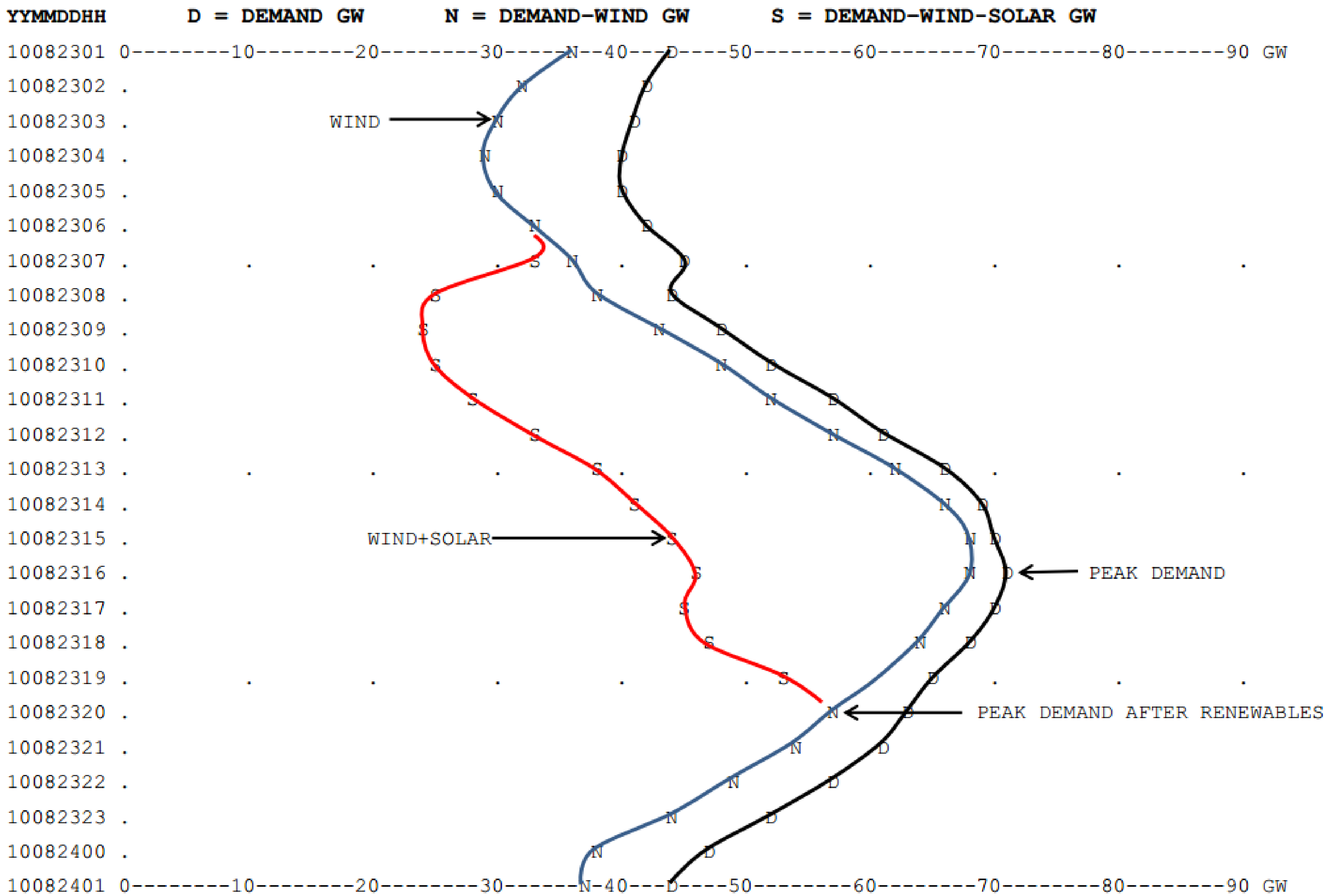
- **Will the highest LOLP's occur at times of system peak demand?**
  - The answer is no and why this is the case is shown below



- **Can a reserve margin be a proxy for LOLE when renewables dominate?**
  - Not likely because of the moving target of renewable's capacity credit



