A Mathematical Procedure For Finding Exact Hourly LOLPs (Loss of Load Probability) For Large Electric Grids.

by

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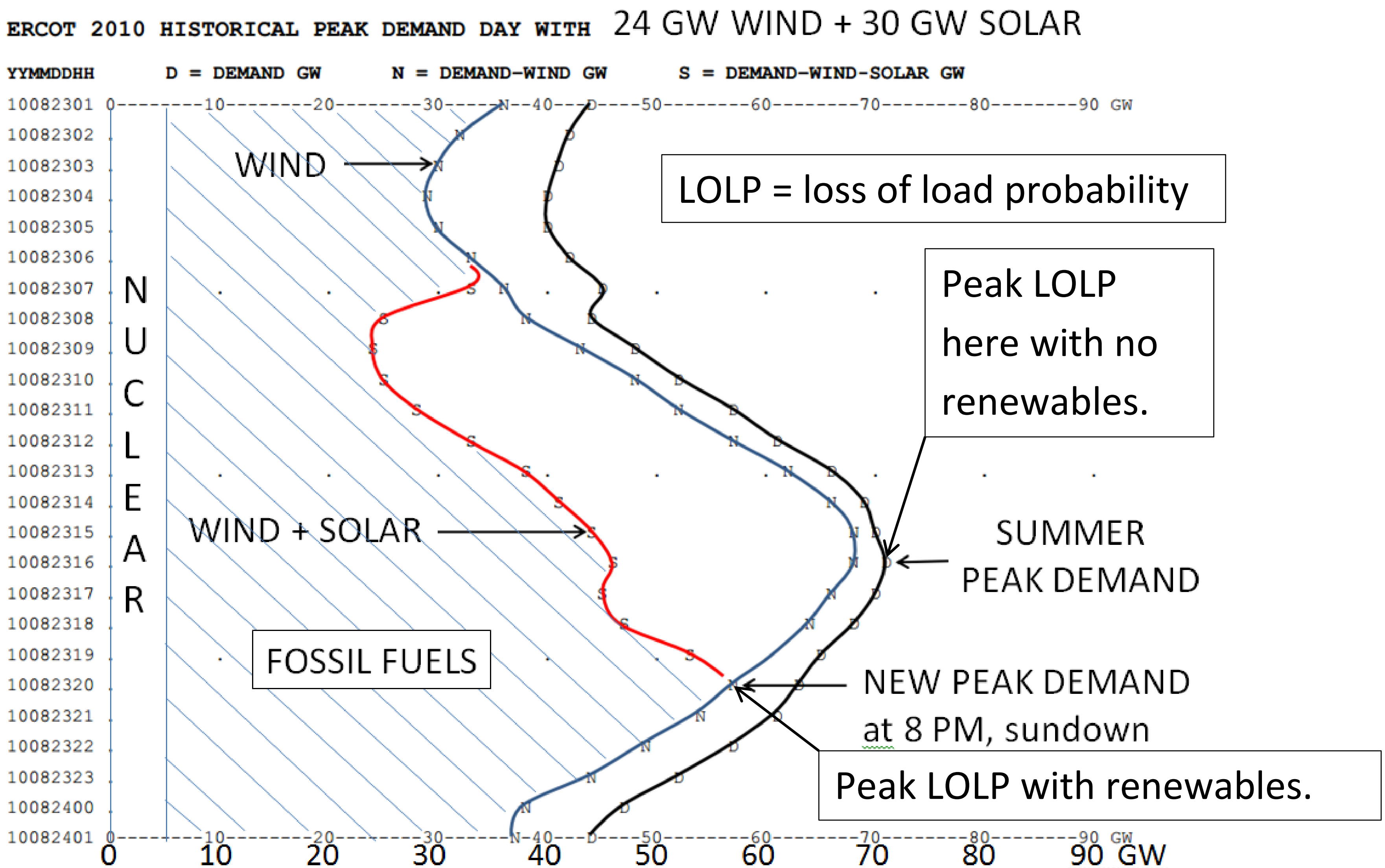
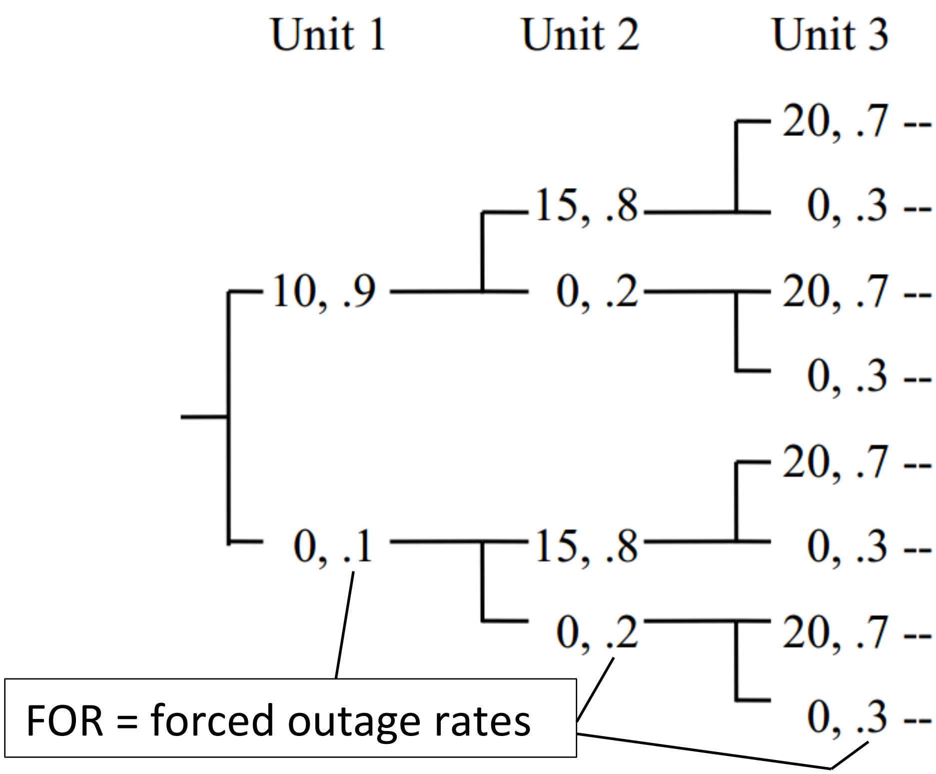
The electric load of a system like ERCOT (Electric Reliability Council Of Texas) varies all the time. The load peaks in the summer months due to a large air conditioning load. Right now the summer peak demand is about 70,000 MW. The graph below shows the hourly profile of the 2010 historical year scaled to have a 70 GW peak.



