Dennard, Carbon & Moore

Scenarios for the Future of NSF Advanced Computational Infrastructure

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Mark J. Dietrich, Bloodstone Solutions Inc.
How can we satisfy continued high growth in scientific computing demand?

Perspectives of system operators, as consortia, as funding agencies?

Quantitative change or disruption?

Replacement cycles, partial upgrades?
Approach and Data

Model performance and total cost of ownership:
- Capital; Rpeak; Power/power costs/CO$_2$ (Scope 2); Space, space costs

Calibrate with a range of real systems
- Wide scale (400:1 Rpeak, 100:1 kW)
- Representative of Top100

Construct scenarios around investment objectives:
- I$_0$: Constant (annualized) capital investment
- I$_1$: Achieve 40% annual growth in capacity

<table>
<thead>
<tr>
<th>System</th>
<th>Site</th>
<th>In Service (Mo/Yr)</th>
<th>Rpeak (Gflops/s)</th>
<th>Compute Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jetstream</td>
<td>Indiana</td>
<td>1/2016</td>
<td>516,096</td>
<td>140.0</td>
</tr>
<tr>
<td>Big Red II+</td>
<td>Indiana</td>
<td>8/2016</td>
<td>286,157</td>
<td>90.0</td>
</tr>
<tr>
<td>Big Red 3</td>
<td>Indiana</td>
<td>8/2019</td>
<td>928,512</td>
<td>179.0</td>
</tr>
<tr>
<td>Comet</td>
<td>SDSC</td>
<td>7/2015</td>
<td>2,831,699</td>
<td>550.9</td>
</tr>
<tr>
<td>Expanse</td>
<td>SDSC</td>
<td>7/2020</td>
<td>5,078,656</td>
<td>407.4</td>
</tr>
<tr>
<td>Stampede 2</td>
<td>TACC</td>
<td>9/2017</td>
<td>18,394,522</td>
<td>2,200.0</td>
</tr>
<tr>
<td>Frontera</td>
<td>TACC</td>
<td>7/2019</td>
<td>40,977,504</td>
<td>3,407.1</td>
</tr>
<tr>
<td>Wrangler</td>
<td>TACC</td>
<td>7/2015</td>
<td>92,160</td>
<td>28.8</td>
</tr>
<tr>
<td>Chameleon</td>
<td>TACC</td>
<td>6/2018</td>
<td>370,944</td>
<td>100.8</td>
</tr>
<tr>
<td>Bridges</td>
<td>PSC</td>
<td>1/2016</td>
<td>2,131,341</td>
<td>283.4</td>
</tr>
<tr>
<td>Bridges 2</td>
<td>PSC</td>
<td>10/2020</td>
<td>2,957,069</td>
<td>257.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average Site</th>
<th>Power Cost/kWyr</th>
<th>kg Carbon/kWyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campus (Site 9)</td>
<td>$764.34</td>
<td>3,829</td>
</tr>
<tr>
<td>Green Data Center (Site 8)</td>
<td>$477.12</td>
<td>-0-</td>
</tr>
</tbody>
</table>
Trends and Scenarios

I* Investment Objective, CD* Compute Density, PD* Power Density, DC Data Center

**Capital Cost/Rpeak**

- CD0: -28.5%/yr ($R^2=0.39$)
- CD-: -15.4%/yr

**Power/Rpeak**

- PD0: -16.8%/yr ($R^2=0.47$)
- PD-: -8.8%/yr
- PD+: -30.7%/yr
- PD++: -47.3%, then -28.3%/yr

**Scenarios**

- 24* Scenarios = \{I0 \times CD0 \times PD0 \times Campus DC, I1 \times CD0 \times PD+ \times Green DC\}

* I0|CD0 = I1|CD0

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PEARC’22: Dietrich & Chien. Dennard, Carbon & Moore; Paper Presentation 13 July 2022
Baseline Scenario: Power Overwhelms Capital by 2037

- **I0**: Constant capital investment of $1M/year (annualized for replacement cycles (RC) >1 year)
- Replacements fix power/space density at each commissioning – penalizing older systems
- Annual power costs > annualized capital costs, dominating Annual TCO, by 2037.
- 2027 number
- Space costs << capital costs
- NB: Log scale for all costs
24 Scenarios: Significant Differences

<table>
<thead>
<tr>
<th>Power density:</th>
<th>Baseline (PD0)</th>
<th>Conservative (PD-)</th>
<th>Better (PD+)</th>
<th>Optimistic (PD++)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Compute Density trend continues (CD0); investment stays constant (I0)</td>
<td>![Annual TCO for Scenario 1: I0][CD0][PD0]<a href="2022-2037">Site 9</a></td>
<td>![Annual TCO for Scenario 2: I0][CD0][PD-]<a href="2022-2037">Site 9</a></td>
<td>![Annual TCO for Scenario 3: I0][CD0][PD+]<a href="2022-2037">Site 9</a></td>
<td>![Annual TCO for Scenario 4: I0][CD0][PD++]<a href="2022-2037">Site 9</a></td>
</tr>
</tbody>
</table>

Not shown: Compute density slows and investment stays constant

| Compute density trend slows 2x (CD-), investment increased to maintain growth of flops/s (I1) | ![Annual TCO for Scenario 17: I1][CD-][PD0][Site 9](2022-2037) | ![Annual TCO for Scenario 18: I1][CD-][PD-][Site 9](2022-2037) | ![Annual TCO for Scenario 19: I1][CD-][PD+][Site 9](2022-2037) | ![Annual TCO for Scenario 20: I1][CD-][PD++][Site 9](2022-2037) |

