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# GRID OPTIMIZATION (GO) COMPETITION

## Analysis of GO Competition Challenge 1 Final Event Problem Difficulty

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# Dick O'Neill's seminal influence on the Grid Optimization (GO) Competition

- ▶ June 2, 2010 (personal notes)  
Day 1 highlights  
Richard O'Neill (FERC): Rule of thumb: "A one percent improvement saves \$1 billion."
- ▶ June 26, 2012 (FERC abstracts)  
**The Linearized IV ACOPF**  
Richard O'Neill, Chief Economic Advisor, Federal Energy Regulatory Commission  
The AC Optimal Power Flow (ACOPF) problem is an important problem because a one percent improvement in dispatch saves roughly 1 to 5 billion dollars per year
- ▶ Dec. 2012, Cain, O'Neill & Castillo "History of optimal power flow and formulations" (\$6-19 billion savings, p. 5) cited by <https://gocompetition.energy.gov/about-competition>
- ▶ Nov. 18, 2014 [ADVANCED BULK POWER SYSTEM OPTIMIZATION TECHNOLOGIES WORKSHOP](#) (Tim Heidel)
  - Dick's [slide 4](#) Over linearized models could be leaving 10% or more of costs on the table
- ▶ June 28, 2016 Tim Hiedel, Optimal Power Flow Competition Design Considerations
- ▶ June 28, 2017 FERC Conference hosts GRID DATA presentations
- ▶ June 13, 2018 FERC Conference hosts Competition Workshop (Kory Hedman)
- ▶ June 27, 2019 Kory Hedman, The ARPA-E Grid Optimization (GO) Competition: Challenge 1 and Beyond
- ▶ Nov. 25, 2019 Dick assumes Competition Program Director role.



# GO Competition Challenge 1 Final Event

- ▶ Concluded with an Outreach Event February 18, 2020, in New Orleans
  - 26 teams took part (including ARPA-E Benchmark)
  - 19 teams funded to participate (18 participated in Final Event)
  - 10 teams shared \$3.4 million in prizes (3 winning teams were not funded)
  
- ▶ Datasets
  - GRIDDATA Sources (17 synthetic networks, 2252 scenario instances)
    - PNNL (Henry Huang, Ruisheng Diao, Renke Huang, Ahmad Tbaileh)
    - Wisconsin (Chris DeMarco, Bernie Lesieutre, Scott Greene)
    - Texas A&M (Tom Overby, Adam Birchfield)
  - Industry Sources (3 real networks, 12 scenario instances)
  - Validation
    - PNNL—Ahmad Tbaileh
    - NREL—Venkat Krishnan
    - LANL—Carleton Coffrin (Benchmark and Hardness assessment, select 340 syn)



# Highlights

▶ Only 8 teams produced the 704 best results

■ LLNL accounted for 408 (58%)

Gold standard for reliability, robustness, and accuracy

■ Lehigh accounted for 141 (20%)

■ BAT accounted for 84 not funded

■ GaTech (Sun) 36

■ Gravityx 24 not funded

■ GERS USA 4

■ Mississippi State 1 not funded

■ OK Reactors 1 not funded

▶ Only 3 teams had no “failures” for any scenario

■ LLNL (D1, D2 place: syn 1,1; ind 1,1)

■ University of Colorado Boulder (syn 7,8; ind 2,4)

■ ARPA-E benchmark (syn 10,11; ind 7,9)

▶ Georgia Tech had no failures in Divisions 1 & 4

3<sup>rd</sup> place

▶ 1/4 of synthetic scenarios submissions failed

▶ 2/3 of industry scenarios submissions failed

▶ Failed=slack score (many possible reasons)

▶ Were the datasets too hard?



# Measuring problem difficulty

- ▶ Measuring the gap between upper and lower bound is a conventional way of measuring quality. Also, a problem with a small gap with the given run time is presumed easier than a problem with a larger gap in the same time.
- ▶ We don't know the bounds here, but we have a range of results.
- ▶ Our gap percent method considers the % difference between
  - The best objective value (score) by any team for a given scenario instance
  - The second-best objective value by any team
$$\text{Gap}\% = O_2/O_1 - 1$$
- ▶ The size of the gap is a measure of difficulty (*a posteriori*)
  - Small gap: neither team had trouble getting nearly the same answer
  - Large gap: the 2<sup>nd</sup> place team is having more difficulty than the 1<sup>st</sup> place team
- ▶ Gap% method based on multiple independent calculations
- ▶ A “Wisdom of the Crowd” technique
  - “noise cancellation” (the larger the set, the less likely a bad result)
  - Dates from Aristotle



