



Sustainability in Computer Science: Green HPC: Paving the Way for Sustainable Supercomputing

Philipp Gschwandtner, Research Center HPC, University of Innsbruck, 05.10.2026

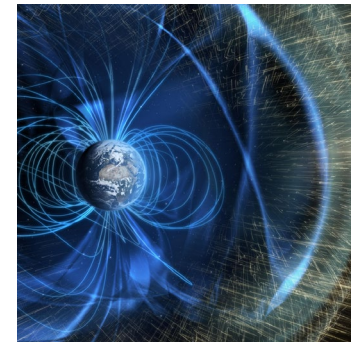
What is Green HPC?

“environmentally friendly”

High Performance Computing

“[...] uses supercomputers and computer clusters
to solve advanced computation problems”
(Wikipedia)

Green HPC



Main sustainability concern in HPC is energy – but why?

▶ Smartphone iPhone 17:

- ▶ Battery Capacity 3.692 mAh
- ▶ With one charge per day (0,30 € per kWh) ▶ approx. 5 kWh or 1,05 € per year

▶ Personal computer

- ▶ Current Intel/AMD multicore processor + GPU
- ▶ Running 4 hours per day ▶ approx. 200 kWh or 60 € per year

▶ Electric vehicle: Skoda Enyaq RS

- ▶ 79 kWh battery, 14,2 kWh/100 km
- ▶ Annual mileage approx. 15.000 km ▶ approx. 2.130 kWh or 639 € per year

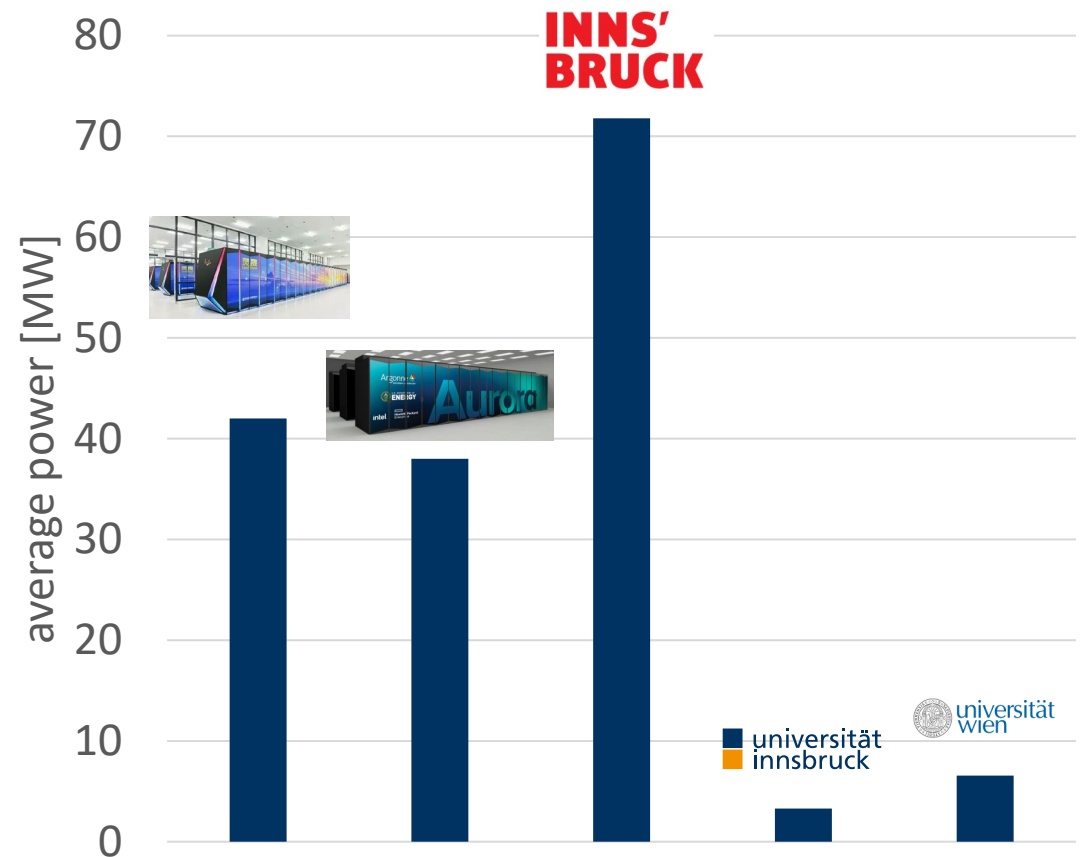
Main sustainability concern in HPC is energy – but why?

- ▶ **Example: LineShine**
 - ▶ currently the fastest supercomputer world-wide, located in Shenzhen, China
- ▶ **Extreme computing and storage capacities**
 - ▶ 13 million cores (LX2 304C 1.55GHz)
 - ▶ 23 petabytes of main memory (1.4 HBM + 11.6 DDR5)
 - ▶ 650 petabytes of storage
 - ▶ measured peak performance of over 2 exaflops ($> 2 \times 10^{18}$ arithmetic operations per second) (2.000.000.000.000.000.000)
- ▶ **High electrical and thermal operating requirements**
 - ▶ 42 megawatts of power
 - ▶ 367 GWh or 110 million € per year
 - ▶ the **main limiting design factor** when building supercomputers

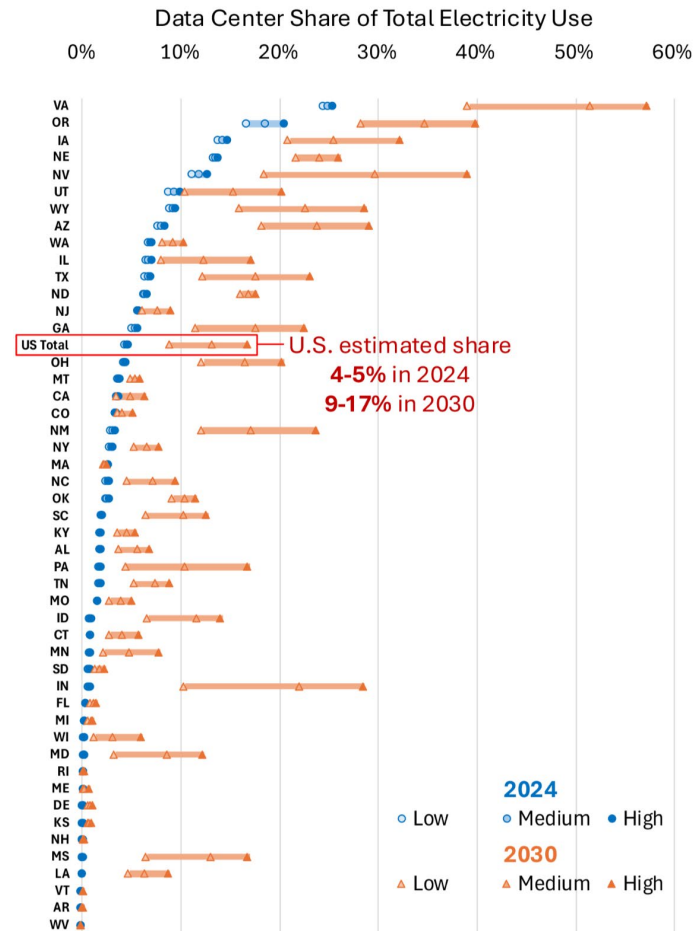


How much is 42 megawatts?