ERCOT 2010 HISTORICAL PEAK DEMAND DAY WITH 24 GW WIND AND SOLAR AT 0 GW AND 30 GW



- **Data collection and execution process for modeling wind and solar**
  - Collect several historical years of hourly MW load data.
  - Collect renewables MW data from different geographical regions such as NREL data https://www.solaranywhere.com/Public/SelectData.aspx
  - Scale historical loads and renewables to match the future test year.
  - Create a net load by subtracting renewable MWs from system load.
  - Apply storage devices to the net load for smoothing the fluctuations.
  - Collect dispatchable generation FOR and maintenance data, i.e. GADS.
  - Calculate F(x) dispatchable generation and the LOLP's of the net load.
  - Scale renewables to new high levels by specific geographical location using hourly historical profiles, then back off fossil fuels to achieve the desired LOLE.
  - The delta MW renewables will drive a specific MW of fossil fuel reduction which allows a capacity credit to be assigned to that renewable. The problem is that the renewables interact with each other and with their own capacity to produce nonlinear results.

Case 1: Calibrate FOR, no wind, 81787 MW conventional generation, peak demand of 71119 MW is a 15% reserve margin; when FOR = 6.874% then LOLE = 0.1 d/y

```
YYMMDDHH 0--------10--------20--------30--------40--------50--------60--------70--------80--------90 GW
12062602 .                                   F    D
12062603 .                                 F    D
12062604 .                                F    D
12062605 .                                F    D                    D = Demand GW     F = Fossil Fuel GW
12062606 .                                  F    D
12062607 .         .         .         .     F   .D        .         .         .         .         .
12062608 .                                     F    D
12062609 .                                          F    D
12062610 .                                               F    D
12062611 .                                                    F    D
12062612 .                                                         F    D
12062613 .         .         .         .         .         .F     D  .         .         .
12062614 .                                                               F    D
12062615 .                                                                 F    D
12062616 .                                                                 F    D <-2012 peak demand
12062617 .                                                                 F    D
12062618 .                                                                F     D
12062619 .         .         .         .         .         .   F    D.         .         .
12062620 .                                                            F    D
12062621 .                                                          F     D
12062622 .                                                       F    D
12062623 .                                                  F    D
12062700 .                                             F    D
12062701 0--------10--------20--------30--------40-F----D-50--------60--------70--------80--------90 GW
 NUCL BASE:       13.064% OF SYS ENGY      100.000% CAP FACT      5150. MW PMAX
 RENEWABLE:        0.000% OF SYS ENGY        0.000% OF RENEWABLE ENERGY LOST
 RENEWABLE:        0.000% OF SYS ENGY LOST
                 -------------------------
    135466. GWH   13.064% OF SYS ENGY IS NON FOSSIL
    901482. GWH   86.936% OF SYS ENGY IS FOSSIL FUEL
   1036948. GWH  100.000% TOTAL  (3 years)
                 -------------------------
 LOAD RAMP UP              95 MW/MIN ON    11120718 YYMMDDHH
 LOAD RAMP DOWN           203 MW/MIN ON    10090100 YYMMDDHH
 MINIMUM DEMAND         23294 MW     ON    11041704 YYMMDDHH
```

Case 1 continued

HOUR OF MAXIMUM LOLP EACH YEAR AND CONDITIONS THAT HOUR

YYMMDDHH	DEM D	REN R	D-R-N	FOSSIL	STORMW	STORHR	LOLP
10082316	71119	0	65969	65969	0	0.000	0.02564637
11080317	71119	0	65969	65969	0	0.000	0.02564637
12062616	71119	0	65969	65969	0	0.000	0.02564637

LOAD UNCERTAINTY = **3.0%** WEIGHT = **45.0%** <-discuss uncertainties/options here

YYMM	MW PKLD	% RESV	LOLH	LOLE	EUE
----	-------	------	-.--3--6--9-12-15-	-.--3--6--9-12-15-	-----.--3--6--9
1201	50525.	61.9	0.0000000000000000	0.0000000000000000	0.000000000
1202	45232.	80.8	0.0000000000000000	0.0000000000000000	0.000000000
1203	45784.	78.6	0.0000000000000000	0.0000000000000000	0.000000000
1204	52147.	56.8	0.0000000000000000	0.0000000000000000	0.000000000
1205	63148.	29.5	0.0000002901908362	0.0000001876514184	0.000146914
1206	**71119.**	**15.0**	0.1400026309008488	0.0446176985404796	135.426634472
1207	70291.	16.4	0.0446346582784303	0.0041347838798402	39.556242784
1208	71016.	15.2	0.1663758107511272	0.0773570995868250	151.952933843
1209	69277.	18.1	0.0328437625942984	0.0140569970210981	26.778310201
1210	51446.	59.0	0.0000000000000000	0.0000000000000000	0.000000000
1211	44329.	84.5	0.0000000000000000	0.0000000000000000	0.000000000
1212	49366.	65.7	0.0000000000000000	0.0000000000000000	0.000000000
ANNUAL			0.3838571527155408	0.1401667666796612	353.714268214