# Division 1 (real-time, 10-minute code1 time limit)

| <b>Synthetic Network</b>                     | <b>2</b>  | <b>3</b>  | <b>6</b>  | <b>8</b>      | <b>9</b> | <b>12</b> | <b>13</b> | <b>14</b> | <b>20</b> | <b>25</b> | <b>30</b> | <b>70</b> | <b>75</b> | <b>82</b> | <b>83</b> | <b>86</b> | <b>88</b> | <b>Totals</b> |
|--|-----------|-----------|-----------|---------------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------------|
| <0.01% exceedingly easy                      | 1         | 5         | 1         | 2             | 0        | 0         | 2         | 8         | 1         | 0         | 1         | 2         | 3         | 7         | 0         | 1         | 0         | <b>34</b>     |
| >0.01% <0.1% very easy                       | 0         | 5         | 19        | 10            | 0        | 0         | 14        | 12        | 9         | 2         | 16        | 14        | 14        | 8         | 7         | 5         | 0         | <b>135</b>    |
| >0.1% <0.5% moderately easy                  | 18        | 6         | 0         | 4             | 0        | 15        | 4         | 0         | 6         | 2         | 3         | 4         | 3         | 1         | 10        | 7         | 20        | <b>103</b>    |
| >0.5% <1.0% easy                             | 1         | 0         | 0         | 3             | 3        | 5         | 0         | 0         | 4         | 14        | 0         | 0         | 0         | 0         | 3         | 7         | 0         | <b>40</b>     |
| >1.0% <2.0% difficult                        | 0         | 4         | 0         | 1             | 2        | 0         | 0         | 0         | 0         | 1         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>8</b>      |
| >2.0% <4.0% somewhat hard                    | 0         | 0         | 0         | 0             | 12       | 0         | 0         | 0         | 0         | 1         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>13</b>     |
| >4.0% exceedingly hard                       | 0         | 0         | 0         | 0             | 3        | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | 0         | <b>3</b>      |
| min teams under threshold per scenario       | 2         | 0         | 5         | 0             | 0        | 3         | 3         | 4         | 3         | 0         | 1         | 1         | 3         | 4         | 2         | 1         | 3         |               |
| count scenarios with min teams under thresh. | 3         | 4         | 1         | 1             | 17       | 14        | 20        | 3         | 5         | 2         | 4         | 2         | 1         | 3         | 2         | 1         | 2         |               |
| max teams under threshold per scenario       | 6         | 13        | 7         | 4             | 2        | 4         | 3         | 6         | 6         | 2         | 3         | 7         | 5         | 8         | 7         | 7         | 5         |               |
| count scenarios with max teams under thresh. | 1         | 1         | 3         | 4             | 1        | 6         | 20        | 4         | 1         | 3         | 15        | 3         | 17        | 3         | 3         | 1         | 6         |               |
| max gap                                      | 0.654%    | 1.451%    | 0.085%    | 1.061%        | 4.208%   | 0.556%    | 0.170%    | 0.069%    | 0.597%    | 2.140%    | 0.306%    | 0.258%    | 0.183%    | 0.100%    | 0.620%    | 0.843%    | 0.404%    |               |
| min gap                                      | 0.010%    | 0.000%    | 0.010%    | 0.001%        | 0.664%   | 0.189%    | 0.002%    | 0.000%    | 0.007%    | 0.076%    | 0.002%    | 0.000%    | 0.002%    | 0.000%    | 0.020%    | 0.005%    | 0.196%    |               |
| geomean gap                                  | 0.231%    | 0.706%    | 0.042%    | 0.288%        | 2.332%   | 0.438%    | 0.057%    | 0.006%    | 0.312%    | 1.755%    | 0.001%    | 0.055%    | 0.042%    | 0.028%    | 0.397%    | 0.604%    | 0.334%    |               |
| dynamic range (max gap / min gap)            | 68        | 20,592    | 9         | 1,096         | 6        | 3         | 98        | 360       | 81        | 28        | 130       | 2,329     | 89        | 255       | 31        | 164       | 2         |               |
| geomean slacks (20% of total)                | 2         | 2         | 3         | 6             | 5        | 6         | 7         | 6         | 9         | 10        | 7         | 2         | 5         | 3         | 4         | 5         | 6         | <b>88</b>     |
| scenario slacks (24% of total)               | 78        | 47        | 99        | 126           | 134      | 131       | 143       | 137       | 193       | 227       | 196       | 73        | 109       | 83        | 120       | 118       | 136       | <b>2150</b>   |
| buses  | 500       | 793       | 2000      | 3022          | 4918     | ~9000     | 10,000    | 10,480    | ~19,000   | ~24,465   | 30,000    | 2312      | 2742      | ~4000     | 4020      | 4619      | ~4837     |               |
| Data Provider                                | TAMU      | PNNL      | TAMU      | PNNL          | PNNL     | Wisc.     | TAMU      | Wisc.     | Wisc.     | Wisc.     | TAMU      | PNNL      | Wisc.     | Wisc.     | Wisc.     | Wisc.     | Wisc.     |               |
| <b>Industry Network</b>                      | <b>40</b> | <b>41</b> | <b>42</b> | <b>Totals</b> |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| <0.01% exceedingly easy                      | 0         | 0         | 0         | <b>0</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| >0.01% <0.1% very easy                       | 2         | 1         | 4         | <b>7</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| >0.1% <0.5% moderately easy                  | 2         | 1         | 0         | <b>3</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| >0.5% <1.0% easy                             | 0         | 0         | 0         | <b>0</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| >1.0% <2.0% difficult                        | 0         | 1         | 0         | <b>1</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| >2.0% <4.0% somewhat hard                    | 0         | 1         | 0         | <b>1</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| >4.0% exceedingly hard                       | 0         | 0         | 0         | <b>0</b>      |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| min teams under threshold per scenario       | 2         | 1         | 2         |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| count scenarios with min teams under thresh. | 1         | 2         | 4         |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| max teams under threshold per scenario       | 3         | 2         | 2         |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| count scenarios with max teams under thresh. | 3         | 2         | 4         |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| max gap                                      | 0.215%    | 3.781%    | 0.084%    |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| min gap                                      | 0.016%    | 0.100%    | 0.014%    |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| geomean gap                                  | 0.062%    | 1.308%    | 0.009%    |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| dynamic range (max gap / min gap)            | 14        | 38        | 6         |               |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| geomean slacks (62% of total)                | 15        | 17        | 16        | <b>48</b>     |          |           |           |           |           |           |           |           |           |           |           |           |           |               |
| scenario slacks (66% of total)               | 63        | 72        | 71        | <b>206</b>    |          |           |           |           |           |           |           |           |           |           |           |           |           |               |

