A Direct High Speed Calculation Procedure For Determining LOLE, LOLH, and EUE For Fossil, Wind, and Solar Generation With A Suggested Procedure For Also Including Transmission Constraints

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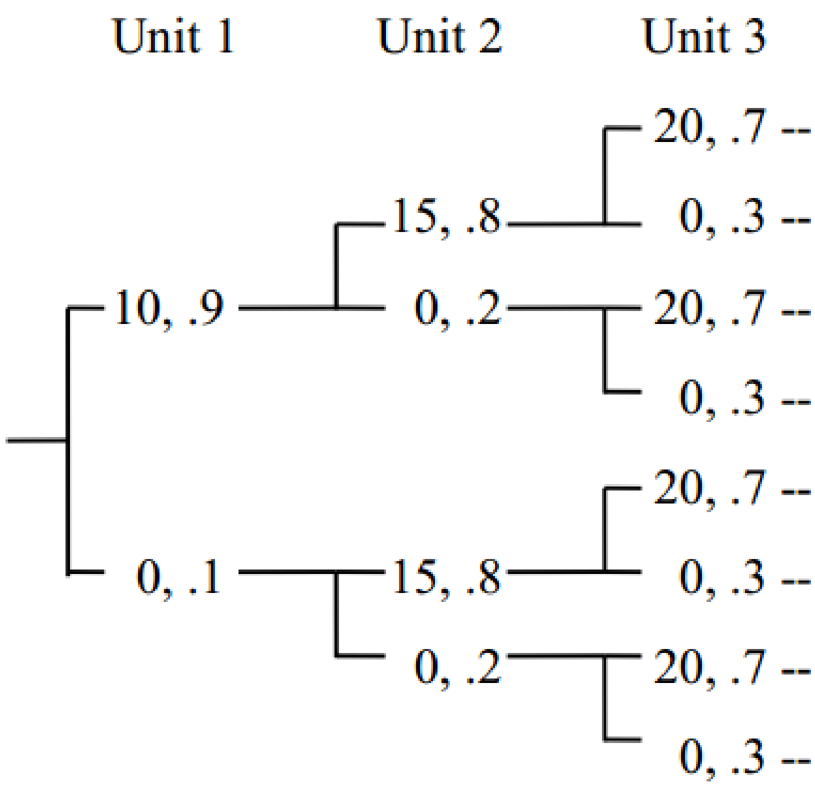
Background:

- **ERCOT studies in 80's and 90's using NARP (N Area Reliability Program):**
  - Small model in which each node represented a major load center
  - Each link between node areas represented multiple "tie" lines
  - Monte Carlo simulated generator outage and derated states
  - Indices collected only after a huge number of iterations
- **Problems with NARP:**
  - Difficulty in making the small equivalent network represent the system
  - Long run times; Stable indices only after a huge number of iterations
  - Transmission constraints were nil for ERCOT's very reliable system
- **The above problems were the motivation for a better solution model:**
  - This resulted in a new method and a PhD http://egpreston.com/bookmod.pdf
  - The direct calculation method is locked in with a binary tree approach
  - The binary tree suggests a way to set up a large transmission model
  - Because the binary tree grows exponentially with system size, the Booth-Baleriaux method is used to linearize and speed up the solution