YEAR	LOLH	**LOLE**	puEUEppm	
----	-.--3--6	**-.--3--6**	-.--3--6	
2017	0.255498	**0.100049**	0.676613	note: LOLH/LOLE = ~2.6

ANNUAL LOSS OF LOAD RISK = 9.5%

Total run time = 0h 0m 5s

Case 4: Case 1 + 24 GW wind + 24 GW solar – 13.534 GW fossil fuel generation

```
12062601 0--------10--------20--------30--------40---D----50--------60--------70--------80--------90 GW
12062602 .                              N         D
12062603 .                            N         D
12062604 .                           N         D       D = Demand GW      N = D - Renewables GW
12062605 .                            N        D       N is served by dispatchable generation
12062606 .                             N         D
12062607 .         .         .       N .         .D        .         .         .         .         .
12062608 .                        N                 D
12062609 .                          N                    D
12062610 .                              N                     D
12062611 .                                  N                      D
12062612 .                                      N                       D
12062613 .         .         .         .         .  N      .         .      D  .         .         .
12062614 .                                              N                     D
12062615 .                                                N                     D
12062616 .                                                  N                   D <- 2012 peak demand
12062617 .                                                   N                  D
12062618 .                                                        N             D
12062619 .         .         .         .         .         .       N .        D.         .         .
12062620 .                                                         N       D
12062621 .                                                       N        D
12062622 .                                                  N         D
12062623 .                                            N          D
12062700 .                                       N          D
12062701 0--------10--------20--------30--------40------D-50--------60--------70--------80--------90 GW
```

NUCL BASE: 13.064% OF SYS ENGY   100.000% CAP FACT   5150. MW PMAX

RENEWABLE: 37.569% OF SYS ENGY   0.924% OF RENEWABLE ENERGY LOST   (Renewables > Demand)

RENEWABLE: -0.347% OF SYS ENGY LOST

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521441. GWH   50.286% OF SYS ENGY IS NON FOSSIL   **(wind and solar are about maxed out at 48 GW)**

515507. GWH   49.714% OF SYS ENGY IS FOSSIL FUELS

1036948. GWH 100.000% TOTAL   (3 years)

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LOAD RAMP UP   319 MW/MIN ON   12012218 YYMMDDHH

LOAD RAMP DOWN   237 MW/MIN ON   10021708 YYMMDDHH

MINIMUM DEMAND   -9845 MW   ON   10022812 YYMMDDHH   (Renewables > Demand, and are curtailed)

Case 4 continued

HOUR OF MAXIMUM LOLP EACH YEAR AND CONDITIONS THAT HOUR **(not at system peak demand times)**

YYMMDDHH	DEM D	REN R	D-R-N	FOSSIL	STORMW	STORHR	LOLP
10081020	62572	3266	54156	54156	0	0.000	0.03016909
11082919	64526	6032	53344	53344	0	0.000	0.01477213
12080919	67113	7174	54789	54789	0	0.000	0.06215242