Starting point information given



# Division 2 (off-line, 45-minute code1 time limit)

| Synthetic Network                            | 2      | 3      | 6      | 8      | 9     | 12     | 13     | 14     | 20      | 25      | 30     | 70     | 75      | 82     | 83     | 86     | 88 Totals |      |
|--|--------|--------|--------|--------|-------|--------|--------|--------|---------|---------|--------|--------|---------|--------|--------|--------|-----------|------|
| <0.01% exceedingly easy                      | 0      | 6      | 5      | 0      | 0     | 1      | 2      | 0      | 3       | 0       | 1      | 3      | 3       | 6      | 2      | 1      | 1         | 34   |
| >0.01% <0.1% very easy                       | 1      | 9      | 15     | 17     | 0     | 4      | 11     | 9      | 17      | 2       | 16     | 14     | 13      | 10     | 8      | 5      | 11        | 162  |
| >0.1% <0.5% moderately easy                  | 17     | 1      | 0      | 3      | 3     | 15     | 7      | 11     | 0       | 2       | 2      | 3      | 4       | 4      | 10     | 14     | 8         | 104  |
| >0.5% <1.0% easy                             | 1      | 4      | 0      | 0      | 3     | 0      | 0      | 0      | 0       | 15      | 1      | 0      | 0       | 0      | 0      | 0      | 0         | 24   |
| >1.0% <2.0% difficult                        | 1      | 0      | 0      | 0      | 10    | 0      | 0      | 0      | 0       | 1       | 0      | 0      | 0       | 0      | 0      | 0      | 0         | 12   |
| >2.0% <4.0% somewhat hard                    | 0      | 0      | 0      | 0      | 4     | 0      | 0      | 0      | 0       | 0       | 0      | 0      | 0       | 0      | 0      | 0      | 0         | 4    |
| >4.0% exceedingly hard                       | 0      | 0      | 0      | 0      | 0     | 0      | 0      | 0      | 0       | 0       | 0      | 0      | 0       | 0      | 0      | 0      | 0         | 0    |
| min teams under threshold per scenario       | 0      | 1      | 5      | 1      | 0     | 3      | 3      | 3      | 3       | 0       | 1      | 2      | 3       | 3      | 3      | 3      | 2         |      |
| count scenarios with min teams under thresh. | 1      | 4      | 1      | 3      | 14    | 12     | 20     | 1      | 5       | 1       | 2      | 1      | 1       | 4      | 1      | 5      | 1         |      |
| max teams under threshold per scenario       | 7      | 13     | 7      | 6      | 2     | 4      | 3      | 6      | 6       | 3       | 3      | 7      | 5       | 7      | 7      | 6      | 5         |      |
| count scenarios with max teams under thresh. | 1      | 1      | 2      | 2      | 2     | 8      | 20     | 2      | 1       | 1       | 12     | 3      | 14      | 1      | 3      | 2      | 4         |      |
| max gap                                      | 1.075% | 0.787% | 0.042% | 0.180% | 3.69% | 0.136% | 0.135% | 0.215% | 0.034%  | 1.061%  | 0.965% | 0.134% | 0.163%  | 0.220% | 0.403% | 0.314% | 0.165%    |      |
| min gap                                      | 0.017% | 0.000% | 0.001% | 0.010% | 0.22% | 0.007% | 0.000% | 0.066% | 0.001%  | 0.034%  | 0.004% | 0.004% | 0.0060% | 0.000% | 0.001% | 0.008% | 0.006%    |      |
| geomean gap                                  | 0.360% | 0.162% | 0.027% | 0.054% | 2.03% | 0.105% | 0.004% | 0.116% | 0.021%  | 1.058%  | 0.143% | 0.049% | 0.0450% | 0.065% | 0.416% | 0.111% | 0.085%    |      |
| dynamic range (max gap / min gap)            | 64     | 40,260 | 31     | 18     | 16    | 19     | 394    | 3      | 25      | 32      | 274    | 30     | 27      | 2,504  | 350    | 42     | 26        |      |
| geomean slacks (20% of total)                | 3      | 2      | 4      | 7      | 6     | 5      | 6      | 7      | 7       | 11      | 9      | 2      | 4       | 4      | 4      | 4      | 5         | 90   |
| scenario slacks (24% of total)               | 93     | 67     | 100    | 148    | 124   | 121    | 167    | 152    | 174     | 224     | 209    | 84     | 123     | 101    | 94     | 115    | 142       | 2238 |
| buses  | 500    | 793    | 2000   | 3022   | 4918  | ~9000  | 10,000 | 10,480 | ~19,000 | ~24,465 | 30,000 | 2312   | 2742    | ~4000  | 4020   | 4619   | ~4837     |      |
| Data Provider                                | TAMU   | PNNL   | TAMU   | PNNL   | PNNL  | Wisc.  | TAMU   | Wisc.  | Wisc.   | Wisc.   | TAMU   | PNNL   | Wisc.   | Wisc.  | Wisc.  | Wisc.  | Wisc.     |      |
| Industry Network                             | 40     | 41     | 42     | Totals |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| <0.01% exceedingly easy                      | 0      | 0      | 2      | 2      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| >0.01% <0.1% very easy                       | 1      | 0      | 2      | 3      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| >0.1% <0.5% moderately easy                  | 2      | 0      | 0      | 2      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| >0.5% <1.0% easy                             | 0      | 1      | 0      | 1      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| >1.0% <2.0% difficult                        | 0      | 2      | 0      | 2      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| >2.0% <4.0% somewhat hard                    | 0      | 0      | 0      | 0      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| >4.0% exceedingly hard                       | 1      | 1      | 0      | 2      |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| min teams under threshold per scenario       | 0      | 0      | 1      |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| count scenarios with min teams under thresh. | 1      | 3      | 4      |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| max teams under threshold per scenario       | 1      | 1      | 1      |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| count scenarios with max teams under thresh. | 3      | 1      | 4      |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| max gap                                      | 10.15% | 12.94% | 0.02%  |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| min gap                                      | 0.08%  | 0.64%  | 0.01%  |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| geomean gap                                  | 2.32%  | 3.78%  | 0.01%  |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| dynamic range (max gap / min gap)            | 126    | 20     | 2      |        |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| geomean slacks (65% of total)                | 15     | 19     | 17     | 51     |       |        |        |        |         |         |        |        |         |        |        |        |           |      |
| scenario slacks (67% of total)               | 63     | 76     | 70     | 209    |       |        |        |        |         |         |        |        |         |        |        |        |           |      |

No starting point information given

- ▶ Network with smallest geomean Gap% has least slack scores
- ▶ Network with largest geomean Gap% NOT the one with the most slacks
- ▶ The range of difficulty seems reasonable.
- ▶ Failure rate is associated with larger problems, not harder ones, and poorly designed codes.
- ▶ Problems observed
  - Time management, failure to produce intermediate results
    - Colorado & Benchmark focused on always getting a valid, not best, solution.
  - Memory management
  - Lack of MPI experience
  - Poorly debugged code resulting in segmentation violations, infeasible results, results larger than slack score, failures to parse input data, NaNs
  - Non-robust algorithms that gave up too easily or too focused on base case
  - Poor use of starting information