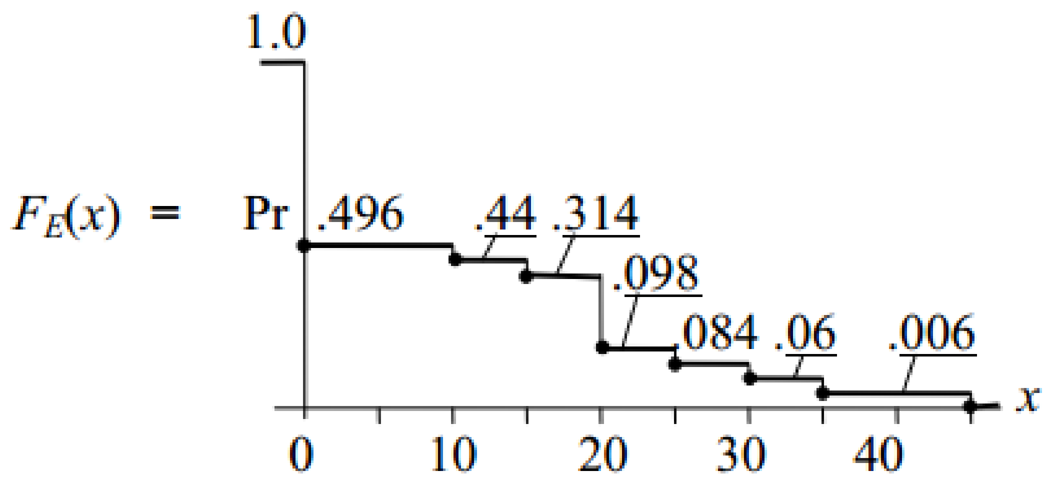
Let's begin with the concept of a binary tree:



Individual States				Cumulative		
MW Pr	MWO		MWO	Pr	ΣPr
45, .504	0		0	.504	1.000
25, .216	20		10	.056	.496
30, .126	15		15	.126	.440
10, .054	35	sort →	20	.216	.314
35, .056	10		25	.014	.098
15, .024	30		30	.024	.084
20, .014	25		35	.054	.060
0, .006	45		45	.006	.006

- For all generators, sum each branch's power and multiply the probabilities.
- Sort the MW's and then sum the probabilities for the cumulative Pr curve.

- **Graphing the cumulative probabilities Pr (the $F_E(x)$ curve) versus x MW:**



$F_E(x)$ = Probability More Than x MW Of Generation Will Be Out Of Service

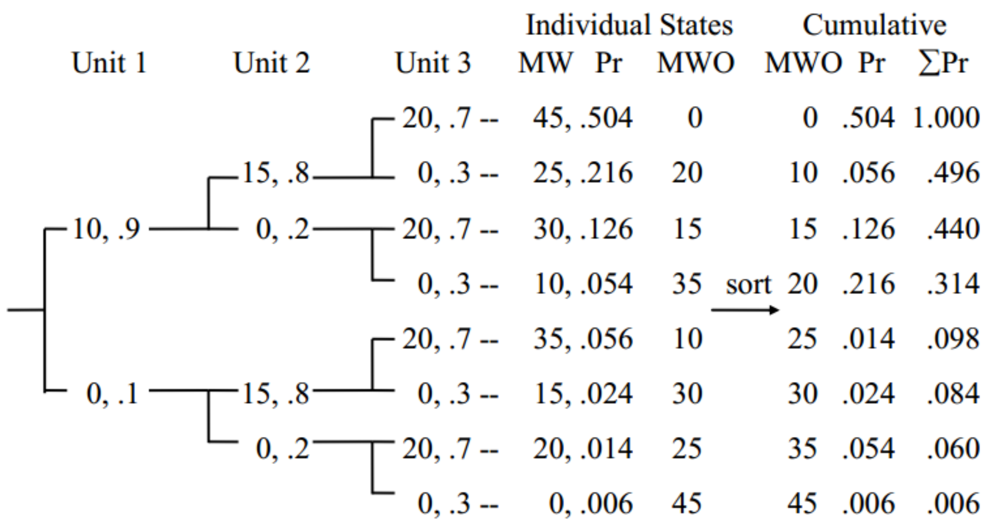
Building $F_E(x)$ directly without creating the binary tree:

- To add a generator i with P_i MW and FOR_i, multiply F_E times ($1-FOR_i$) and also multiply F_E times FOR_i. Now shift the FOR_i curve to the right by P_i and then add the two curves together to create a new F_E curve.
- This process produces exactly the same F_E as the binary tree approach.