- ▶ 100% LineShine supercomputer
- ▶ 109% Aurora supercomputer (No. 4 world-wide)
- ▶ 58% of Innsbruck
- ▶ 13x University of Innsbruck
- ▶ 6.4x University of Vienna



Projection of data center energy demands



Source: <https://www.epri.com/research/products/000000003002034696>

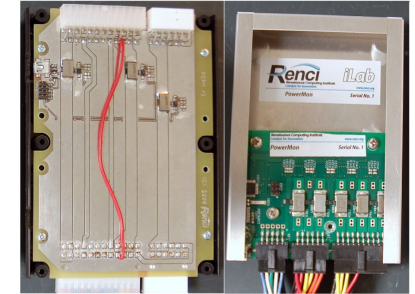
To be able to optimize, we need to measure first!

- ▶ Need power/energy instrumentation

- ▶ “homemade” examples on the right, good for experimental research but does not scale to large systems (also: fire hazard!)
- ▶ modern supercomputers have this built-in
- ▶ note that there is also a plethora of power/energy models – some better, some worse



Voltech PM1000+



PowerMon2

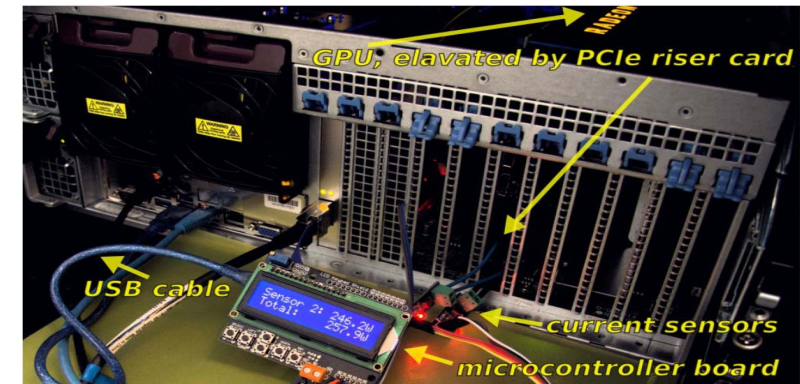
- ▶ Need metrics to be able to evaluate, compare and optimize

- ▶ e.g. Power Usage Effectiveness

$$PUE = \frac{\text{total facility energy}}{\text{IT equipment energy}}$$

- ▶ e.g. Energy-Delay Product (EDP)

$$EDP = \text{energy} \times \text{walltime}$$



PowerSensor 2

TOP500 List

- ▶ List of the fastest supercomputers world-wide
 - ▶ released twice every year
 - ▶ high performance linpack (HPL) benchmarking (linear algebra stress-testing)
 - ▶ very interesting analyses and statistics around supercomputing and HPC
 - ▶ <https://www.top500.org>
- ▶ Currently June 2026 edition
 - ▶ Power consumption reported for many (but not all!) systems
- ▶ Also: Green500
 - ▶ Performance-per-energy ranking

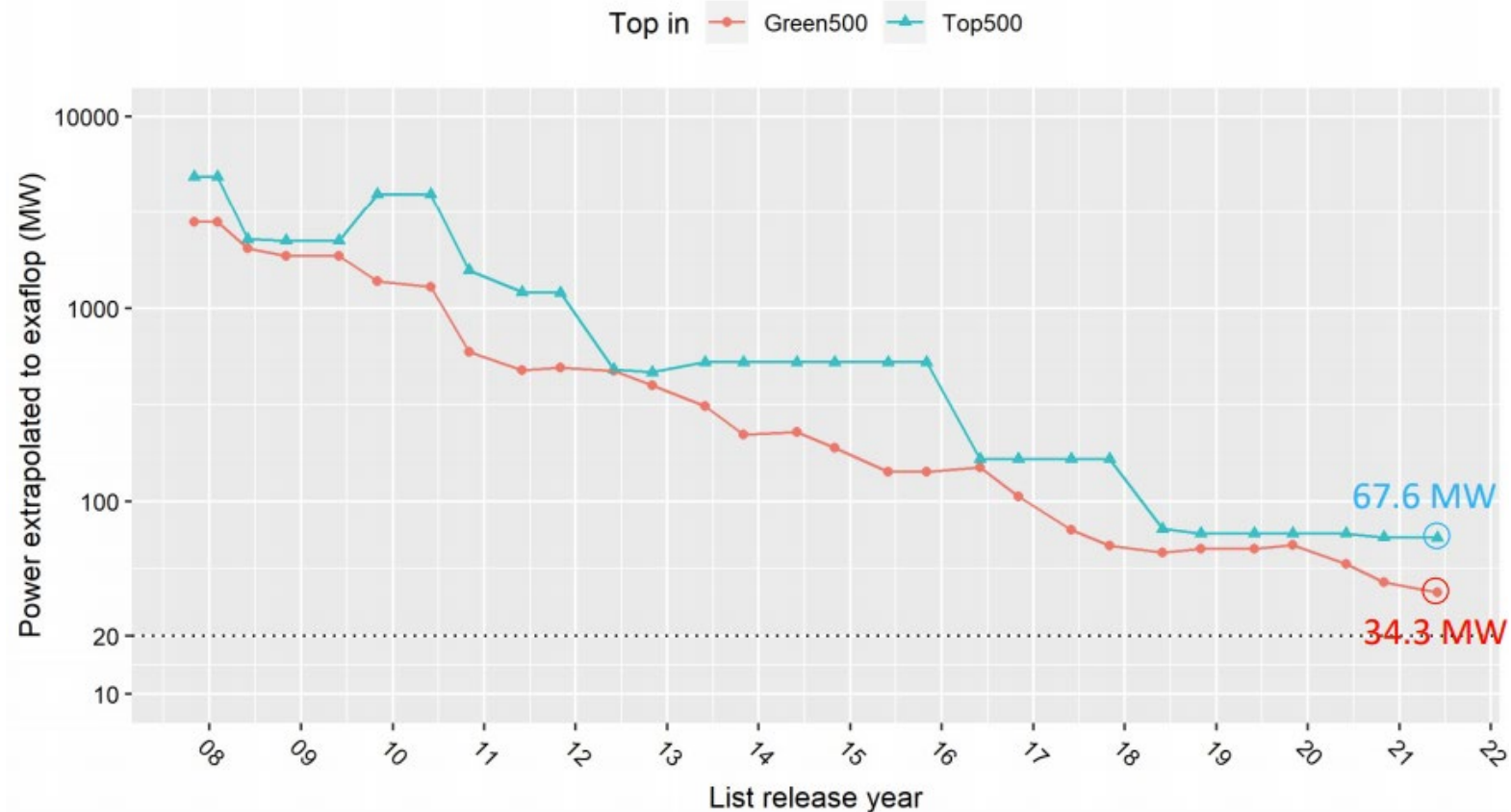
Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	LineShine - LingKun, LX2 304C 1.55GHz, LingQi, Kylin OS, Shenzhen Cloud Computing Center Co., Ltd. National Supercomputing Centre in Shenzhen (NSCS) China	13,789,440	2,198.40	2,735.82	42,220
2	El Capitan - HPE Cray EX255a, AMD 4th Gen EPYC 24C 1.8GHz, AMD Instinct MI300A, Slingshot-11, TOSS, HPE DOE/NNSA/LLNL United States	11,340,000	1,809.00	2,821.10	29,685
3	Frontier - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE Cray OS, HPE DOE/SC/Oak Ridge National Laboratory United States	9,066,176	1,353.00	2,055.72	24,607
4	Aurora - HPE Cray EX - Intel Exascale Compute Blade, Xeon CPU Max 9470 52C 2.4GHz, Intel Data Center GPU Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States	9,264,128	1,012.00	1,980.01	38,698
5	JUPITER Booster - BullSequana XH3000, GH Superchip 72C 3GHz, NVIDIA GH200 Superchip, Quad-Rail NVIDIA InfiniBand NDR200, RedHat Enterprise Linux, Bull EuroHPC/FZJ Germany	4,801,344	1,000.00	1,226.28	15,794

Green500 measurement methodology

- ▶ 33 pages of definitions: measurement devices, topology, workload requirements, averaging, etc.
- ▶ Level 1 requires to measure
 - ▶ The entire “core” phase ≥ 1 minute, compute-nodes + measure or estimate network interconnect
 - ▶ Power and take the average, at least $\text{std} : \max(\{2 \text{ kW}, 10\% \text{ of the system}, 15 \text{ nodes}\})$
- ▶ Level 2
 - ▶ Level 1 + average power of full run, intermediate measurements (at least 10 averages in core phase)
 - ▶ Compute-node subsystem + measure or estimate all other subsystems, at least $\text{std} : \max(\{10 \text{ kW}, 12\% \text{ of the system}, 15 \text{ nodes}\})$
- ▶ Level 3
 - ▶ Level 2 but measure energy and compute average power consumption
 - ▶ Energy measurement resolution: 120 Hz for DC, 5 KHz for AC, entire system (all components, all nodes, no extrapolations!)