# Selection of Final Event Datasets

- ▶ Based on a “Hardness” index developed by Carleton Coffrin (LANL)
- ▶ Hardness index is a product of 3 values
  - Relative cost ( $C^r$ ), the difference of DC-SCOP and AC-OPF generation cost normalized by the AC-OPF cost value
  - Relative penalty ( $P^r$ ), the AC penalty value divided by the cost,
  - $\log_{10}$  of a relative upper bound penalty ( $P^{ubr}$ ), the AC penalty upper bound divided by the cost

$$H = C^r P^r \log_{10} P^{ubr}$$

- ▶ Calculated using Coffrin’s benchmark code on the Division 2 datasets
  - Metric breaks down completely on the larger cases (Networks 20, 25, and 30)
  - Partial break down on some others (8 from Network 75 & 6 from Network 82)
  - Selections made using approximations
- ▶ Final selection aimed for a distribution of Hardness values

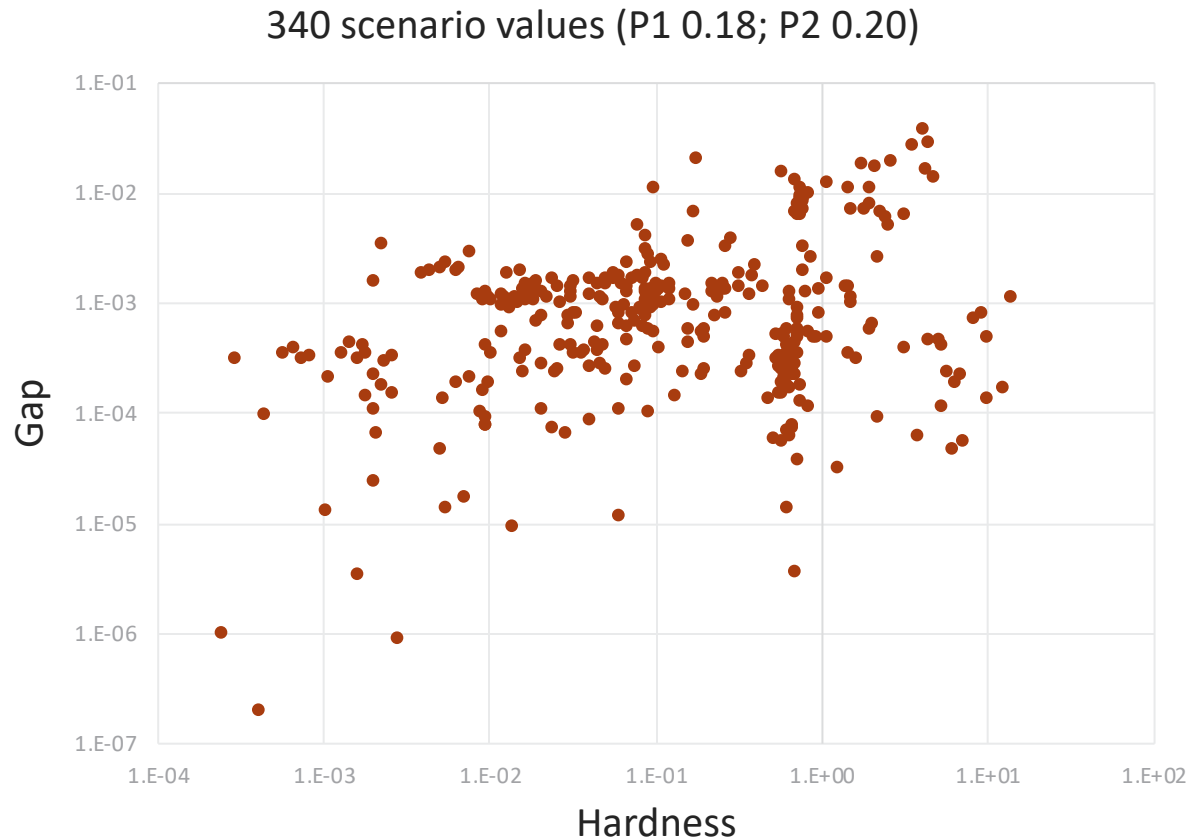


# Distribution of Gap% and Hardness values

| value greater than | but less than | Gap% count | Hardness count |
|--------------------|---------------|------------|----------------|
| 0                  | 0.001         | 6          | 8              |
| 0.001              | 0.01          | 28         | 42             |
| 0.01               | 0.1           | 162        | 110            |
| 0.1                | 1             | 128        | 132            |
| 1                  | 10            | 16         | 45             |
| 10                 | 100           | 0          | 3              |
| maximum gap%       | minimum gap%  | total      |                |
| 3.69               | 1.95E-05      | 340        |                |

The gap% distribution is comparable to the Hardness distribution.  
The Pearson coefficient between the two distributions is a strong **0.94**.

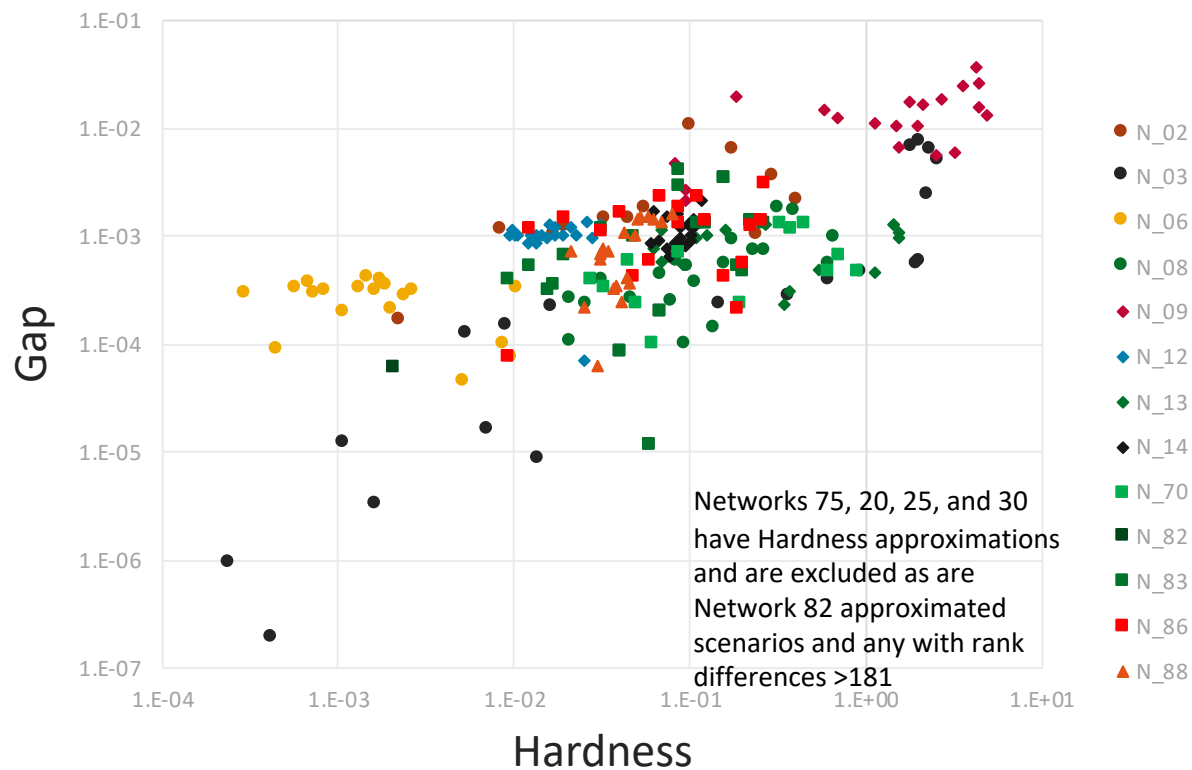
# A different perspective at the scenario level...