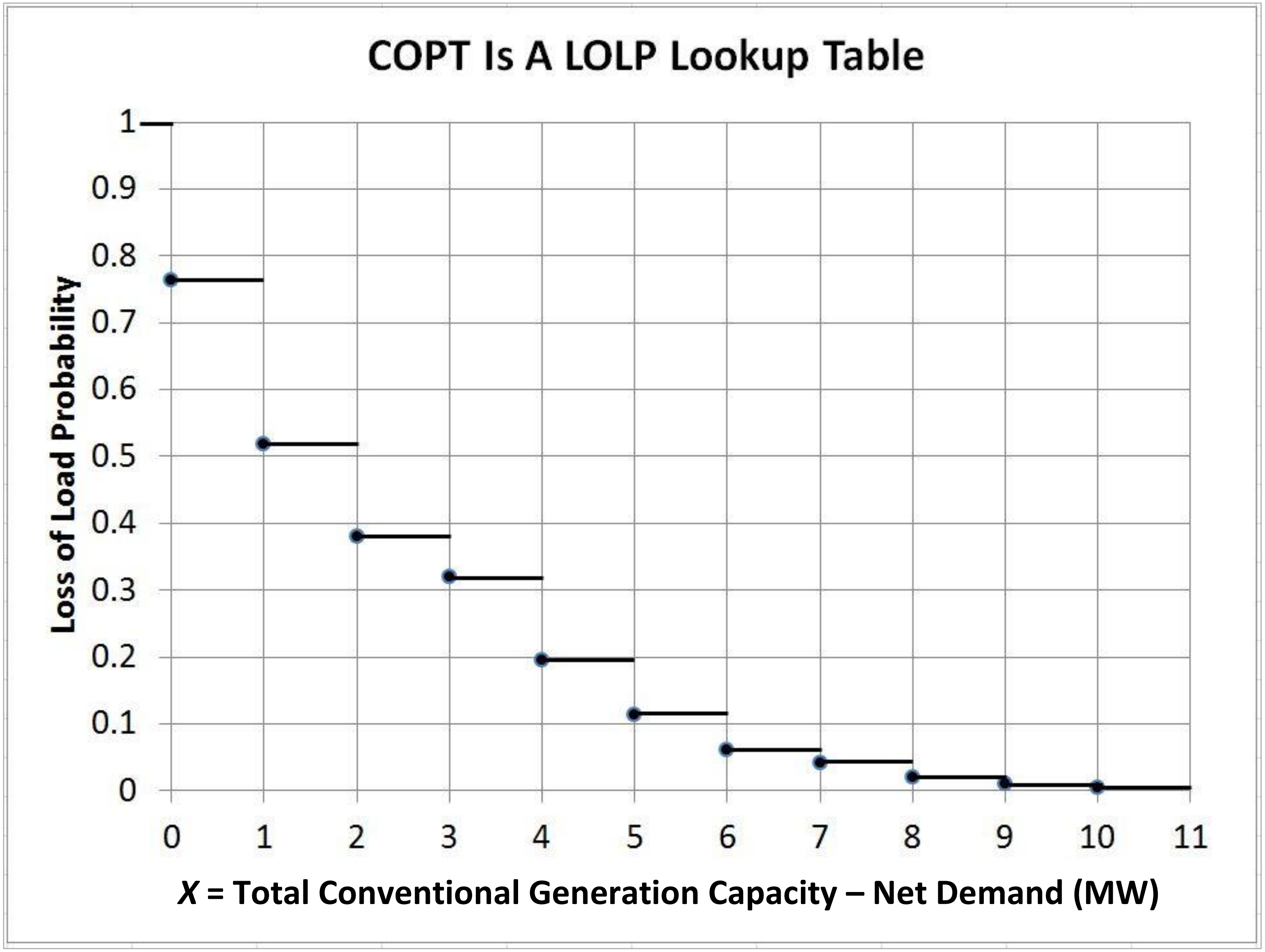
Generators are not 100% reliable. They are constantly failing and being repaired. An example with three generators of capacity 10, 15, and 20 MW with outage probabilities of 0.1, 0.2, and 0.3 shown as a binary tree of all combinations of 'up' and 'down' states:



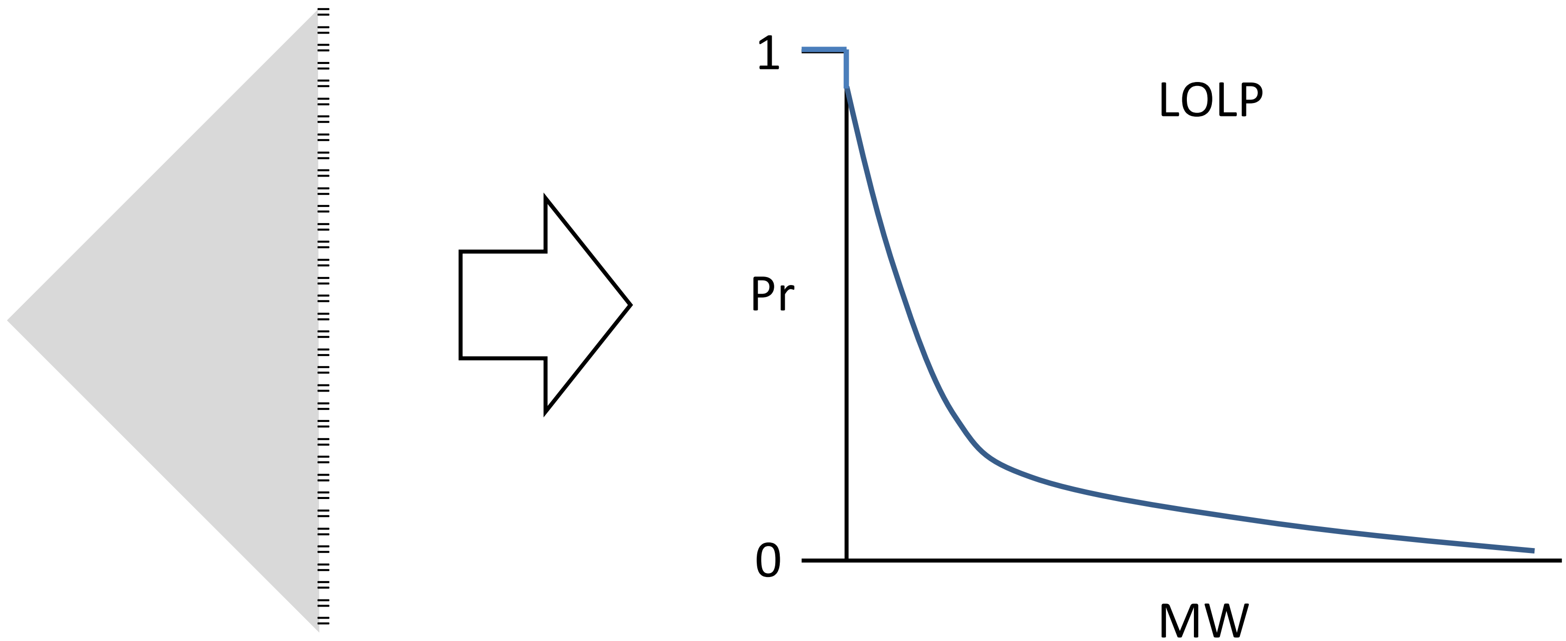
Individual States				Cumulative		
MW, Pr	MWO			MWO	Pr	∑Pr
45, .504	0			0	.504	1.000
25, .216	20			10	.056	.496
30, .126	15			15	.126	.440
10, .054	35	sort →		20	.216	.314
35, .056	10			25	.014	.098
15, .024	30			30	.024	.084
20, .014	25			35	.054	.060
0, .006	45			45	.006	.006

The sum of units 'up' is the MW column. The probabilities are multiplied to the ends of each branch. The sum of all probabilities is 1. The MWO (megawatts outaged) is the 45 MW total minus the MW available. The MWO can be sorted in ascending order along with the branch probabilities. Summing the branch probabilities creates a distribution.