Rank	TOP500 Rank	System	Cores	Rmax (PFlop/s)	Power (kW)	Energy Efficiency (GFlops/watts)
1	445	KAIROS - BullSequana XH3000, GH Superchip 72C 3GHz, NVIDIA GH200 Superchip, Quad-Rail NVIDIA InfiniBand NDR200, RedHat Enterprise Linux, Bull CALMIP / University of Toulouse - CNRS France	13,056	3.05	46	73.282
2	192	ROME0-2025 - BullSequana XH3000, Grace Hopper Superchip 72C 3GHz, NVIDIA GH200 Superchip, Quad-Rail NVIDIA InfiniBand NDR200, Red Hat Enterprise Linux, Bull ROME0 HPC Center - Champagne-Ardenne France	47,328	9.86	160	70.912
3	250	Levante GPU extension - BullSequana XH3000, GH Superchip 72C 3GHz, NVIDIA GH200 Superchip, Quad-Rail NVIDIA InfiniBand NDR200, RedHat Enterprise Linux, Bull DKRZ - Deutsches Klimarechenzentrum Germany	35,904	6.75	110	69.426
4	238	Isambard-AI phase 1 - HPE Cray EX254n, NVIDIA Grace 72C 3.1GHz, NVIDIA GH200 Superchip, Slingshot-11, HPE University of Bristol United Kingdom	34,272	7.42	117	68.835

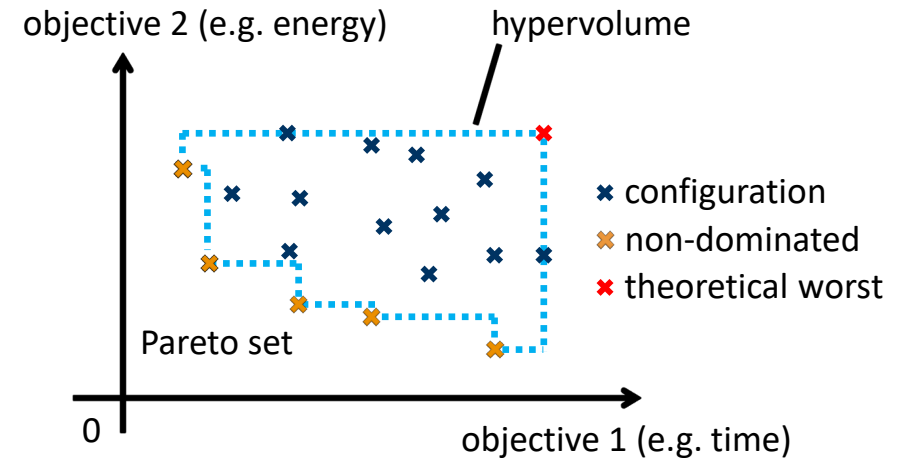
Power consumption projected to 1 exaflop



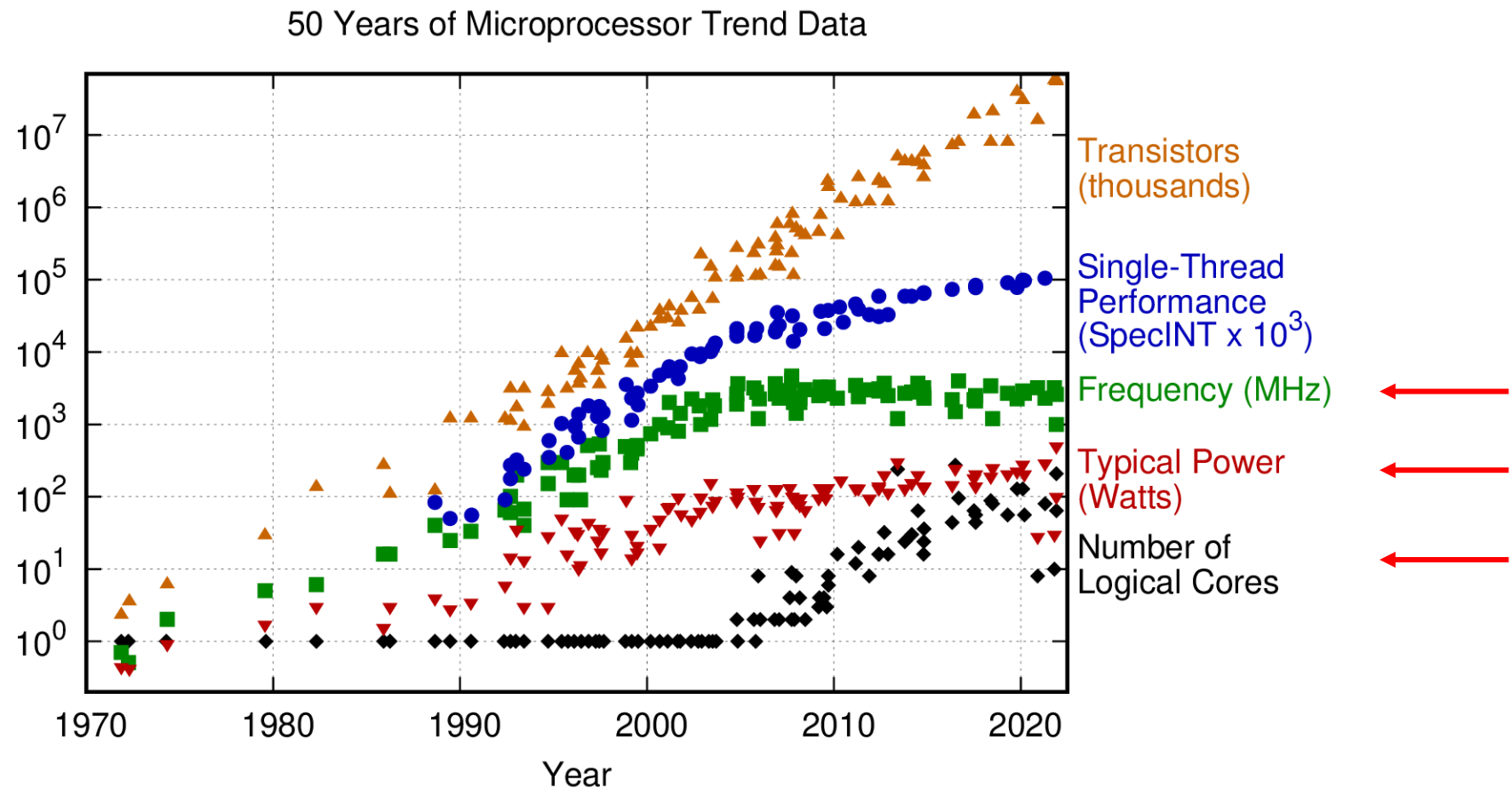
<https://www.hpcwire.com/2021/07/15/15-years-later-the-green500-continues-its-push-for-energy-efficiency-as-a-first-order-concern-in-hpc/>