Note log-log scale

- ▶ Assigning a bin number to each value (binning) can smooth variance
  - Sort the list of values into ascending order and assign bins according to rank
  - Sort again the absolute value of the difference between bins of each set to find “problem” values.
  - Exclude “problem values” and recalculate Pearson
  
- ▶ We use two types of binning
  - Global, where the Pearson’s correlation coefficient considers the two sets (Gap% and H) of all values sorted and ranked: P2
  - Local, where the 20 values belonging to a given network are sorted and ranked: P3
  - P1 is when no binning is used, and Pearson’s considers the two sets of Gap% and H values.

### 229 scenario values (67%) (P1 0.75; P2 0.61)





# Texas datasets Gap% vs. Hardness

| Texas 500  |      |      |      | Texas 2000 |       |       |       | Texas 10,000 |       |       |       | Texas 30,000 |      |      |      |
|------------|------|------|------|------------|-------|-------|-------|--------------|-------|-------|-------|--------------|------|------|------|
| Network_02 |      |      |      | Network_06 |       |       |       | Network_13   |       |       |       | Network_30   |      |      |      |
| scenarios  | P1   | P2   | P3   | scenarios  | P1    | P2    | P3    | scenarios    | P1    | P2    | P3    | scenarios    | P1   | P2   | P3   |
| 20         | 0.24 | 0.32 | 0.26 | 20         | -0.47 | -0.42 | -0.27 | 20           | -0.02 | -0.22 | -0.07 | 20           | 0.37 | 0.65 | 0.56 |
| 19         | 0.31 | 0.39 | 0.38 | 19         | -0.37 | -0.28 | -0.19 | 19           | 0.05  | -0.07 | 0.02  | 19           | 0.37 | 0.62 | 0.67 |
| 18         | 0.32 | 0.48 | 0.51 | 18         | -0.30 | -0.16 | -0.08 | 18           | 0.14  | 0.01  | 0.09  | 18           | 0.37 | 0.76 | 0.82 |
| 17         | 0.33 | 0.53 | 0.59 | 17         | -0.20 | -0.01 | 0.05  | 17           | 0.24  | 0.07  | 0.16  | 17           | 0.36 | 0.76 | 0.82 |
| 16         | 0.33 | 0.58 | 0.67 | 16         | -0.18 | 0.04  | 0.13  | 16           | 0.28  | 0.14  | 0.22  | 16           | 0.36 | 0.76 | 0.83 |
| 15         | 0.32 | 0.58 | 0.71 | 15         | 0.22  | 0.33  | 0.32  | 15           | 0.36  | 0.26  | 0.31  | 15           | 0.35 | 0.77 | 0.87 |
| 14         | 0.31 | 0.58 | 0.73 | 14         | 0.26  | 0.35  | 0.36  | 14           | 0.45  | 0.31  | 0.36  | 14           | 0.34 | 0.78 | 0.93 |
| 13         | 0.30 | 0.64 | 0.78 | 13         | 0.30  | 0.44  | 0.44  | 13           | 0.46  | 0.34  | 0.38  | 13           | 0.33 | 0.76 | 0.93 |
| 12         | 0.28 | 0.78 | 0.85 | 12         | 0.34  | 0.44  | 0.47  | 12           | 0.56  | 0.41  | 0.45  | 12           | 0.64 | 0.84 | 0.94 |
| 11         | 0.26 | 0.78 | 0.87 | 11         | 0.36  | 0.51  | 0.47  | 11           | 0.67  | 0.48  | 0.52  | 11           | 0.62 | 0.83 | 0.95 |
| 10         | 0.49 | 0.82 | 0.89 | 10         | 0.41  | 0.58  | 0.55  | 10           | 0.66  | 0.47  | 0.53  | 10           | 0.60 | 0.81 | 0.95 |
| 9          | 0.74 | 0.80 | 0.90 | 9          | 0.47  | 0.69  | 0.65  | 9            | 0.76  | 0.52  | 0.61  | 9            | 0.57 | 0.79 | 0.94 |
| 8          | 0.74 | 0.80 | 0.92 | 8          | 0.47  | 0.70  | 0.71  | 8            | 0.87  | 0.61  | 0.67  | 8            | 0.68 | 0.84 | 0.94 |
| 7          | 0.74 | 0.88 | 0.98 | 7          | 0.47  | 0.79  | 0.81  | 7            | 0.91  | 0.71  | 0.75  | 7            | 0.76 | 0.92 | 0.97 |
| 6          | 0.73 | 0.90 | 0.98 | 6          | 0.54  | 0.81  | 0.90  | 6            | 0.90  | 0.71  | 0.76  | 6            | 0.76 | 0.93 | 0.99 |
| 5          | 0.70 | 0.95 | 0.98 | 5          | 0.63  | 0.94  | 0.97  | 5            | 0.91  | 0.78  | 0.76  | 5            | 0.73 | 0.91 | 0.99 |