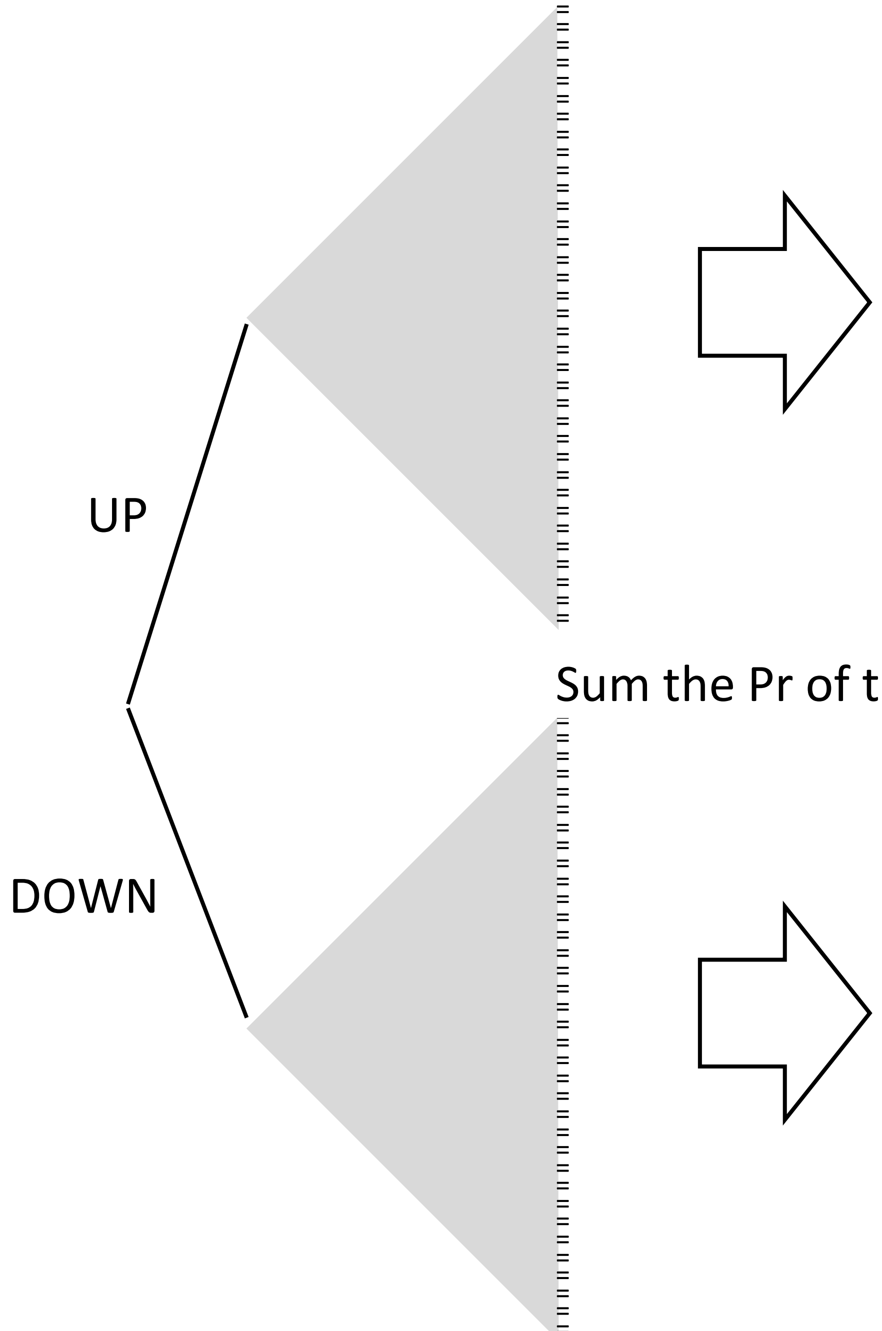
When we plot this distribution, which we call the COPT, or capacity outage probability table, we need to interpret it this way: (note - the points below are not from the above table)

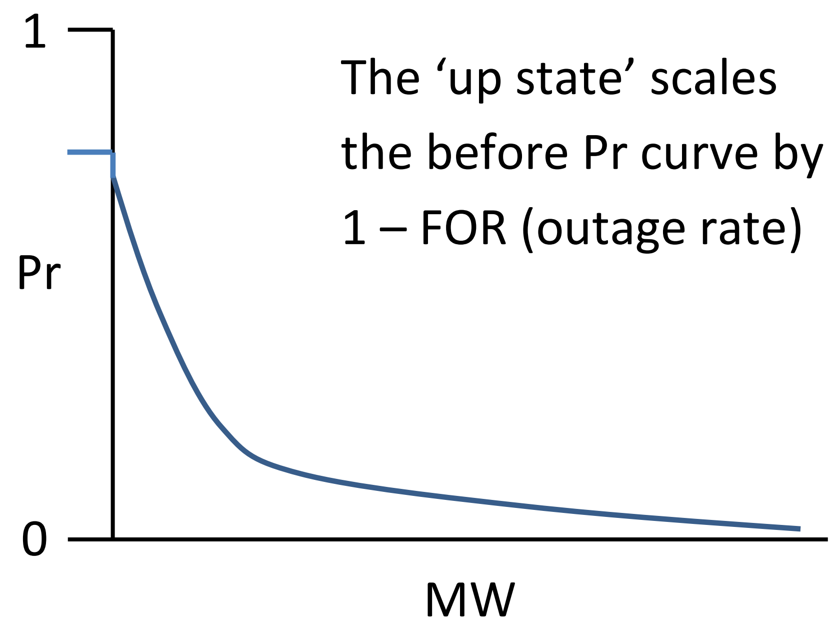


The binary tree MW and probabilities are shown mapped to a cumulative distribution.