Avenues of optimization

- ▶ Multiple attack points for making HPC more energy-efficient
 - ▶ increased parallelism
 - ▶ cooling
 - ▶ what and how the hardware is used
- ▶ When working with energy-efficient HPC, it's always a multi-objective problem
 - ▶ optimizing for power and/or energy often means sacrificing (a little bit of) performance
 - ▶ e.g. Pareto-optimality



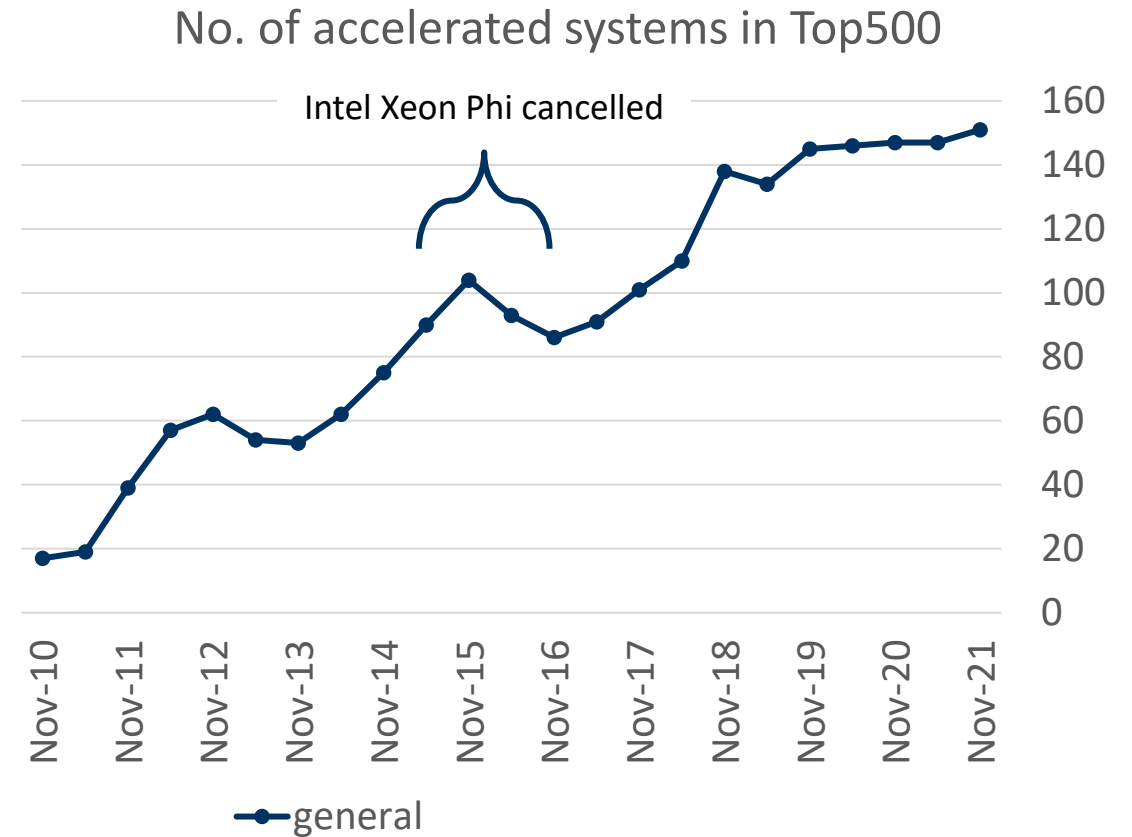
Reducing energy in computing: Parallelism!



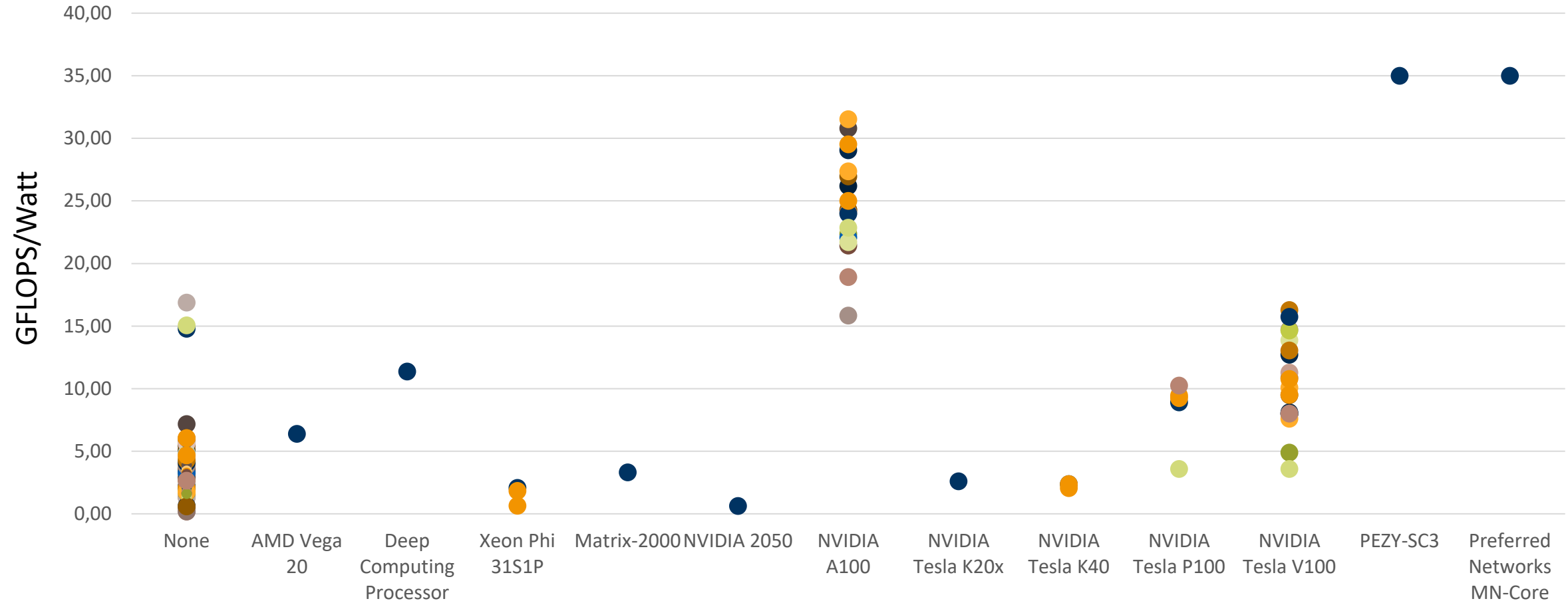
Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2021 by K. Rupp

Reducing energy in computing: Accelerators!