20 approximate H

| Scenarios Needed for Pearson coeff. | Network_02 | Network_06 | Network_13 | Network_30 | Texas 500 | Texas 2000 | Texas 10,000 | Texas 30,000 | >0.5 | >0.6 | >0.7 | >0.8 | >0.9 | sum |
|-------------------------------------|------------|------------|------------|------------|-----------|------------|--------------|--------------|------|------|------|------|------|-----|
|                                     |            |            |            |            |           |            |              |              | 18   | 16   | 15   | 12   | 9    | 70  |
|                                     |            |            |            |            |           |            |              |              | 11   | 9    | 8    | 7    | 6    | 41  |
|                                     |            |            |            |            |           |            |              |              | 12   | 11   | 9    | 8    | 7    | 47  |
|                                     |            |            |            |            |           |            |              |              | 20   | 20   | 18   | 18   | 14   | 90  |



# PNNL datasets Gap% vs. Hardness

| PNNL 793 Network_03 |      |      |      | PNNL 2312 Network_70 |       |       |       | PNNL 3022 Network_08 |      |      |      | PNNL 4918 Network_09 |      |      |      |
|---------------------|------|------|------|----------------------|-------|-------|-------|----------------------|------|------|------|----------------------|------|------|------|
| scenarios           | P1   | P2   | P3   | scenarios            | P1    | P2    | P3    | scenarios            | P1   | P2   | P3   | scenarios            | P1   | P2   | P3   |
| 20                  | 0.75 | 0.90 | 0.93 | 20                   | -0.46 | -0.33 | -0.42 | 20                   | 0.59 | 0.65 | 0.74 | 20                   | 0.57 | 0.56 | 0.55 |
| 19                  | 0.75 | 0.92 | 0.95 | 19                   | -0.40 | -0.29 | -0.33 | 19                   | 0.59 | 0.77 | 0.80 | 19                   | 0.65 | 0.58 | 0.66 |
| 18                  | 0.77 | 0.94 | 0.97 | 18                   | -0.33 | -0.18 | -0.22 | 18                   | 0.59 | 0.82 | 0.85 | 18                   | 0.70 | 0.66 | 0.72 |
| 17                  | 0.77 | 0.95 | 0.98 | 17                   | -0.27 | -0.09 | -0.10 | 17                   | 0.74 | 0.86 | 0.89 | 17                   | 0.78 | 0.68 | 0.77 |
| 16                  | 0.70 | 0.94 | 0.98 | 16                   | -0.24 | 0.04  | 0.04  | 16                   | 0.74 | 0.87 | 0.91 | 16                   | 0.83 | 0.76 | 0.85 |
| 15                  | 0.67 | 0.94 | 0.98 | 15                   | -0.24 | 0.07  | 0.09  | 15                   | 0.73 | 0.87 | 0.93 | 15                   | 0.86 | 0.82 | 0.89 |
| 14                  | 0.76 | 0.94 | 0.98 | 14                   | -0.12 | 0.24  | 0.29  | 14                   | 0.72 | 0.89 | 0.94 | 14                   | 0.93 | 0.83 | 0.92 |
| 13                  | 0.76 | 0.95 | 0.99 | 13                   | 0.30  | 0.42  | 0.46  | 13                   | 0.71 | 0.91 | 0.96 | 13                   | 0.93 | 0.84 | 0.93 |
| 12                  | 0.76 | 0.94 | 0.99 | 12                   | 0.47  | 0.49  | 0.53  | 12                   | 0.75 | 0.92 | 0.96 | 12                   | 0.94 | 0.84 | 0.96 |
| 11                  | 0.87 | 0.96 | 0.99 | 11                   | 0.48  | 0.54  | 0.59  | 11                   | 0.77 | 0.92 | 0.97 | 11                   | 0.96 | 0.89 | 0.97 |
| 10                  | 0.89 | 0.95 | 0.99 | 10                   | 0.60  | 0.59  | 0.62  | 10                   | 0.77 | 0.93 | 0.98 | 10                   | 0.97 | 0.87 | 0.96 |
| 9                   | 0.90 | 0.95 | 0.99 | 9                    | 0.62  | 0.58  | 0.61  | 9                    | 0.95 | 0.94 | 0.99 | 9                    | 0.99 | 0.88 | 0.98 |
| 8                   | 0.90 | 0.94 | 0.99 | 8                    | 0.20  | 0.71  | 0.69  | 8                    | 0.95 | 0.95 | 1.00 | 8                    | 0.99 | 0.87 | 0.98 |
| 7                   | 0.89 | 0.93 | 1.00 | 7                    | 0.22  | 0.81  | 0.80  | 7                    | 0.96 | 0.97 | 1.00 | 7                    | 0.98 | 0.85 | 0.97 |
| 6                   | 0.90 | 0.98 | 1.00 | 6                    | 0.85  | 0.91  | 0.91  | 6                    | 0.99 | 0.99 | 1.00 | 6                    | 0.99 | 0.83 | 0.97 |
| 5                   | 0.84 | 0.98 | 1.00 | 5                    | 0.90  | 0.90  | 0.91  | 5                    | 0.98 | 0.99 | 1.00 | 5                    | 1.00 | 0.89 | 0.98 |

| Scenarios Needed for Pearson coeff. | Network_03 | PNNL 793 | Pearson |      |      |      |      | Sum |
|-------------------------------------|------------|----------|---------|------|------|------|------|-----|
|                                     |            |          | >0.5    | >0.6 | >0.7 | >0.8 | >0.9 |     |
| Network_70                          | PNNL 2312  |          | 12      | 10   | 8    | 7    | 6    | 43  |
| Network_08                          | PNNL 3022  |          | 20      | 20   | 20   | 19   | 16   | 95  |
| Network_09                          | PNNL 4918  |          | 20      | 19   | 18   | 16   | 14   | 87  |