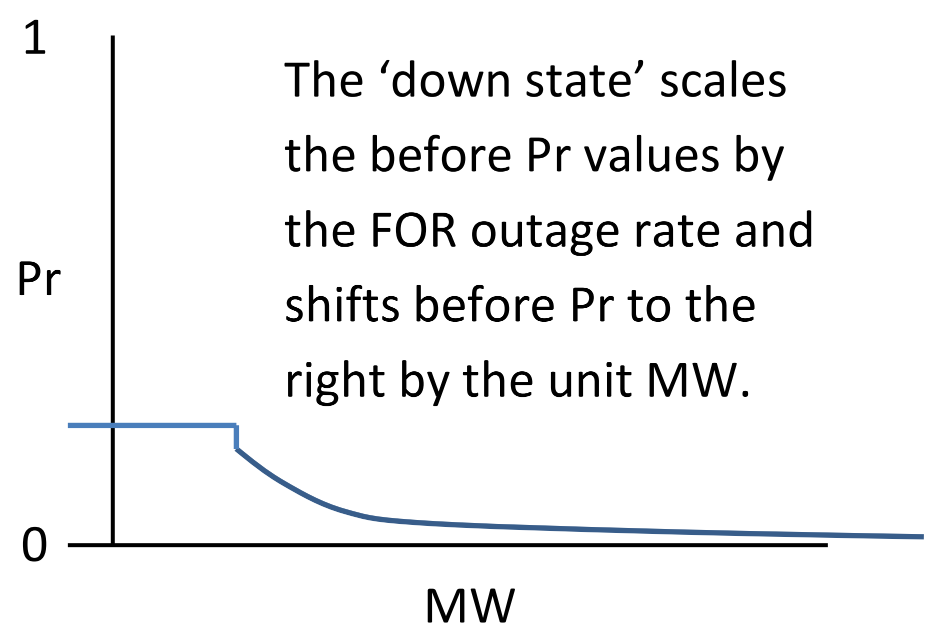
Now we can easily add one more generator to the left of the binary tree and this causes two new trees to be formed and two new LOLP curves to be formed.