- The solution time is ~linear as each generator is successively added.
- If generators are in 1 MW sizes and the F_E is a table of 1 MW increments, then the F_E curve is an exact solution for any system size.
- To use the F_E table for a certain load level x_L, look up the F_E probability of insufficient generation for x_L = (sum of all gen Pmax) – MW load level L.
- Then the LOLH (loss of load hours) is the sum of these hourly probabilities for a year. Consider that each probability is a fraction of an hour.
- The LOLE (loss of load expectation) is the sum of these probabilities using only the peak load hour each day (0.1 is the historical planning target).
- Finally, the EUE (expected unserved energy) of each hour is the integral under the F_E curve from the x_L value to the far right of the F_E curve which quickly drops to zero. Sum these energies for all hours in a year.

Note that this process only works for conventional generation. Modeling renewables requires they be handled differently than as generators.

To add transmission to this model, consider the binary tree again:



- Model each of the ‘states’ above as a separate load flow solution.
- Set the generators at either their Pmax or 0 MW depending on the ‘states’.
- Use the load level as the MW slack variable and solve each load flow.
- The load flow can model N-0, N-1, N-2 line outages for each ‘state’ above.
- These line outage states also have their own forced outage probabilities.
- Solutions curtailing generation is more loss of load shifting F_E to the right.

Modeling transmission probabilistic flows without building the binary tree:

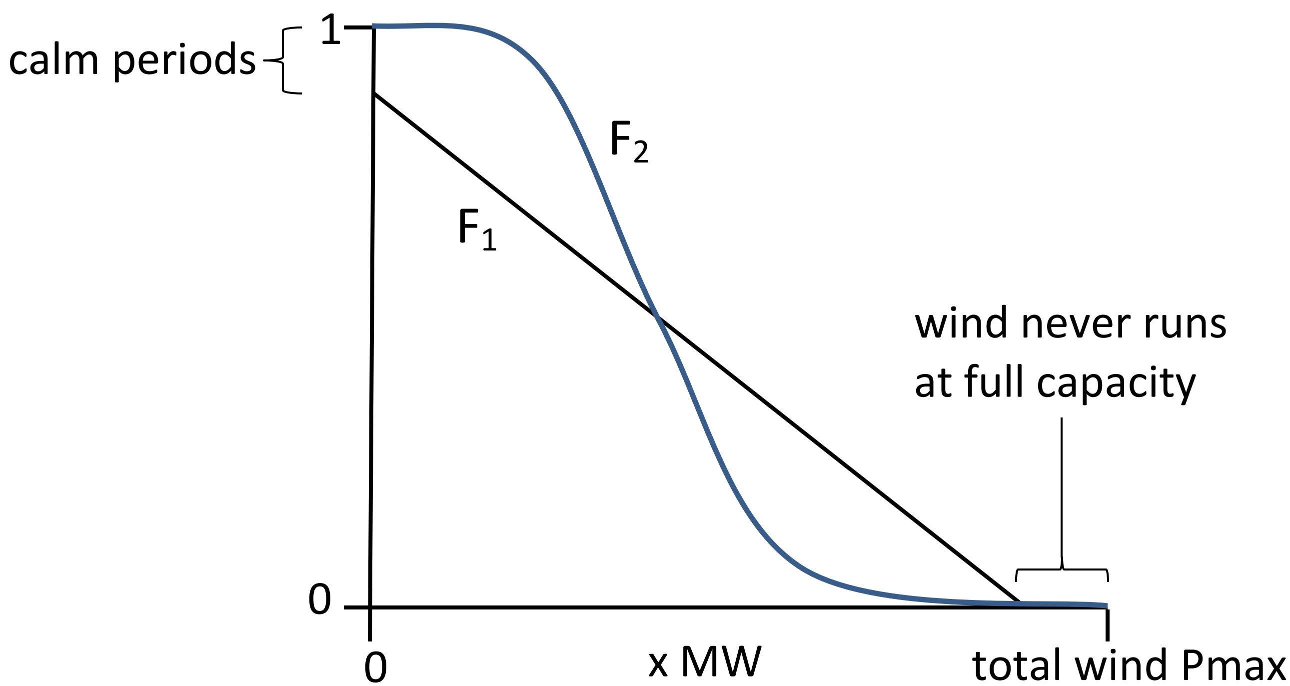
- Build a load flow case with some generators at Pmax and others off line.
- We select a few lines as flow gates to monitor.
- The initial base case has a MW flow on our flow gate lines.
- We run a set of load flows in which each generator is either put on line or taken off and note the incremental change in flow on each flowgate line.
- Using the convolution process described on page 4, the i_{th} generator incremental flow uses the generator FOR_i and 1-FOR_i to shift and sum the two curves. As generators are added, a line flow distribution appears.
- The line flow distribution may extend beyond the line rating(s).
- If the line is overloaded probabilistically, then the generation harmers will have to be reduced in output to remove the overload.
- The process for unloading these probabilistic overloads is too complicated to describe here, but is covered in detail in my dissertation.
- The unloading of line overloads shifts the F_E curve to the right resulting in higher LOLH, higher LOLE, and higher EUE.