- ▶ Accelerator market share in HPC has been steadily increasing and will likely continue to do so
 - ▶ Why? Distributed memory clusters with accelerators provide some of the best cost- and energy-efficiency in HPC
 - ▶ All 10 out of the top 10 entries in the November 2022 “Green 500” list are accelerator clusters (9/10 GPUs)

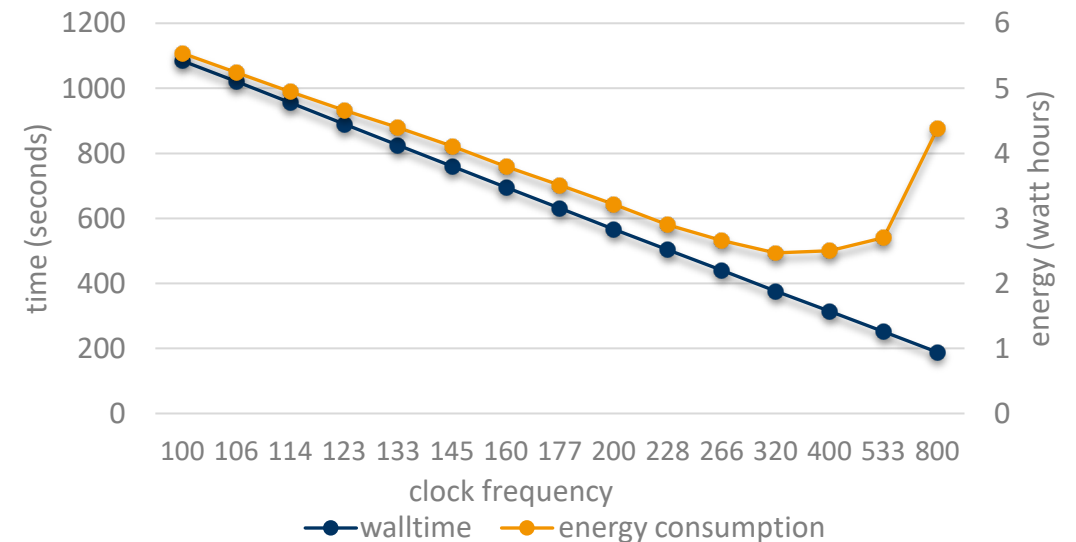
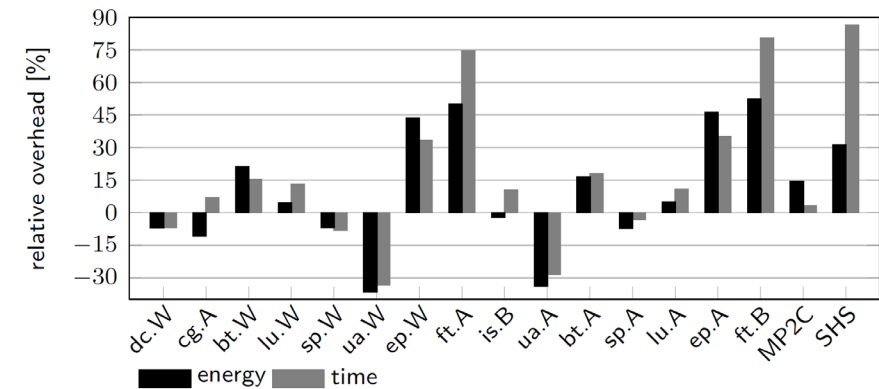


Power efficiency of all TOP500 systems (2021)



Reducing energy in computing: Tuning!

- ▶ Lots of research in software means for reducing energy consumption
- ▶ Top figure: effects of instruction mix on energy consumption of an IBM POWER7 CPU (using GCC vs. IBM XL compilers)
 - ▶ Result: In general, IBM XL produces more efficient binaries, but not always!
- ▶ Bottom figure: Dynamic Frequency and Voltage Scaling (DVFS) of the Intel SCC (experimental many-core CPU)
 - ▶ reduce clock frequency to save power and often also energy, effect heavily depends on workload
 - ▶ used in most CPUs these days (laptops, desktops, server, smartphones, etc.)
 - ▶ used on supercomputers (e.g. Energy Aware Runtime)



Reducing energy in cooling: use oil!

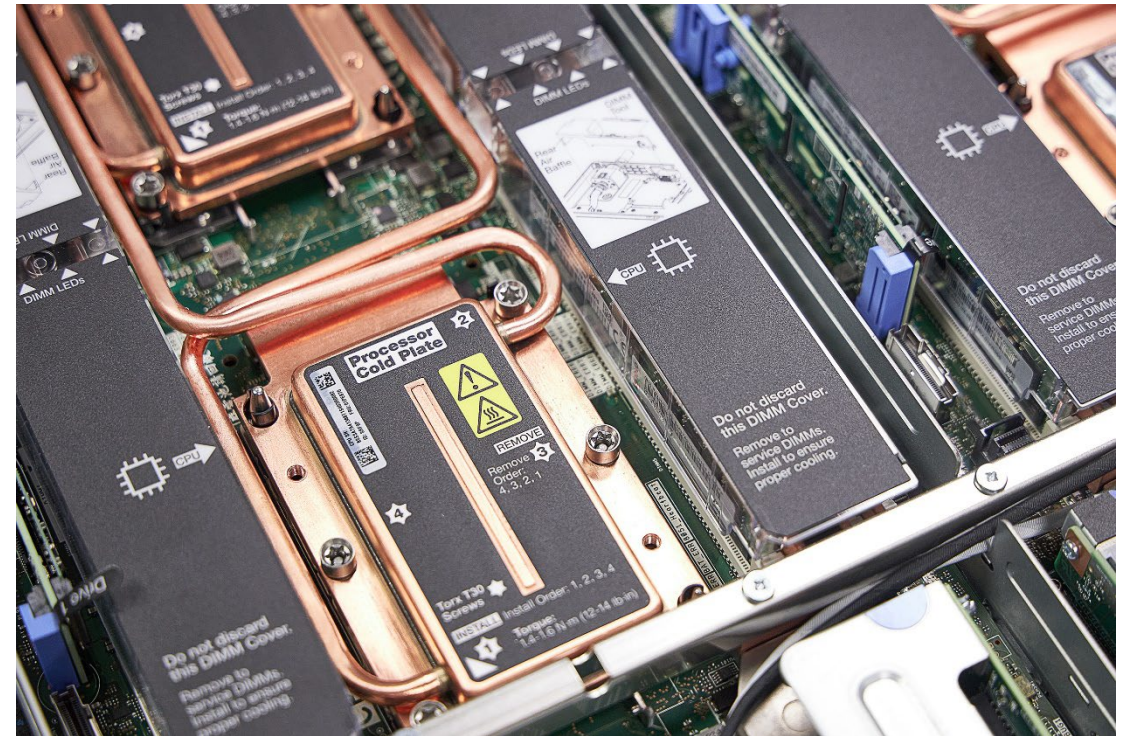
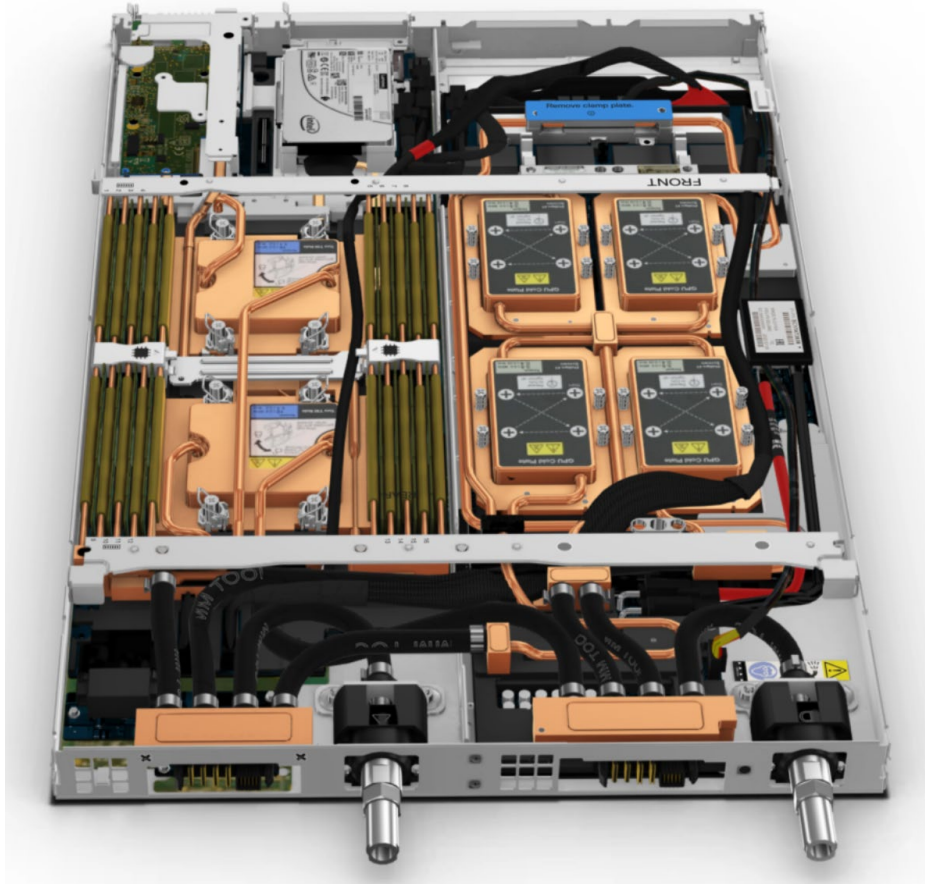
- ▶ VSC-3, fastest supercomputer in Austria in 2014
 - ▶ ranked 85th world-wide
 - ▶ 32.768 cores
 - ▶ 450 kW
 - ▶ mechanical PUE of **1.02!**
 - ▶ compare to VSC-2 (water-cooled): mPUE of 1.18
 - ▶ VSC-4 (water-cooled): 1.05