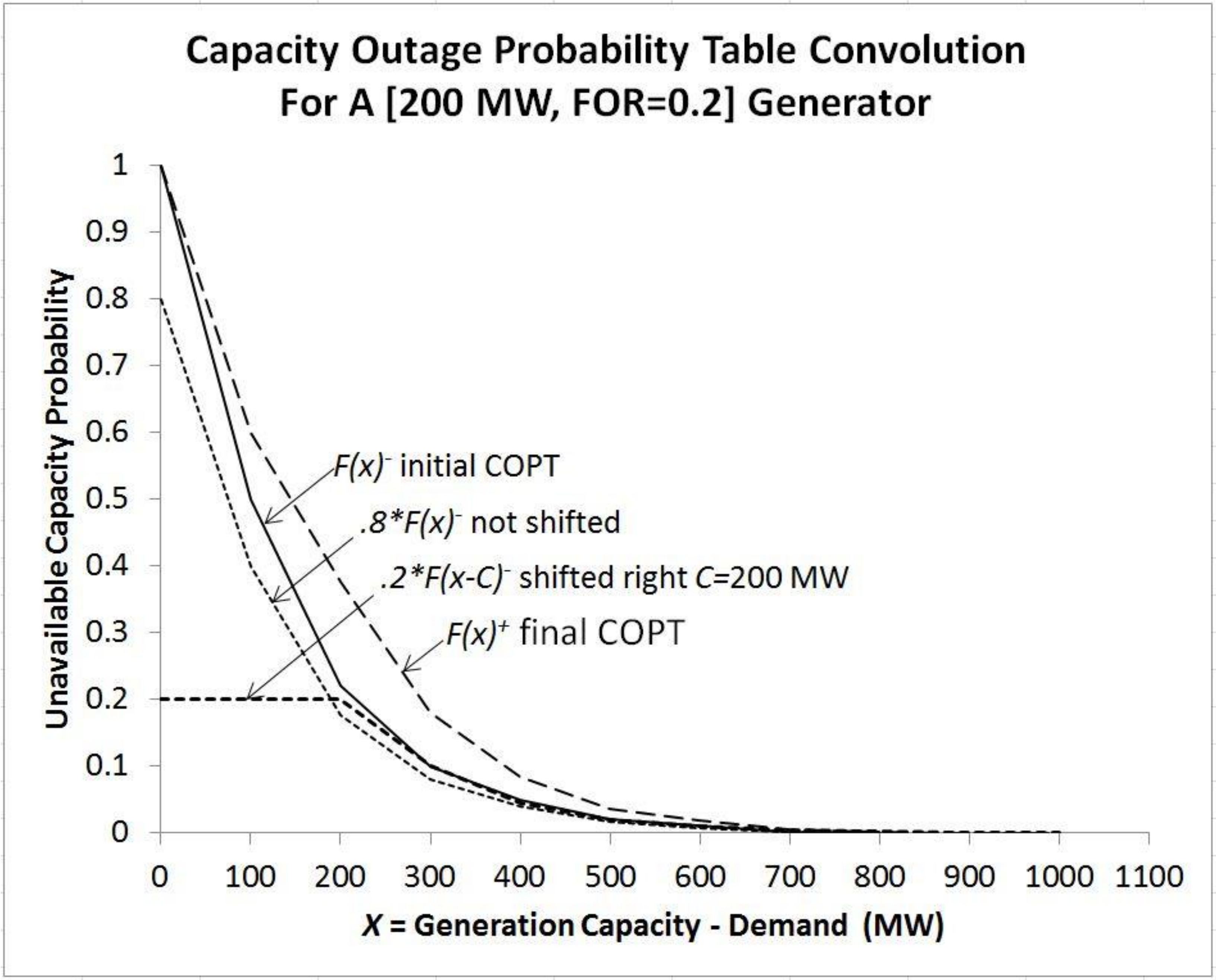


The ‘up state’ scales the before Pr curve by 1 – FOR (outage rate)

Sum the Pr of these two curves to create an ‘after’ Pr curve.



The ‘down state’ scales the before Pr values by the FOR outage rate and shifts before Pr to the right by the unit MW.



$$[F(x)^{+} = (1 - FOR_k) \cdot F(x)^{-} + FOR_k \cdot F(x - C_k)^{-}] \ \forall \ x = 0, x_{max}$$

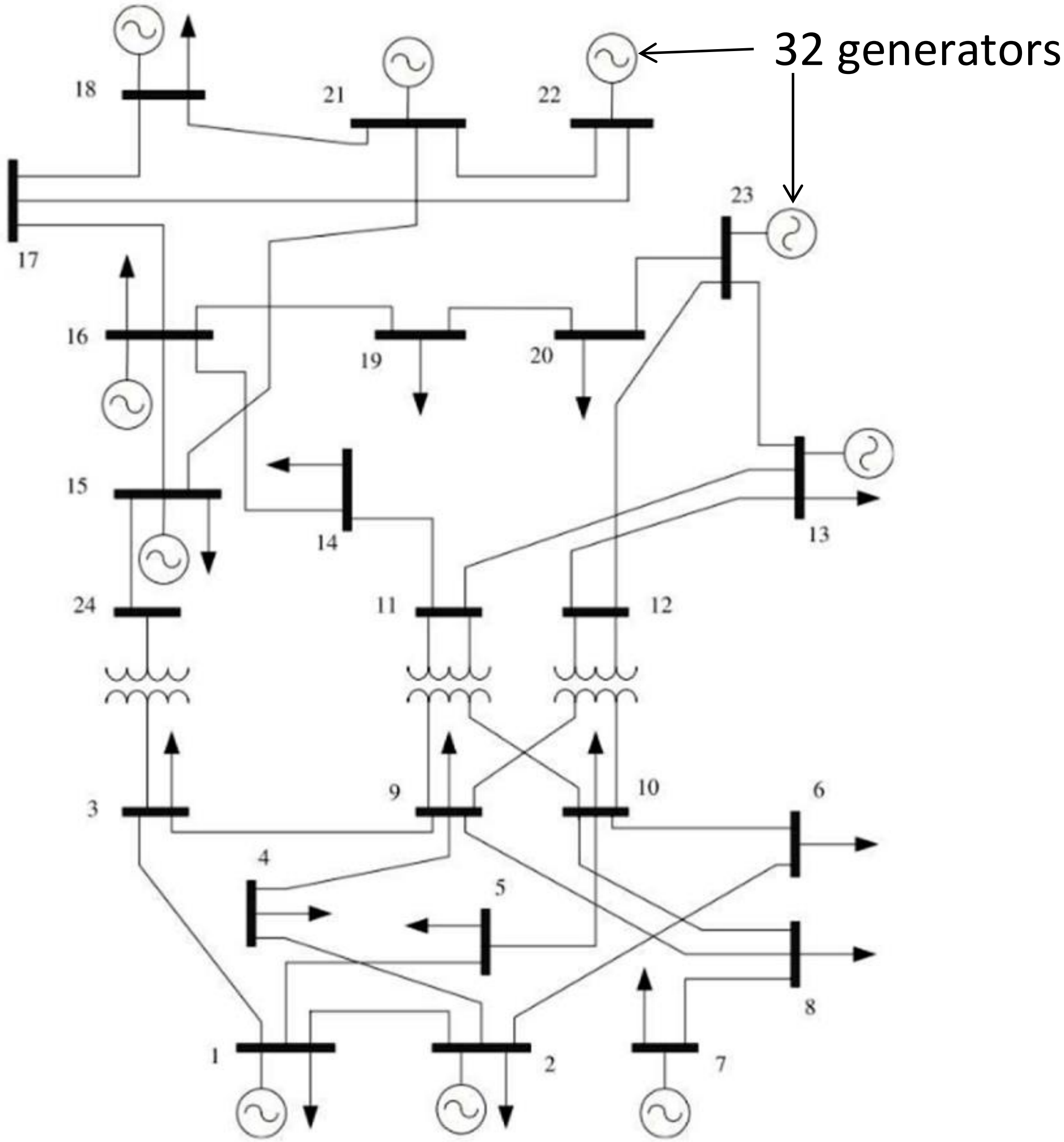
Once the COPT is created, the indices LOLE (loss of load expectation), LOLH (loss of load hours), and EUE (expected unserved energy) are calculated directly from the LOLPs:

LOLE = ∑ daily maximum LOLPs for a year (days/year)

LOLH = ∑ hourly LOLPs for a year (hours/year)

EUE = ∑ integral of all LOLP×MW from net MW demand down to 0 MW every hour (MWh)

IEEE 1979 RTS (Reliability Test System)



COPT Array Size Is Small and Execution Speed Is High

- The 1979 RTS tree was large; 32 generators 2^{32} > 4 billion states.
- The 1979 RTS COPT size in RTS3 “exact” LOLPs is 2652 numbers.
- COPT saves space by use of integer 1 or .1 MW grid increments.

- The 1996 RTS tree was larger; 96 generators $2^{96} > 10^{28}$ states.
- The 1996 RTS COPT size in RTS3 “exact” LOLPs is 5156 numbers.

- The ERCOT system with 380 generators COPT is 16296 numbers.
- The CAISO system with 530 generators COPT is 26961 numbers.
- Creation of COPT uses linear arrays which are efficiently executed.
- Once COPT is created, LOLP becomes a simple lookup (no math).

- RTS3 generator data looks like:

```
PMAX ,RM%, FOR, DER,DMW,  BU#,GENERATORNAM,TP,
  :    :    :    :   :     :        :
 155.,100,.040,.000, 0.,  115,ARTHUR_Coal3,ST,
 155.,100,.040,.000, 0.,  116,ASSER__Coal1,ST,
 355.,100,.033,.000, 0.,  118,ASTOR__NG__1,CC,
 400.,100,.120,.000, 0.,  121,ATLEE__Nucl1,NU,
 155.,100,.040,.000, 0.,  123,AUSTEN_Coal2,ST,
 350.,100,.080,.000, 0.,  123,AUSTEN_Coal3,ST,
  :    :    :    :   :     :        :
```

- RTS3 hourly data looks like:

```
YYYYMMDDHH,D, DEMAND, HYDRO,    WIND,   SOLAR,  SOLARR(rooftop),
2020010101,4,0.40740,0.1842,0.850074,0.000000,0.000000,
2020010102,4,0.39809,0.1990,0.909606,0.000000,0.000000,
2020010103,4,0.39639,0.1638,0.843176,0.000000,0.000000,
2020010104,4,0.39852,0.1678,0.819610,0.000000,0.000000,
2020010105,4,0.41540,0.1626,0.796922,0.000000,0.000000,
2020010106,4,0.44828,0.1410,0.773835,0.000000,0.000000,
2020010107,4,0.48201,0.1506,0.681646,0.000000,0.000000,
2020010108,4,0.48668,0.2886,0.541848,0.416726,0.145686,
2020010109,4,0.48862,0.2514,0.464612,0.600515,0.365249,
2020010110,4,0.49224,0.3386,0.309143,0.671727,0.531686,
2020010111,4,0.49111,0.3506,0.169146,0.703056,0.635784,
```

- RTS3 program results versus the 1986 paper results.

1979 Base Case = 2850 MW Load,
3405 MW Total Generation, LFU=0

	1986 Paper	RTS3 Program
LOLE =	**1.36886** d/y	**1.368863** d/y
LOLH =	**9.39418** h/y	**9.394175** h/y
EUE =	**1176** MWh	**1176** MWh

1979 Base Case with 3 State Gens

	1986 Paper	RTS3 Program
LOLE =	**0.88258** d/y	**0.882573** d/y

1979 Base Case with 2% LFU

	1986 Paper	RTS3 Program
LOLE =	**1.45110** d/y	**1.451109** d/y

1979 Base Case with 10% LFU

	1986 Paper	RTS3 Program
LOLE =	**3.99763** d/y	**3.986904** d/y

1979 Base Case, Demand = 2394 MW

	1986 Paper	RTS3 Program
LOLE =	**0.04756** d/y	**0.047559** d/y

1979 Base Case, Demand = 3135 MW

	1986 Paper	RTS3 Program
LOLE =	**6.68051** d/y	**6.680512** d/y

1979 Base Case with 5% LFU

	1986 Paper	RTS3 Program
LOLE =	**1.91130** d/y	**1.911295** d/y

1979 Base Case with 15% LFU

	1986 Paper	RTS3 Program
LOLE =	**9.50630** d/y	**8.205766** d/y

- RTS3 program results for two RTS 2020 cases, both with LOLE = 0.1 d/y.

