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Federal Ministry of Education and Research

I don’t want to move to the Arctic

-

a HPC Data Center Take on PUE and Energy Efficiency

Torsten Wilde (LRZ), PPAM‘15, Kraków, Poland

lrz Fraunhofer SCAI SorTech AG IBM Johnson Controls GOHL GCS Gauss Centre for Supercomputing

Facebook – Lulea

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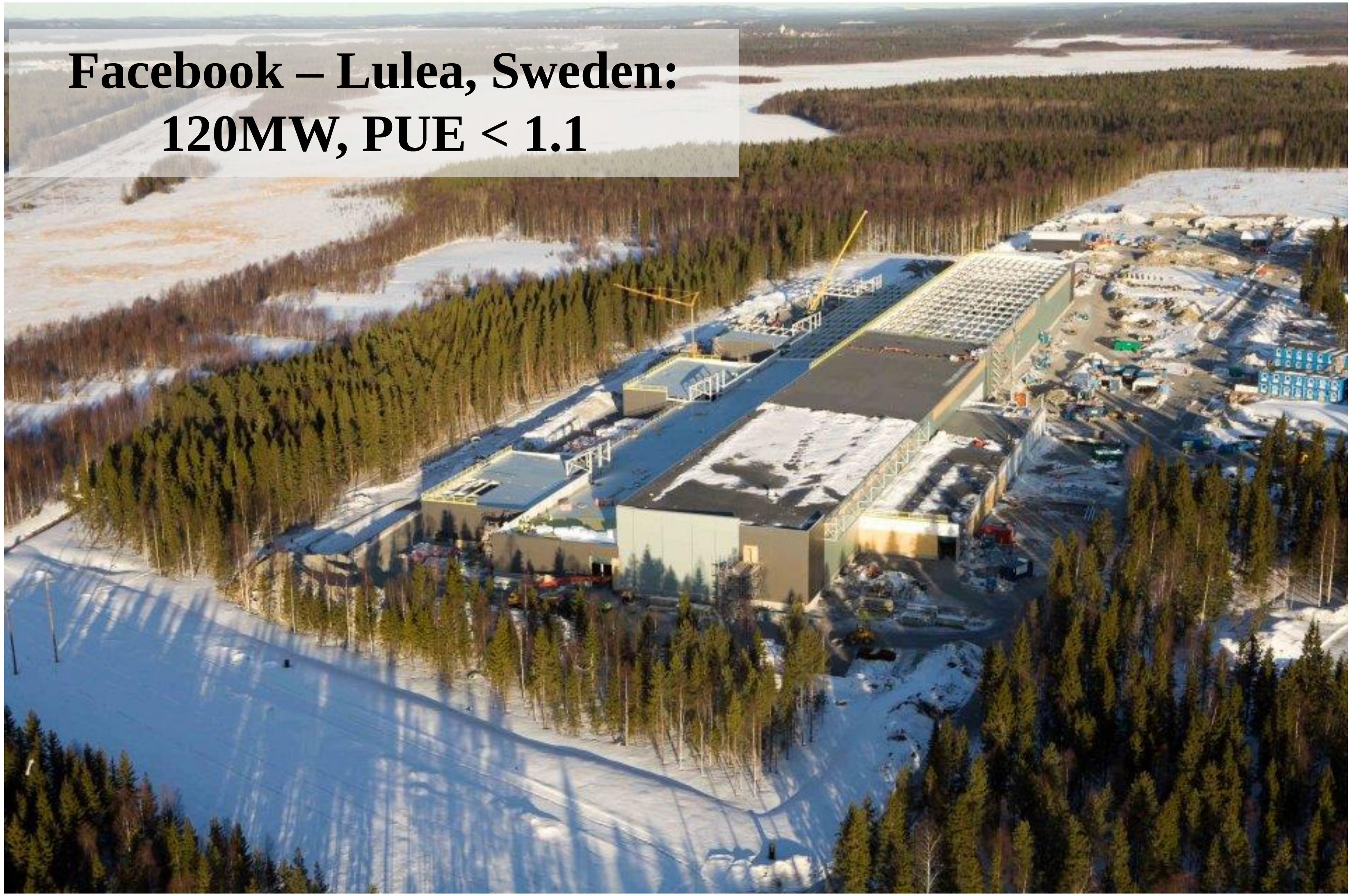
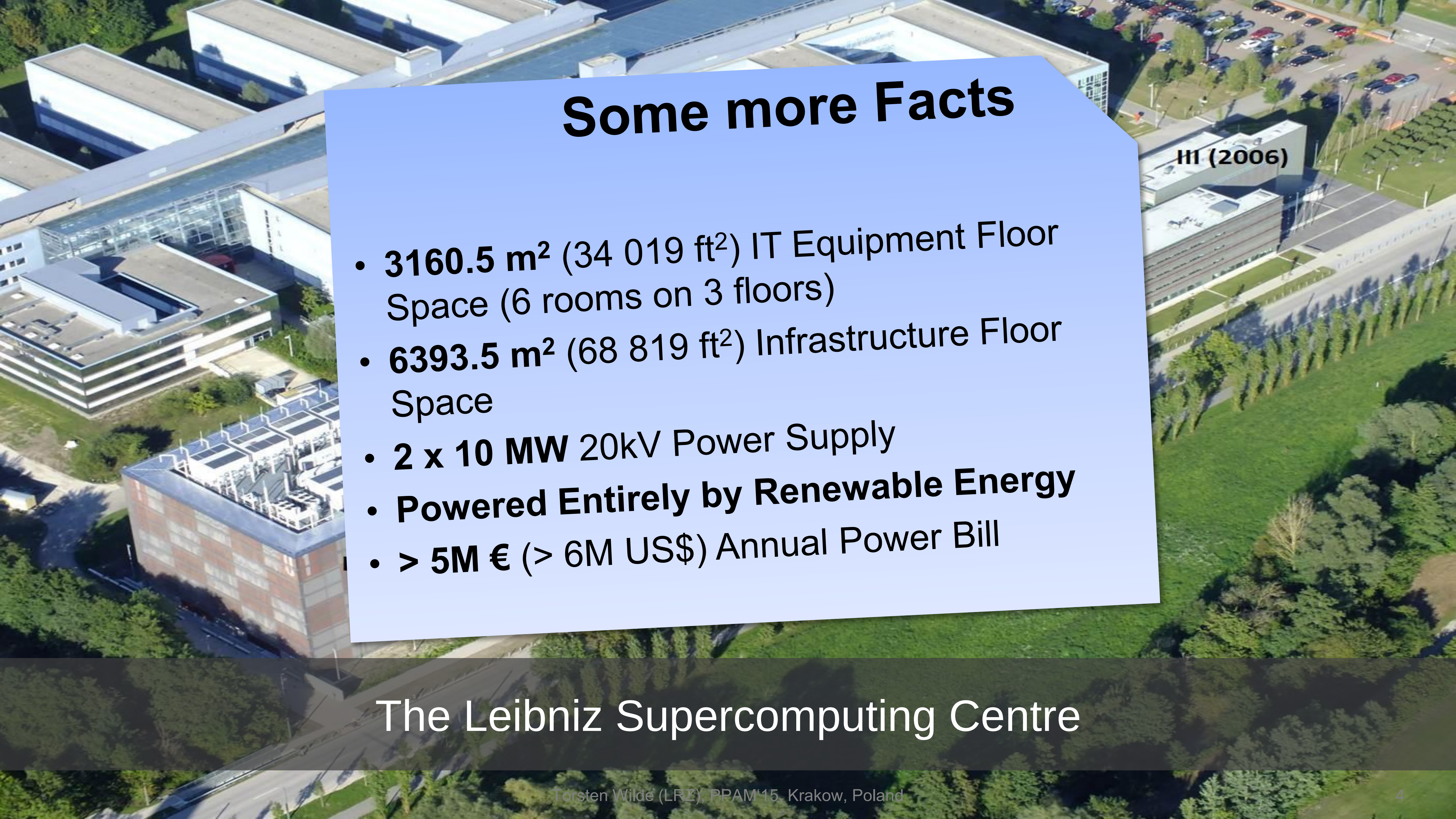