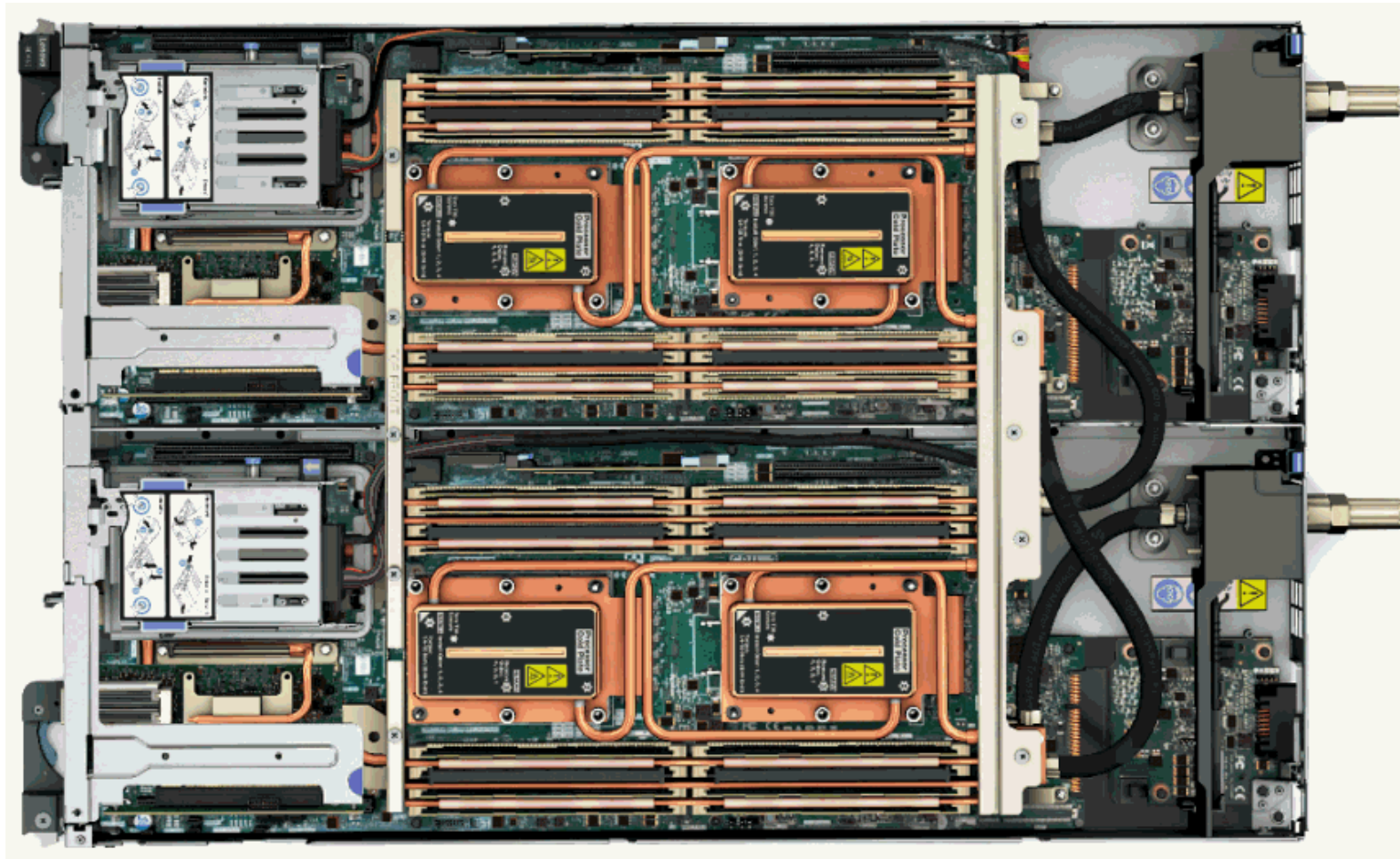
“Immersion cooling”



Supermuc-NG (Lenovo SD650 nodes, direct water cooling)