LOAD UNCERTAINTY = 3.0%   WEIGHT = 45.0%

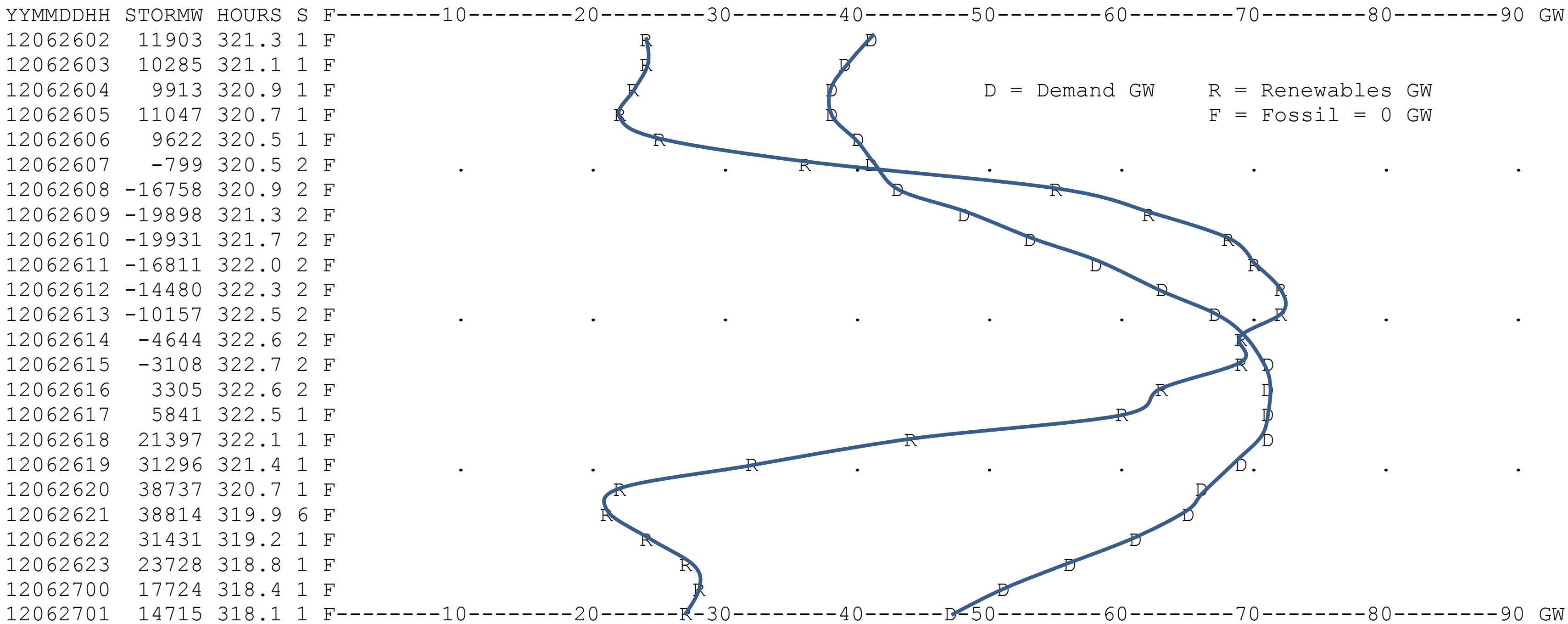
YYMM	MW PKLD	% RESV	LOLH	LOLE	EUE
----	-------	------	-.--3--6--9-12-15-	-.--3--6--9-12-15-	-----.--3--6--9
1201	50525.	93.5	0.0000000000000000	0.0000000000000000	0.000000000
1202	45232.	116.2	0.0000000000000000	0.0000000000000000	0.000000000
1203	45784.	113.6	0.0000000000000000	0.0000000000000000	0.000000000
1204	52147.	87.5	0.0000000000000000	0.0000000000000000	0.000000000
1205	63148.	54.8	0.0000000128790163	0.0000000123584884	0.000005488
1206	**71119.**	**37.5**	0.0435435654598130	0.0309328894353080	37.805938167
1207	70291.	39.1	0.0001894973383422	0.0000041828042186	0.118772470
1208	71016.	37.7	0.1202683555747404	0.0650475284283481	119.789786075
1209	69277.	41.1	0.0008849697198853	0.0008498866206432	0.600635378
1210	51446.	90.0	0.0000000000000000	0.0000000000000000	0.000000000
1211	44329.	120.6	0.0000000000000000	0.0000000000000000	0.000000000
1212	49366.	98.1	0.0000000000000000	0.0000000000000000	0.000000000
ANNUAL			0.1648864009717971	0.0968344996470063	158.315137578

YEAR	LOLH	**LOLE**	puEUEppm	
----	-.--3--6	**-.--3--6**	-.--3--6	
2017	0.158882	**0.100178**	0.410984	note LOLH/LOLE = ~1.6

ANNUAL LOSS OF LOAD RISK = 9.6%

Total run time   =   0h 0m 5s

Case 6: Case 1 + 68 GW wind + 76 GW solar – 69.264 GW fossil (12.523 GW remains) + 50 GW storage for 330 hours (~14 days) to achieve zero fossil fuel generation for 3 yrs