Google – Hamina

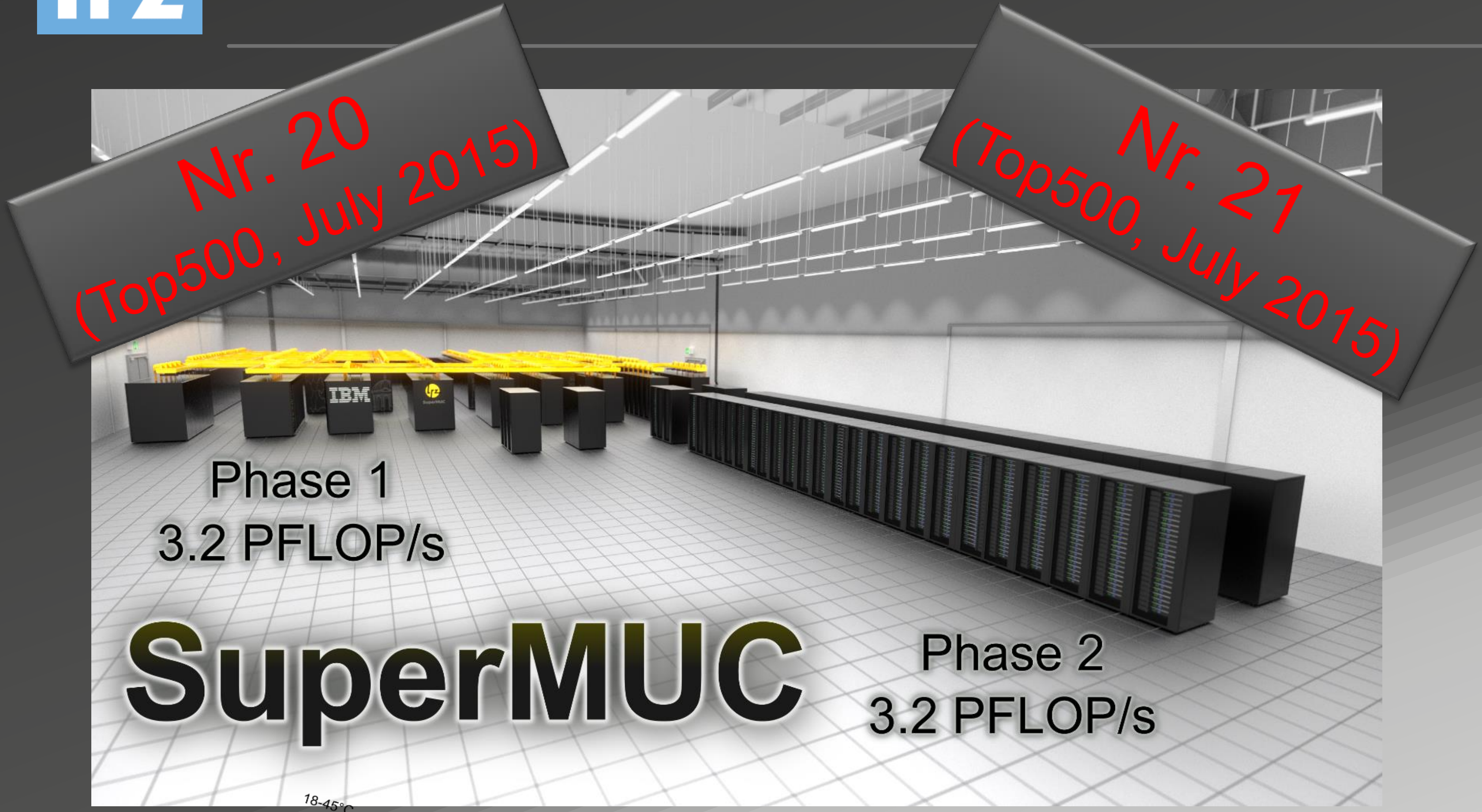


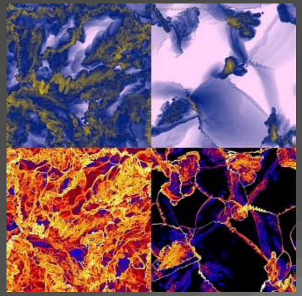
Some more Facts

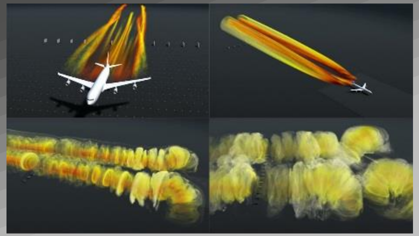
- **3160.5 m²** (34 019 ft²) IT Equipment Floor Space (6 rooms on 3 floors)
- **6393.5 m²** (68 819 ft²) Infrastructure Floor Space
- **2 x 10 MW** 20kV Power Supply
- **Powered Entirely by Renewable Energy**
- **> 5M €** (> 6M US$) Annual Power Bill