- Legend: same as prior chart, log scale for costs
- Not shown: Scenarios for green data centres
Two Key Patterns

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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Annual TCO for Scenario 1: I0||CD0|PD0|Site 9
- Annual TCO for Scenario 2: I0||CD0|PD-|Site 9
- Annual TCO for Scenario 3: I0||CD0|PD+|Site 9
- Annual TCO for Scenario 4: I0||CD0|PD++|Site 9

Not shown: Compute density slows and investment stays constant

- Annual TCO for Scenario 17: I1||CD-|PD0|Site 9
- Annual TCO for Scenario 18: I1||CD-|PD-|Site 9
- Annual TCO for Scenario 19: I1||CD-|PD+|Site 9
- Annual TCO for Scenario 20: I1||CD-|PD++|Site 9

Compute density trend slows 2x (CD-), investment increased to maintain growth of flops/s (I1)

Power costs grow 10-40x by 2037

Capital costs grow 12x by 2037
Capital/Space Explode 12x by 2037 if Compute Density Slows

Increase 5x by 2027

…if we increase investment to grow capacity to meet demand → Consider new hosting options? Otherwise capital & space requirements stay under control.
Power Overwhelms Capital in 10-15 Yrs in Many Scenarios

Increase 2-3x, accounting for 11-17% of TCO, by 2027
More kW → Higher Power costs (absolute and as % of TCO), More CO$_2$
→ New data center designs, new cooling tech
→ Need to consider green options
Slower Compute Density Trend Extends Replacement Cycles

- Using systems through their full “economic life” optimizes TCO ($) per unit capacity
- Slower compute density/performance improvement trends extend replacement cycles - optimizing TCO/capacity
Power and Carbon Mitigation Need to Start Soon: Green Data Centers Offer Solutions

- Eliminate Scope 2 GHG emissions
- Reduce costs by 37% exploiting stranded power
Key Conclusions

Capital & Hosting Space Explode 28x in 20 Yrs if Compute Density Trend Slows

Power Overwhelms Capital in 10-15 Yrs if Power Density Trend Continues (or slows)

Slowing Compute Density Trend Lengthens Optimum Replacement Cycle

Green Data Centers Mitigate Extreme Impacts of Carbon and Power Costs

Link to short paper: https://dl.acm.org/doi/10.1145/3491418.3535156

Link to more detailed analysis: https://newtraell.cs.uchicago.edu/research/publications/techreports/TR-2022-04

BOF at PEARC’20: http://people.cs.uchicago.edu/~aachien/lssg/research/zccloud/lifetime/bof-index.html

CASC survey: https://newtraell.cs.uchicago.edu/research/publications/techreports/TR-2020-05
Thank you!
Questions?

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Mark: mjdietrich@bloodstonesolutions.org

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Thanks to the Zero-carbon Cloud group!
## Baseline Scenario: Projecting Key Parameters

<table>
<thead>
<tr>
<th>Year</th>
<th>2022</th>
<th>2027</th>
<th>2032</th>
<th>2037</th>
<th>2042</th>
<th>20-year Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Investment</td>
<td>$1,000,000</td>
<td>$1,000,000</td>
<td>$1,000,000</td>
<td>$1,000,000</td>
<td>$1,000,000</td>
<td>1.00x</td>
</tr>
<tr>
<td>Petaflops/s (PF)</td>
<td>0.9</td>
<td>4.5</td>
<td>24.2</td>
<td>129.1</td>
<td>688.3</td>
<td>809x</td>
</tr>
<tr>
<td>System Power (kW)</td>
<td>65</td>
<td>139</td>
<td>297</td>
<td>634</td>
<td>1,352</td>
<td>20.7x</td>
</tr>
<tr>
<td>Cost of power ($/kWyear, 1st year of operation, average campus site)</td>
<td>$764</td>
<td>$921</td>
<td>$1,110</td>
<td>$1,337</td>
<td>$1,612</td>
<td>2.11x</td>
</tr>
<tr>
<td>Power costs (annual, average campus site)</td>
<td>$49,907</td>
<td>$128,272</td>
<td>$329,689</td>
<td>$847,378</td>
<td>$2,177,955</td>
<td>43.6x</td>
</tr>
<tr>
<td>Scope 2 CO2 Emissions (MT, annual, average campus site)</td>
<td>250</td>
<td>533</td>
<td>1,137</td>
<td>2,426</td>
<td>5,175</td>
<td>20.7x</td>
</tr>
<tr>
<td>System Size (Racks)</td>
<td>1.8</td>
<td>2.0</td>
<td>2.3</td>
<td>2.5</td>
<td>2.8</td>
<td>1.56x</td>
</tr>
<tr>
<td>Space costs (annual, average campus site)</td>
<td>$10,026</td>
<td>$11,208</td>
<td>$12,529</td>
<td>$14,005</td>
<td>$15,656</td>
<td>1.56x</td>
</tr>
<tr>
<td>TCO (annual)</td>
<td>$1,059,933</td>
<td>$1,139,480</td>
<td>$1,342,218</td>
<td>$1,861,383</td>
<td>$3,193,611</td>
<td>3.01x</td>
</tr>
<tr>
<td>TCO/PF</td>
<td>$1,245,840</td>
<td>$251,129</td>
<td>$55,465</td>
<td>$14,422</td>
<td>$4,640</td>
<td>0.00372x</td>
</tr>
</tbody>
</table>
Power density in the Top500: GPU-heavy systems significantly better on W/Gflops/s

N=2,235 unique systems

Trend: -26-27%/yr, $R^2>.078$

- except for “hiCPU”
  (CPUs account for 14-99.9% of total Rpeak): -19%/yr

W/Rpeak parallels W/Rmax