# Wisconsin datasets (1) Gap% vs. Hardness

| WI 2742 Network_75 |       |       |      | WI 3970+ Network_82 |       |       |      | WI 4020 Network_83 |      |      |      | WI 4619 Network_86 |      |      |      | WI 4837 Network_88 |      |      |      |
|--------------------|-------|-------|------|---------------------|-------|-------|------|--------------------|------|------|------|--------------------|------|------|------|--------------------|------|------|------|
| Scen.              | P1    | P2    | P3   | Scen.               | P1    | P2    | P3   | Scen.              | P1   | P2   | P3   | Scen.              | P1   | P2   | P3   | Scen.              | P1   | P2   | P3   |
| 20                 | -0.06 | -0.04 | 0.05 | 20                  | -0.30 | -0.25 | 0.20 | 20                 | 0.27 | 0.51 | 0.55 | 20                 | 0.14 | 0.09 | 0.08 | 20                 | 0.74 | 0.71 | 0.72 |
| 19                 | 0.02  | 0.08  | 0.19 | 19                  | -0.27 | 0.00  | 0.30 | 19                 | 0.33 | 0.53 | 0.61 | 19                 | 0.23 | 0.23 | 0.17 | 19                 | 0.78 | 0.78 | 0.77 |
| 18                 | 0.03  | 0.14  | 0.29 | 18                  | 0.03  | 0.14  | 0.29 | 18                 | 0.43 | 0.54 | 0.63 | 18                 | 0.29 | 0.31 | 0.27 | 18                 | 0.80 | 0.81 | 0.80 |
| 17                 | 0.11  | 0.23  | 0.36 | 17                  | 0.11  | 0.23  | 0.36 | 17                 | 0.42 | 0.59 | 0.67 | 17                 | 0.39 | 0.39 | 0.36 | 17                 | 0.82 | 0.84 | 0.83 |
| 16                 | 0.18  | 0.35  | 0.45 | 16                  | 0.18  | 0.35  | 0.45 | 16                 | 0.48 | 0.64 | 0.71 | 16                 | 0.48 | 0.50 | 0.46 | 16                 | 0.83 | 0.85 | 0.86 |
| 15                 | 0.46  | 0.49  | 0.57 | 15                  | -0.07 | 0.21  | 0.60 | 15                 | 0.57 | 0.66 | 0.74 | 15                 | 0.56 | 0.53 | 0.54 | 15                 | 0.84 | 0.87 | 0.88 |
| 14                 | 0.79  | 0.66  | 0.74 | 14                  | -0.09 | 0.20  | 0.64 | 14                 | 0.57 | 0.74 | 0.80 | 14                 | 0.58 | 0.58 | 0.58 | 14                 | 0.85 | 0.90 | 0.90 |
| 13                 | 0.82  | 0.72  | 0.80 | 13                  | -0.07 | 0.22  | 0.68 | 13                 | 0.62 | 0.74 | 0.82 | 13                 | 0.60 | 0.64 | 0.64 | 13                 | 0.86 | 0.91 | 0.92 |
| 12                 | 0.84  | 0.77  | 0.88 | 12                  | -0.09 | 0.24  | 0.73 | 12                 | 0.64 | 0.78 | 0.85 | 12                 | 0.77 | 0.67 | 0.73 | 12                 | 0.87 | 0.91 | 0.93 |
| 11                 | 0.90  | 0.87  | 0.92 | 11                  | 0.56  | 0.77  | 0.80 | 11                 | 0.62 | 0.79 | 0.86 | 11                 | 0.82 | 0.69 | 0.76 | 11                 | 0.87 | 0.91 | 0.95 |
| 10                 | 0.94  | 0.95  | 0.97 | 10                  | 0.59  | 0.79  | 0.82 | 10                 | 0.60 | 0.91 | 0.92 | 10                 | 0.86 | 0.74 | 0.82 | 10                 | 0.87 | 0.92 | 0.96 |
| 9                  | 0.99  | 0.97  | 0.98 | 9                   | 0.51  | 0.79  | 0.81 | 9                  | 0.58 | 0.91 | 0.93 | 9                  | 0.89 | 0.73 | 0.84 | 9                  | 0.89 | 0.92 | 0.96 |
| 8                  | 0.99  | 0.98  | 1.00 | 8                   | 0.99  | 0.98  | 1.00 | 8                  | 0.53 | 0.90 | 0.93 | 8                  | 0.93 | 0.86 | 0.91 | 8                  | 0.91 | 0.93 | 0.97 |
| 7                  | 0.99  | 0.98  | 1.00 | 7                   | 0.54  | 0.90  | 0.91 | 7                  | 0.83 | 0.94 | 0.96 | 7                  | 0.93 | 0.87 | 0.94 | 7                  | 0.91 | 0.97 | 0.98 |
| 6                  | 0.98  | 0.98  | 1.00 | 6                   | 0.53  | 0.94  | 0.93 | 6                  | 0.86 | 0.95 | 0.97 | 6                  | 0.96 | 0.88 | 0.97 | 6                  | 0.90 | 0.97 | 0.99 |
| 5                  | 0.98  | 0.98  | 1.00 | 5                   | 0.91  | 0.93  | 0.94 | 5                  | 0.90 | 0.97 | 0.98 | 5                  | 0.96 | 0.88 | 0.99 | 5                  | 0.93 | 0.97 | 0.99 |