NUCL BASE: 13.064% OF SYS ENGY 100.000% CAP FACT 5150. MW PMAX

RENEWABLE: 110.873% OF SYS ENGY 20.918% OF RENEWABLE ENERGY LOST

RENEWABLE: -23.937% OF SYS ENGY LOST

1036948. GWH 100.000% OF SYS ENGY IS NON FOSSIL

0. GWH 0.000% OF SYS ENGY IS FOSSIL FUELS

1036948. GWH 100.000% TOTAL (3 years)

LOAD RAMP UP 1027 MW/MIN ON 11020718 YYMMDDHH

LOAD RAMP DOWN 939 MW/MIN ON 12030508 YYMMDDHH

MINIMUM DEMAND -44850 MW ON 12122815 YYMMDDHH

STORAGE: 49755 MAXIMUM DISCHARGE (+) MW -50000 MAXIMUM CHARGING (-) MW

16500000 MAXIMUM CHARGE ENERGY MWH 330.0 MAXIMUM CHARGE ENERGY HR 4.7 MINIMUM CHARGE ENERGY HR

Case 6 continued

HOUR OF MAXIMUM LOLP EACH YEAR AND CONDITIONS THAT HOUR

YYMMDDHH	DEM D	REN R	D-R-N	FOSSIL	STORMW	STORHR	LOLP	
10082316	71119	64451	1518	0	1517	125.166	0.00212962	
11080317	71119	83313	-17343	0	-17343	313.951	0.00212962	
12062616	**71119**	**62663**	**3306**	**0**	**3305**	**322.597**	**0.00212962**	**(at peak demand)**

LOAD UNCERTAINTY = 3.0%   WEIGHT = 45.0%

YYMM	MW PKLD	% RESV	LOLH	LOLE	EUE
----	-------	------	-.--3--6--9-12-15-	-.--3--6--9-12-15-	-----.--3--6--9
1201	50525.	112.3	0.0050209684091107	0.0006646800186583	1.868494928
1202	45232.	137.1	0.0038588928223453	0.0003932450696459	1.385491525
1203	45784.	134.2	0.0038108115199510	0.0003501458283600	1.366464995
1204	52147.	105.7	0.0105337971019300	0.0013299077376261	4.287725591
1205	63148.	69.8	0.0480157539491068	0.0070492018490035	22.736217566
1206	**71119.**	**50.8**	0.1548613737441516	0.0205683160181854	77.829189746
1207	70291.	52.6	0.1776233098387205	0.0221505664033504	89.847077963
1208	71016.	51.0	0.2431702558733248	0.0340016997616575	124.283646082
1209	69277.	54.8	0.1019211459306053	0.0157137199790405	50.908014518
1210	51446.	108.5	0.0120873602688904	0.0015580798978239	5.027546567
1211	44329.	141.9	0.0033168730101391	0.0003794574649517	1.171310379
1212	49366.	117.2	0.0076234297710044	0.0008962155702801	2.947375385
ANNUAL			0.7718439722392798	0.1050552355985833	383.658555244

YEAR	LOLH	**LOLE**	puEUEppm	
----	-.--3--6	**-.--3--6**	-.--3--6	
2017	0.746318	**0.100243**	1.074074	now LOLH/LOLE = ~7.5

ANNUAL LOSS OF LOAD RISK = 9.5%

Total run time = 0h 0m 9s

- **What has been learned studying extreme renewables in ERCOT:**
    - Renewable capacity value with respect to dispatchable generation declines as more renewable capacity is added.
    - If renewable capacity is given too high a capacity value, the LOLE results show the reserve margin must be increased to keep reliability.
    - In order for renewables to provide a high percentage of energy, very high MW capacities of renewables are added, so much so that the renewable power is likely to exceed the demand frequently.
    - When renewable power exceeds demand the market clearing price is expected to go to zero or possibly negative.
    - This zero or negative priced power will make it difficult for conventional generation to financially survive, so there is likely to be capacity shortages on the system with high renewables.
    - Capacity shortages during peak demands are likely to drive the market clearing price to new highs without resulting in much new capacity.
    - This volatility will make it difficult to operate the network reliably.

Advantages of the direction calculation procedure:

- Simple raw input data allows studies to proceed with minimal setup effort
- Up to 20 years of historical hourly data for up to 100 renewables sources provides a detailed description of their expected MW performance
- Each run calculates all the reliability indices: LOLE, LOLH, and EUE
- Fast six digit accuracy solutions allow a quick turnaround on studies
- Types of studies that are possible:
  - Reserve margins versus indices
  - Effective Load Carrying Capability or Fossil Fuel capacity of renewables
  - The effectiveness of MW and MWh storage for improving reliability
  - Optimizing the amount of storage needed by a renewable source
  - How to minimize CO2 emissions while maintaining a reliable system
  - Developing alternative plans for meeting CO2 reduction goals
  - Studying simple and complex transmission constraints