Estimating transmission FOR without collecting individual line stats:

- For a large system with many lines, observe the actual lines outaged at times when all lines should be in service (summer peak for ERCOT).
- 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 that the model agrees with what is being observed in the system as far as totals are concerned.
- This process can be used to check GADS data to see if your computer program agrees with what is happening to generators in the system for the total MW generation out of service as well as the number of generators out of service at a time when they should all be in service.
- This process might not be valid if the system has more generation and/or transmission capacity than is needed during peak load periods. This is certainly not the case in ERCOT.

Modeling wind and solar interruptible sources of power:

- The ERCOT annual wind curve $F_1(x)$=Pr[x MW is available] is almost linear.



- If wind farms are treated as generators and convolved together, then the capacity duration curve F_2 appears as shown. F_2 should match F_1.
- This error is caused because wind farm MW outputs are not independent.
- To overcome this problem we <u>must</u> treat wind as an hourly load reducer.

Modeling wind and solar power:

- Collect several historical years of hourly MW loads and wind MW data.
- If possible, collect the wind and solar data as separate geographic regions.
- Scale the load levels and renewables data to match the future test year.
- Create a net hourly load by subtracting renewable MWs from system load.
- Apply storage devices to the net load for further net load smoothing.
- Calculate the reliability indices for the net load as described on page 5.

Calculating the ELCC (effective load carrying capability) of renewables:

- Set up a load level with no wind or solar to produce an LOLE=0.1
- Add 1000 MW wind (large system) and increase the load to get LOLE=0.1
- The per unit ELCC is the increased load divided by 1000 MW.
- Now put in all the renewables in the base case and repeat these steps.
- Note the ELCC is quite a bit lower for the same wind addition. Why?

- Answer - If the first wind farms reduce peak loads, those loads may no longer be peak loads. As more and more renewables are added, the load hours not served well by renewables tend to dominate the LOLE and LOLH.

- The sample reliability indices listed below uses 2013 hourly loads, 2017 ERCOT non-wind generation, and adjusts all FORs to achieve an LOLE=0.1

```
LOAD UNCERTAINTY = 2.3%   WEIGHT = 25.0%       (all 2010 - 2013 hours are modeled)
YYMM   MW PKLD   % RESV         LOLH                   LOLE                  EUE
----   -------   ------   -.--3--6--9-12-15-   -.--3--6--9-12-15-   -----.--3--6--9
1301     54144.     51.1   0.0000000000000000   0.0000000000000000        0.000000000
1302     43922.     86.2   0.0000000000000000   0.0000000000000000        0.000000000
1303     44722.     82.9   0.0000000000000000   0.0000000000000000        0.000000000
1304     48148.     69.9   0.0000000000000000   0.0000000000000000        0.000000000
1305     59481.     37.5   0.0000000000126446   0.0000000000000386        0.000000005
1306     68270.     19.8   0.0044330368963651   0.0020388305070055        2.942775435
1307     68789.     18.9   0.0051878011356770   0.0006365372365713        3.512532267
1308     71119.     15.0   0.1668168141327948   0.0704421467421531      138.746259650
1309     67095.     21.9   0.0005476891084150   0.0002488518203859        0.329354606
1310     57787.     41.5   0.0000000000001692   0.0000000000000916        0.000000000
1311     49732.     64.5   0.0000000000000000   0.0000000000000000        0.000000000
1312     57286.     42.8   0.0000000000000114   0.0000000000000112        0.000000000
ANNUAL                     0.1769853412860772   0.0733663663062573      145.530921963
                                                           puEUEppm       0.414555423
 LOAD UNCERTAINTY = 2.3%
 YEAR       LOLH          LOLE        puEUEppm
 ----      -.--3--6      -.--3--6      -.--3--6
 2017      0.247359      0.100005      0.590091   <- FOR adjusted to achieve LOLE=0.1


Total run time        =   0h  0m  4s
```