8 approximate H                      6 approximate H





# Wisconsin datasets (2) Gap% vs. Hardness

| WI 8718    |       |       |      | WI 10,480  |      |      |      | WI 18,877+ |       |       |       | WI 24,464        |      |                  |      |
|------------|-------|-------|------|------------|------|------|------|------------|-------|-------|-------|------------------|------|------------------|------|
| Network_12 |       |       |      | Network_14 |      |      |      | Network_20 |       |       |       | Network_25       |      |                  |      |
| scenarios  | P1    | P2    | P3   | scenarios  | P1   | P2   | P3   | scenarios  | P1    | P2    | P3    | scenarios        | P1   | P2               | P3   |
| 20         | -0.01 | -0.07 | 0.25 | 20         | 0.30 | 0.26 | 0.30 | 20         | -0.16 | -0.10 | -0.09 | 20               | 0.32 | 0.47             | 0.44 |
| 19         | 0.47  | 0.44  | 0.39 | 19         | 0.50 | 0.45 | 0.47 | 19         | -0.07 | -0.01 | 0.01  | 19               | 0.51 | 0.50             | 0.63 |
| 18         | 0.62  | 0.58  | 0.54 | 18         | 0.62 | 0.61 | 0.61 | 18         | 0.06  | 0.11  | 0.15  | 18               | 0.62 | 0.51             | 0.72 |
| 17         | 0.69  | 0.67  | 0.64 | 17         | 0.70 | 0.75 | 0.72 | 17         | 0.17  | 0.22  | 0.25  | 17               | 0.66 | 0.52             | 0.81 |
| 16         | 0.70  | 0.70  | 0.67 | 16         | 0.72 | 0.78 | 0.75 | 16         | 0.35  | 0.36  | 0.34  | 16               | 0.66 | 0.52             | 0.84 |
| 15         | 0.72  | 0.74  | 0.73 | 15         | 0.74 | 0.80 | 0.79 | 15         | 0.37  | 0.42  | 0.42  | 15               | 0.68 | 0.54             | 0.86 |
| 14         | 0.78  | 0.78  | 0.75 | 14         | 0.78 | 0.85 | 0.81 | 14         | 0.52  | 0.53  | 0.53  | 14               | 0.72 | 0.57             | 0.89 |
| 13         | 0.80  | 0.82  | 0.80 | 13         | 0.79 | 0.86 | 0.83 | 13         | 0.61  | 0.61  | 0.62  | 13               | 0.83 | 0.67             | 0.91 |
| 12         | 0.81  | 0.84  | 0.83 | 12         | 0.83 | 0.87 | 0.86 | 12         | 0.66  | 0.70  | 0.72  | 12               | 0.83 | 0.66             | 0.93 |
| 11         | 0.83  | 0.87  | 0.88 | 11         | 0.84 | 0.89 | 0.86 | 11         | 0.67  | 0.71  | 0.77  | 11               | 0.84 | 0.67             | 0.96 |
| 10         | 0.82  | 0.87  | 0.89 | 10         | 0.88 | 0.92 | 0.89 | 10         | 0.84  | 0.81  | 0.81  | 10               | 0.85 | 0.67             | 0.98 |
| 9          | 0.88  | 0.95  | 0.94 | 9          | 0.87 | 0.92 | 0.90 | 9          | 0.91  | 0.89  | 0.87  | 9                | 0.82 | 0.66             | 0.99 |
| 8          | 0.92  | 0.95  | 0.95 | 8          | 0.91 | 0.94 | 0.95 | 8          | 0.92  | 0.90  | 0.89  | 8                | 0.81 | 0.66             | 0.99 |
| 7          | 0.92  | 0.95  | 0.97 | 7          | 0.96 | 0.98 | 0.97 | 7          | 0.96  | 0.96  | 0.94  | 7                | 0.78 | 0.65             | 0.99 |
| 6          | 0.91  | 0.96  | 0.97 | 6          | 0.96 | 0.97 | 0.97 | 6          | 0.96  | 0.97  | 0.96  | 6                | 0.78 | 0.65             | 1.00 |
| 5          | 0.91  | 0.97  | 0.97 | 5          | 0.98 | 0.98 | 0.99 | 5          | 0.95  | 0.95  | 0.94  | 5                | 0.78 | 0.66             | 1.00 |
|            |       |       |      |            |      |      |      |            |       |       |       | 20 approximate H |      | 20 approximate H |      |

# Gap% vs Hardness summary



Pacific Northwest  
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|            | Pearson   | >0.5 | >0.6 | >0.7 | >0.8 | >0.9 | Sum |
|------------|-----------|------|------|------|------|------|-----|
| Network_02 | TX 500    | 18   | 16   | 15   | 12   | 9    | 70  |
| Network_06 | TX 2000   | 11   | 9    | 8    | 7    | 6    | 41  |
| Network_13 | TX 10,000 | 12   | 11   | 9    | 8    | 7    | 47  |
| Network_30 | TX 30,000 | 20   | 20   | 18   | 18   | 14   | 90  |

|            | Pearson   | >0.5 | >0.6 | >0.7 | >0.8 | >0.9 | Sum |
|------------|-----------|------|------|------|------|------|-----|
| Network_03 | PNNL 793  | 20   | 20   | 20   | 20   | 20   | 100 |
| Network_70 | PNNL 2312 | 12   | 10   | 8    | 7    | 6    | 43  |
| Network_08 | PNNL 3022 | 20   | 20   | 20   | 19   | 16   | 95  |
| Network_09 | PNNL 4918 | 20   | 19   | 18   | 16   | 14   | 87  |

| Sum from | Sum to | Networks |
|----------|--------|----------|
| 80       | 100    | 6        |
| 60       | 79     | 7        |
| 40       | 59     | 4        |

|            | Pearson    | >0.5 | >0.6 | >0.7 | >0.8 | >0.9 | Sum |
|------------|------------|------|------|------|------|------|-----|
| Network_75 | WI 2742    | 15   | 14   | 14   | 13   | 11   | 67  |
| Network_82 | WI 3970+   | 15   | 15   | 12   | 11   | 8    | 61  |
| Network_83 | WI 4020    | 20   | 19   | 16   | 14   | 10   | 79  |
| Network_86 | WI 4619    | 16   | 13   | 12   | 11   | 8    | 60  |
| Network_88 | WI 4837    | 20   | 20   | 20   | 18   | 14   | 92  |
| Network_12 | WI 8718    | 18   | 18   | 15   | 13   | 9    | 73  |
| Network_14 | WI 10,480  | 19   | 18   | 17   | 15   | 10   | 79  |
| Network_20 | WI 18,877+ | 14   | 13   | 12   | 10   | 9    | 58  |
| Network_25 | WI 24,464  | 19   | 18   | 18   | 17   | 13   | 85  |



# Observations/Conclusions

- ▶ Gap% agrees reasonably well with Coffrin Hardness values.
- ▶ Approximate Hardness values correlate well when not mixed with other values
- ▶ The source of differences is difficult to ascertain.
- ▶ Another metric needed to make the determination
  - Support Vector Machine (machine learning) metric is under development
  - SVM will be an *a priori* method
  
- ▶ Distribution of difficulty seems reasonable.
- ▶ Failures due to other causes.
  
- ▶ *Why* some scenarios are harder is not currently discernable. Reasons likely complex.

# Questions?

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