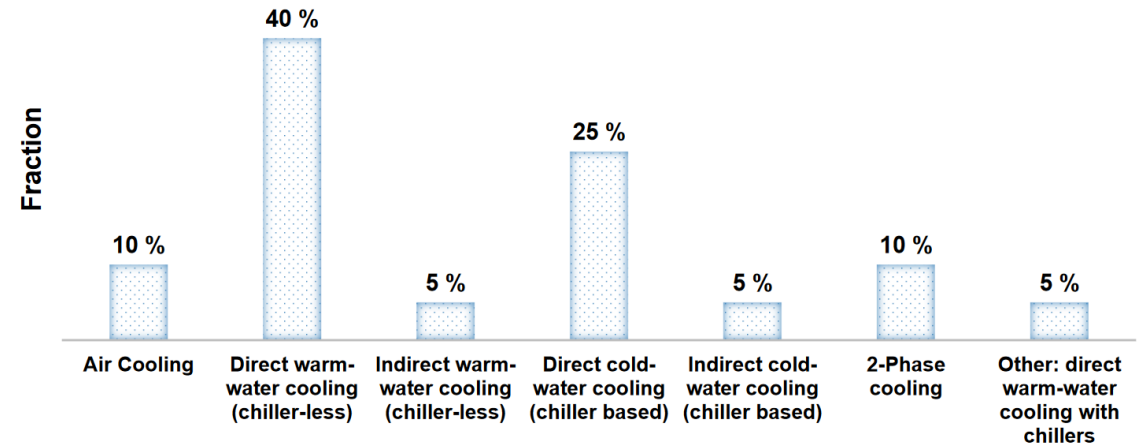


Lenovo SD650 direct water cooling



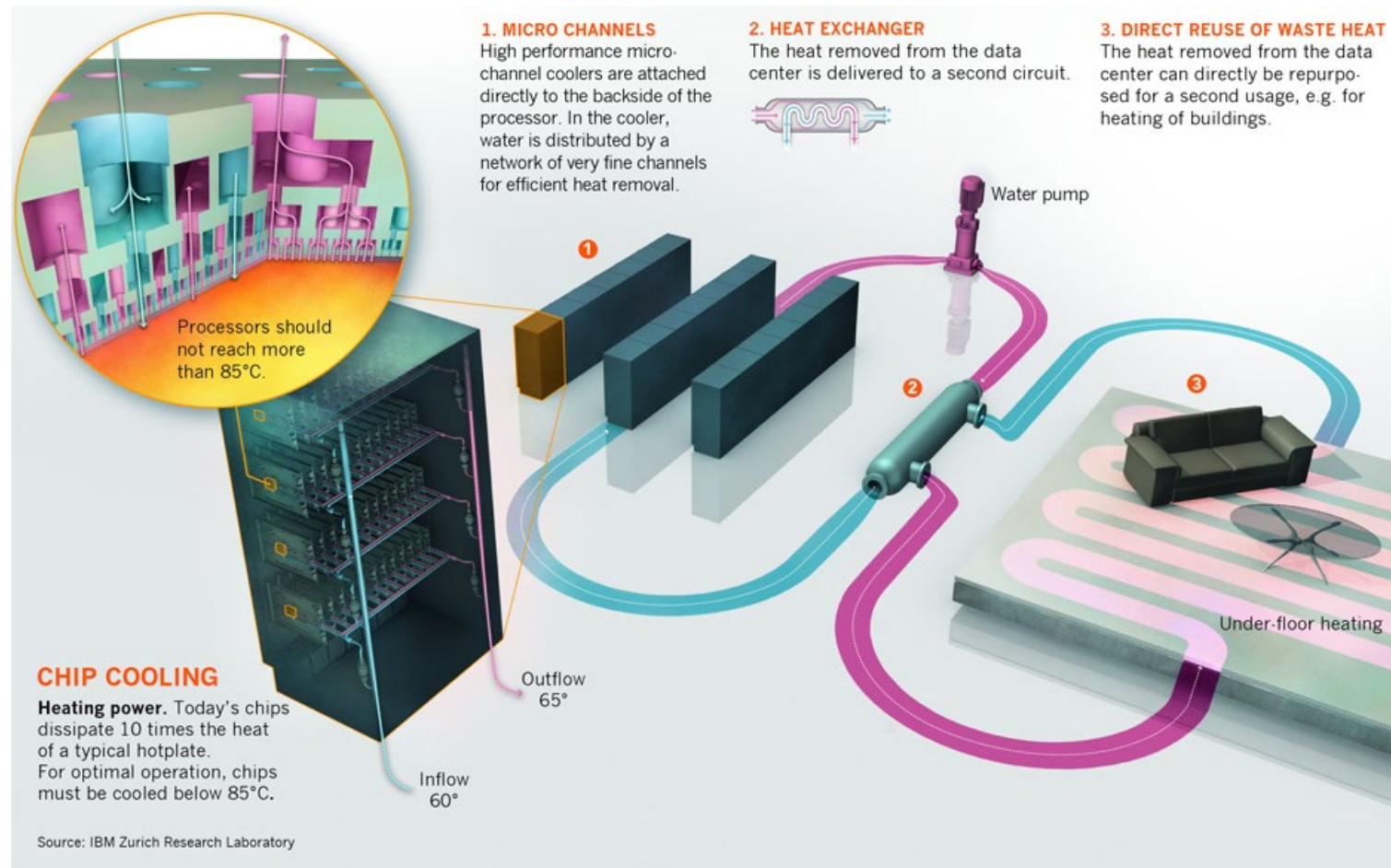
Cooling technologies

- ▶ **Air cooling**
 - ▶ easy to build and maintain, inefficient
- ▶ **Direct water cooling**
 - ▶ warm: difficult to build and maintain, very efficient, only for cooler climates (“free air cooling”)
 - ▶ cold: difficult to build and maintain, semi-efficient, for warmer climates
- ▶ **Indirect cooling**
 - ▶ cool hardware with air, cool air with water

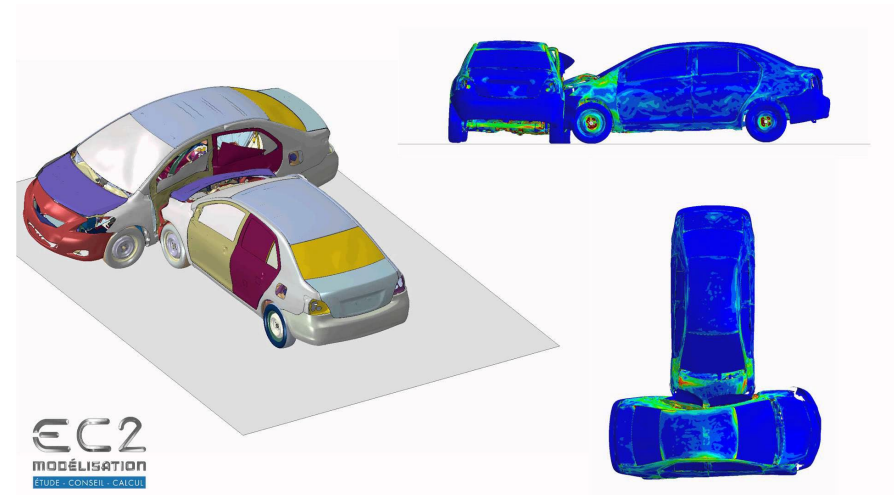
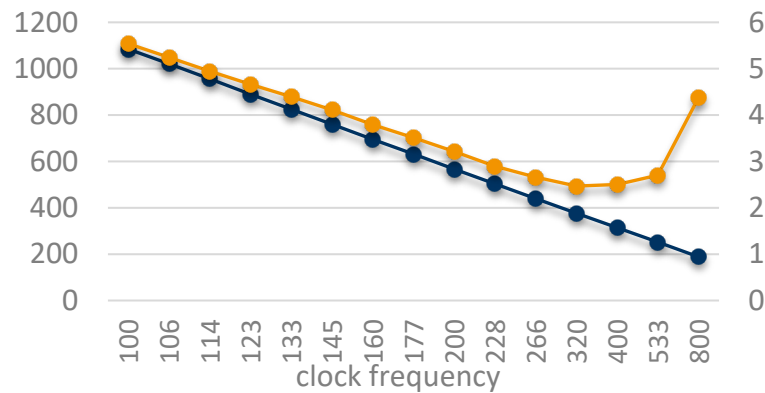
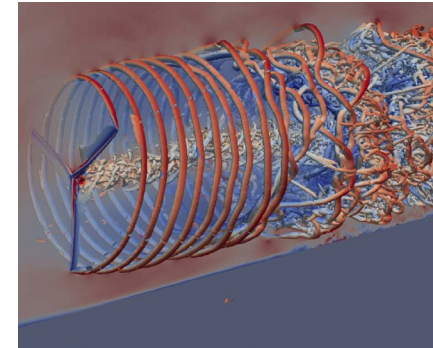
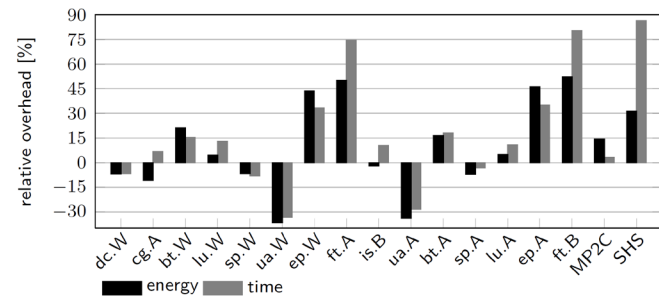


2020 survey among tier-0 and tier-1 HPC sites in Europe

How can we recycle any remaining energy consumption?