The ERCOT 2017 system for integration of large amounts of wind and storage:

- Case 1 - no wind, 81787 MW conventional generation, peak demand set to 71119 MW (15% reserve), FOR of .077263 results in an LOLE = 0.1
- Case 1C – Coastal wind ELCC found to be 50.6%
- Case 1P – Panhandle wind ELCC found to be 27.1%
- Case 1W – West Texas wind ELCC found to be 9.8%
- Case 1F – non-nuclear, i.e. fossil generation ELCC found to be 88%
- Case 2 – add 18495 MW wind, 10600 WTx, 2380 coastal, 5515 Panhandle, scale down fossil generation by 4.145% or 3177 MW to get an LOLE = 0.1
- Case 2C – Coastal wind ELCC found to be 27.3%
- Case 2P – Panhandle wind ELCC found to be 13.3%
- Case 2W – West Texas wind ELCC found to be 5.1%
- Case 2B – add 10 GW batteries, 8 hours storage (at 10 GW) allows fossil generation to be reduced by an additional 10362 MW for an LOLE of 0.1

Here is the 2013 historical hourly data scaled to 2017 with 10 GW storage:

```
D=DEMAND GW    N=D-RENEWABLES GW    A=STORAGE SMOOTHED N GW    S=STORAGE GW   H=STORAGE HRS.
YYMMDDHH-20       -10        0         10        20        30        40        50        60        70        80 GW
13080701 0---------1-S-----H-2---------3---------4---------5-------N-6---AD--|-7---------8---------9---------10 HR
13080702           S         .      H                          N        A    |
13080703           S         .               H                N       D A    |
13080704          S          .                         H      N      D  A    |
13080705           S         .                                 N H   D  A    |
13080706            S        .                                   N     D H   |
13080707 .         . S       .         .         .         .      N  .  DA   | .H        .         .         .
13080708              S      .                                      N     A  |        H
13080709                  S  .                                          N A D |         H   10,000 MW STORAGE 8 HRS
13080710                    S.                                             A  | D       H  <=STORAGE IS CHARGED UP
13080711                     S                                                |AN    D H
13080712                     .  S                                             |  AH  N  D
13080713 .         .         .     S   .         .         .         .     H  |.   A     .N D      .         .
13080714                     .       S                            H           |     A        N  D
13080715                     .        S                 H                      |    A         N   D
13080716                     .        S       H                                |    A         N    D -ANNUAL PEAK
13080717                     .       H                                         |    A         N    D
13080718                     H      S                                          |   A       N      D
13080719 .         .   H     .    S    .         .         .         .         |  A     N.      D  .         .
13080720          H          .   S                                             |  A    N     D
13080721      H              .  S                                              | A   N     D
13080722    H  STORAGE       .S                                                |A N    D
13080723    H<=DISCHARGED  S .                                                A|   D
13080800-20      H-10   S    0         10        20        30        40 N   A D|0        60        70        80 GW
13080801 0---------1--SH-----2---------3---------4---------5---------6N---DA---|---------8---------9---------10 HR
```

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 include:
  - Reserve margins versus indices
  - ELCC of wind, solar, and other renewable sources
  - 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