2020 RTS has three areas that individually peak at 2850 MW. The coincident peak demand is 8191.8 MW. The cases have 8076 MW conventional generation and 1000 MW of hydro. In the first 2020 Model RTS case the LFU = 0%, wind is 810 MW, and 500 MW solar is split between rooftop and tracking PV.

```
Indices for a  0.00% LFU:
LOLE       =   0.100005 d/y
LOLH       =   0.236470 h/y
EUE MWh    =        37. MWh
EUE ppm    =       0.98 pu ppm
LOLP>.0004=         117 hrs
```

A second RTS case is run that utilizes VER capacities of 2508 MW wind and 2716 MW solar. The LFU is increased to 7.68% to achieve LOLE = 0.1 d/y.

```
Indices for a  7.68% LFU:
LOLE       =   0.100048 d/y
LOLH       =   0.282378 h/y
EUE MWh    =        58. MWh
EUE ppm    =       1.54 pu ppm
LOLP>.0004=         168 hrs
```

```
GDATA File: G2020.TXT   <- NREL 2020 RTS generator data with wind and solar on Github
HDATA File: H2020.txt   <- NREL 2020 RTS hourly file with wind and solar on Github

2020 IEEE RTS  8192 MW load  8076 MW conventional generation with 1000 MW hydro 810 MW wind 500 MW solar.
2020 IEEE RTS hourly demand wind hydro and solar profiles created from https://github.com/GridMod/RTS-GMLC

MAX GENR   =       8076 MW
VARBL RES =        1043 MW
GENR+VRES =        9119 MW
MAX COPT   =       4524 (90000 MAX)

2020 RESULTS:
PERIOD     =       8784 HOURS
PEAK DEMD =    8191.800 MW
RESERVE    =       11.3 %
LOAD ENGY =      37656. GWh
LOAD FACT =      52.331 %
PEAK NETD =    7017.141 MW (DEMD-VR)
VR E USED =       7457. GWh
VR E LOST =          0. GWh
Indices for a  0.00% LFU:
LOLE(AM)   =   0.000000 d/y
LOLE(PM)   =   0.100005 d/y
LOLE       =   0.100005 d/y
LOLEV **   =   0.100005 events/y
LOLEMW     =       156. MW
LOLH       =   0.236470 h/y
LOLH/event=    2.364584 h/event
EUE MWh    =        37. MWh
EUE ppm    =       0.98 pu ppm
EUE %      =   0.000098 %
LOLP>1.E-4=         117 hrs

Variable Resource Capacity Credits
Max Net Demand hrs for LOLP>1.E-4:

 76.6%   9.3%  43.1%  37.6%

** LOLE  measures events/24 hrs
   LOLEV measures events/12 hrs
```

2020 NREL RTS3 Update Adding Wind and Solar NREL Project Overview:

https://github.com/GridMod/RTS-GMLC/blob/master/RTS-GMLC.pdf

2020 NREL RTS3 program code and data:

https://github.com/GridMod/RTS-GMLC/tree/master/RTS_Data/FormattedData/RELIABILITY

RTS3 program (with a new storage model):

http://egpreston.com/RTS3S.zip

- RTS3 automatically finds a demand to achieve a desired LOLE:

```
GENERATOR DATA FILE NAME:  G20
TARGET LOLE (OR RETURN):   1.0 (desired LOLE)
 RTS3 is executing...
 calculating the COPT
 LOLE d/y  MW Demand     Upper MW     Lower MW
30.199082   9999.000     9999.000     0.000000
 0.000000   4999.500     9999.000     4999.500
 0.001158   7499.250     9999.000     7499.250
 1.397416   8749.125     8749.125     7499.250
 0.068313   8124.188     8749.125     8124.188
 0.349934   8436.656     8749.125     8436.656
 0.747597   8592.891     8749.125     8592.891
 1.021407   8671.008     8671.008     8592.891
 0.869544   8631.949     8671.008     8631.949
 0.942400   8651.479     8671.008     8651.479
 0.980704   8661.243     8671.008     8661.243
 1.002307   8666.125     8666.125     8661.243
 0.989530   8663.684     8666.125     8663.684
 0.994424   8664.905     8666.125     8664.905
 0.995016   8665.515     8666.125     8665.515
 1.000506   8665.820     8665.820     8665.515
 1.000449   8665.668     8665.668     8665.515
 0.995484   8665.591     8665.668     8665.591
 0.995484   8665.630     8665.668     8665.630
 0.995484   8665.649     8665.668     8665.649
 0.995484   8665.658     8665.668     8665.658
 1.000449   8665.663     8665.663     8665.658
 1.000449   8665.663     8665.663     8665.658 < finished in 8 sec
 LOLE~=1    8198.8 was the LOLE = 0.1 d/y load.
```