Sustainability in HPC vs. HPC for sustainability



Open issues

- ▶ There is more than just energy and power
 - ▶ Carbon Usage Effectiveness (CUE)
 - ▶ Water Usage Effectiveness (WUE)
 - ▶ Space Usage Effectiveness (SpUE)
- ▶ There are too many metrics and many are inaccurate
 - ▶ Power Usage Effectiveness (PUE)
 - ▶ Partial PUE (pPUE)
 - ▶ Energy Reuse Effectiveness (ERE)
 - ▶ Energy Reuse Factor (ERF)
- ▶ The metrics are often flawed
 - ▶ e.g. PUE cannot be used to compare HPC sites in different climate zones
- ▶ There are diverging interests
 - ▶ Operator: minimize power/energy, maximize workload throughput
 - ▶ User: minimize wall time
 - ▶ Taxpayer/politicians: minimize costs

Current developments and ideas

▶ High-bandwidth memory (HBM)

- ▶ Memory and computational units physically as close together as possible, minimize data transport distance
- ▶ Next steps: Near-memory computing, High-Bandwidth Flash (HBF), memory-as-compute

▶ Fabrication size reduction

- ▶ Research in new designs and materials (away from silicon) to decrease below ~2 nm threshold

▶ Special purpose hardware

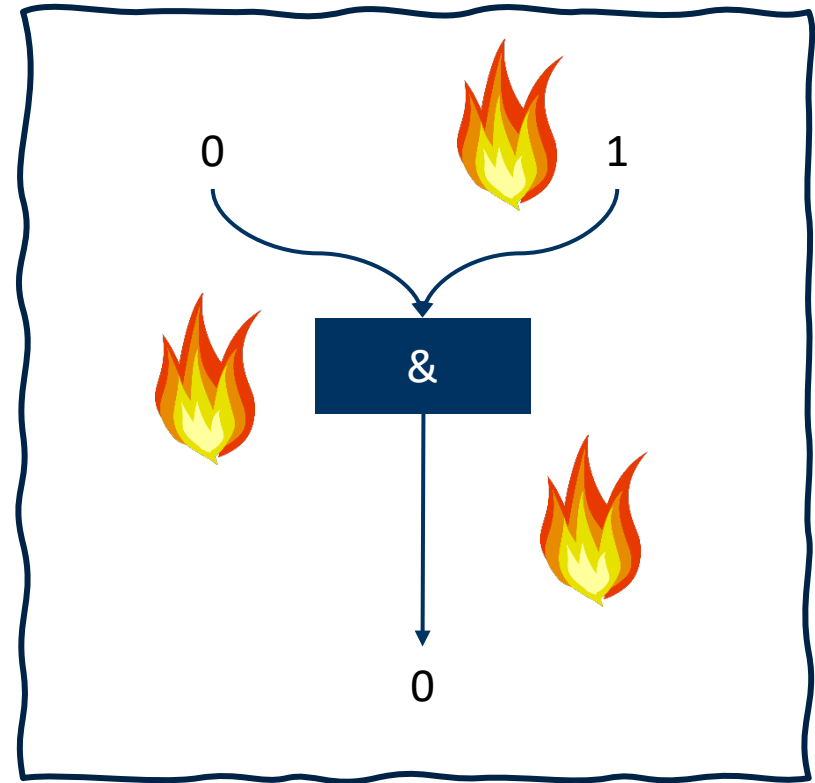
- ▶ Accelerators (scientific computing, AI, etc.)
- ▶ FPGAs
- ▶ Custom hardware designs for domain-specific problems

▶ Optical computing

- ▶ Use photons instead of electrons
- ▶ Various approaches in research, not clear yet if viable alternative

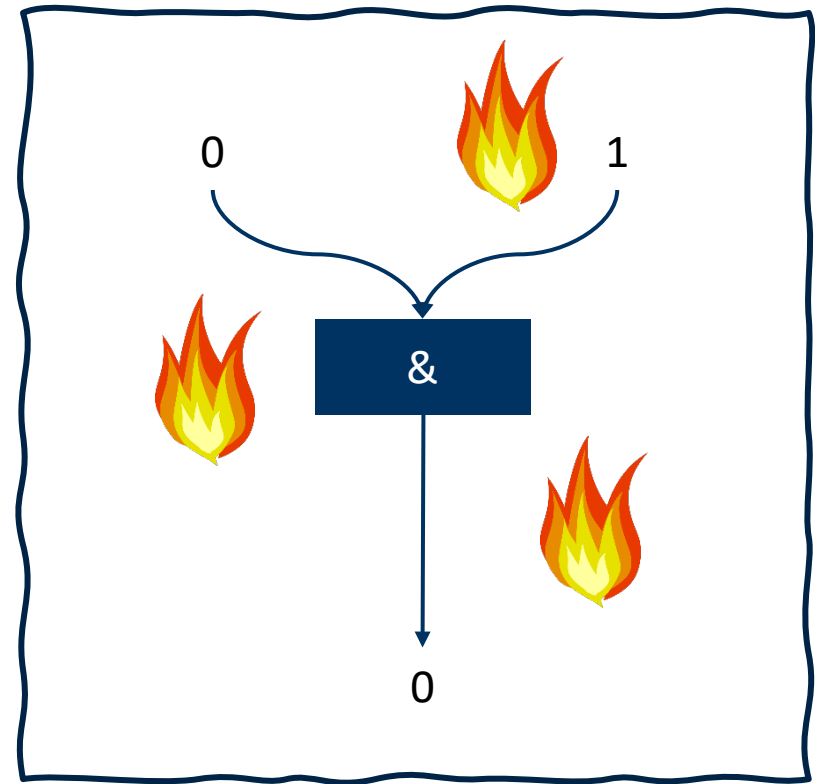
Reversible computing and Landauer principle: the future?

- ▶ There's a lower theoretical limit ("Landauer limit") to energy consumption of computation
 - ▶ Irreversible computation (e.g. logical AND) erases information, hence must be accompanied by corresponding entropy increase (=heat) in a closed system
 - ▶ because thermodynamics $\sim \ln(2)$
 - ▶ Landauer limit is approx. 0.0175 eV or $2.805 \cdot 10^{-21}$ J at room temperature
 - ▶ We're currently still several orders of magnitude away from that...



Reversible computing and Landauer principle: the future?

- ▶ **Koomey's Law:** The number of computations per joule doubles every 1.57 years
 - ▶ Coupled with Landauer limit: no more energy efficiency increase after 2080...
 - ▶ Can also apply to quantum computing
 - ▶ depends on your method/technology
- ▶ **Solution: reversible computing**
 - ▶ In theory, computing without losing information doesn't need to increase entropy, hence no heat



Today's takeaway

- ▶ There's a lot of research and engineering going on
 - ▶ in sustainability for HPC
 - ▶ in sustainability with HPC
- ▶ Power/heat are the main limiting factors in HPC
 - ▶ almost everything uses water cooling these days
 - ▶ waste heat is recycled as much as possible and “freely cooled” afterwards (no active chillers)
 - ▶ short-term developments quite clear, long-term future very unclear

▶ How to reach me/us

- ▶ philipp.gschwandtner@uibk.ac.at
- ▶ <https://dps.uibk.ac.at/~philipp>
- ▶ <https://uibk.ac.at/fz-hpc>



Image sources

- ▶ Green HPC: <https://www.hpcwire.com/2021/07/15/15-years-later-the-green500-continues-its-push-for-energy-efficiency-as-a-first-order-concern-in-hpc/>, <https://www.chemistryworld.com/features/oil-spill-cleanup/3008990.article>, Marcel Ritter (UIBK), <https://twitter.com/maven2mars/status/984440044659159040>, <https://www.nasa.gov/ames/image-feature/nasa-highlights-simulations-at-supercomputing-conference-like-aircraft-landing-gear>
- ▶ TOP500 Trend: <https://www.top500.org/statistics/perfdevel/>
- ▶ Lenovo SD650 Water Cooling Images and Animation: <https://lenovopress.lenovo.com/lp0636-thinksystem-sd650-direct-water-cooled-server-xeon-sp-gen-1>
- ▶ Cooling Technology Survey: <https://events.prace-ri.eu/event/1186/attachments/1587/2924/Shoukourian.pdf>
- ▶ IBM Research Energy Reuse: https://www.zurich.ibm.com/st/energy_efficiency/zeroemission.html
- ▶ Wind turbine: <https://www.nrel.gov/docs/fy22osti/81212.pdf>