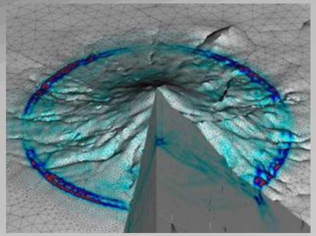
The Leibniz Supercomputing Centre

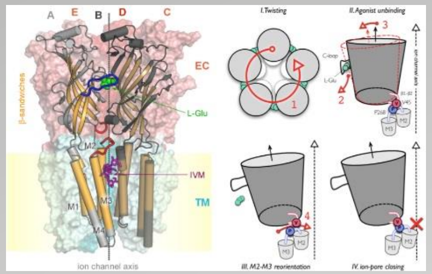
Scientific Computing at LRZ

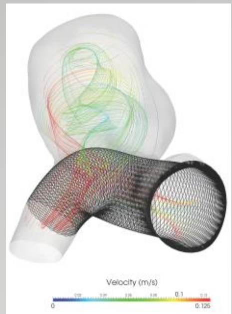


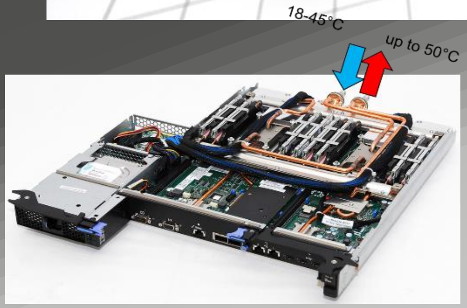


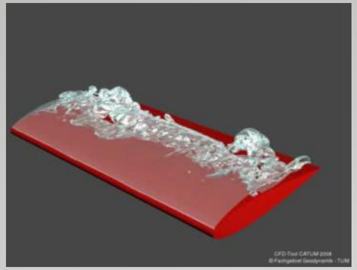


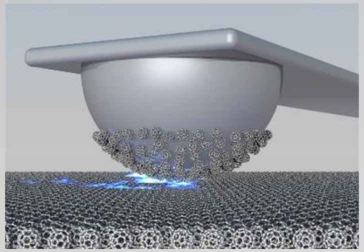


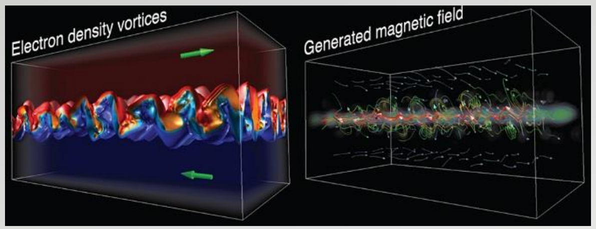








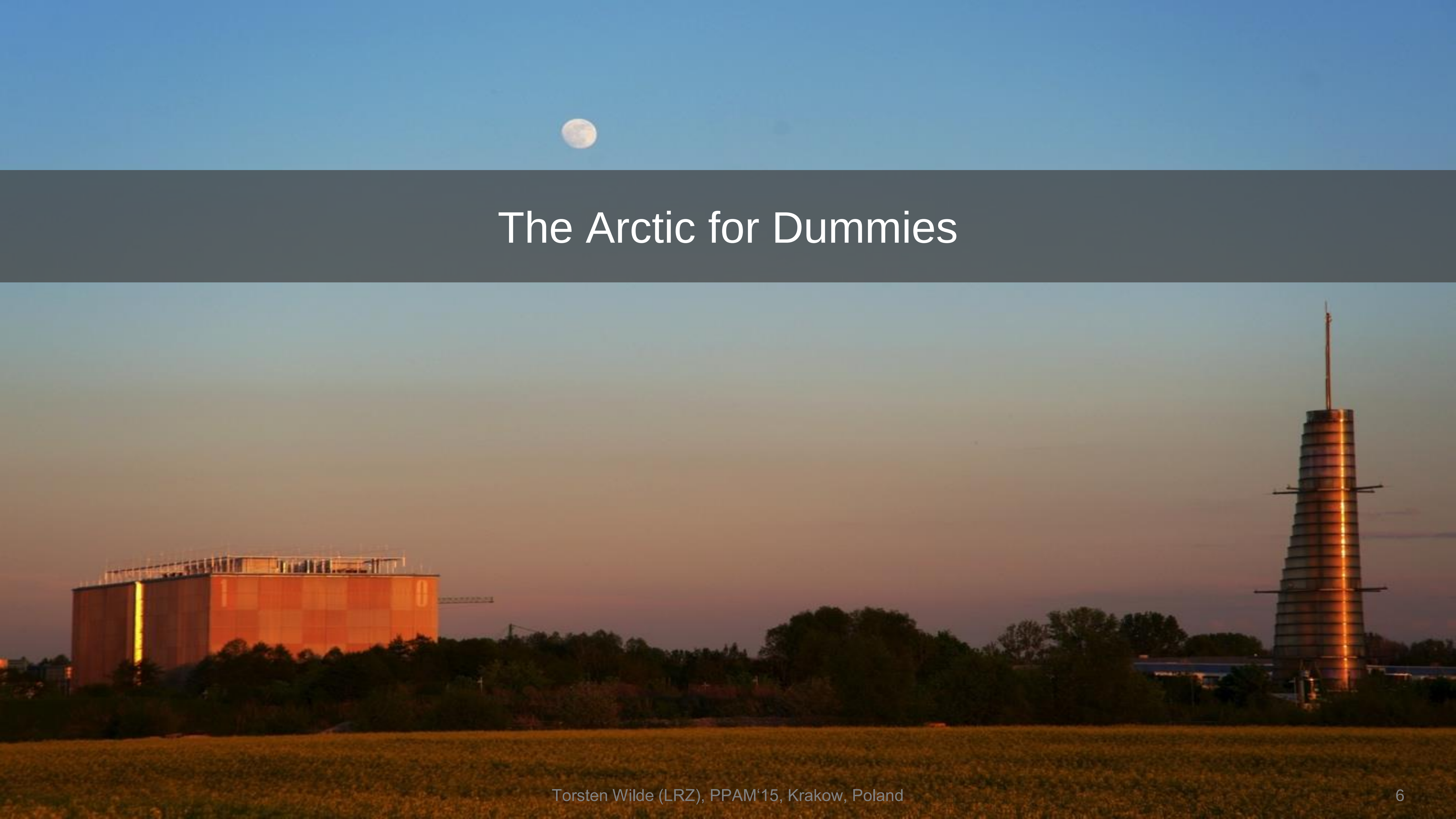




http://www.lrz.de/services/compute/supermuc/magazinesbooks/2014_SuperMUC-Results-Reports.pdf

http://www.gauss-centre.eu/gauss-centre/EN/Projects/projects_node.html

The Arctic for Dummies



The Pros

- Very good (low) Power Usage Effectiveness (PUE)
  - Cold outside air temperature all year around (doesn’t need evaporative cooling)
  - Cold water temperatures all year around (the cooler the IT the lower the leakage currents)
- Low population density, cheap real estate
- Most stable renewable energy grid in the world (Hydroelectric, Wind)
  - Low energy prices

The Pros - Torsten

The Cons - Snow, Snow, and …

Optimal PUE

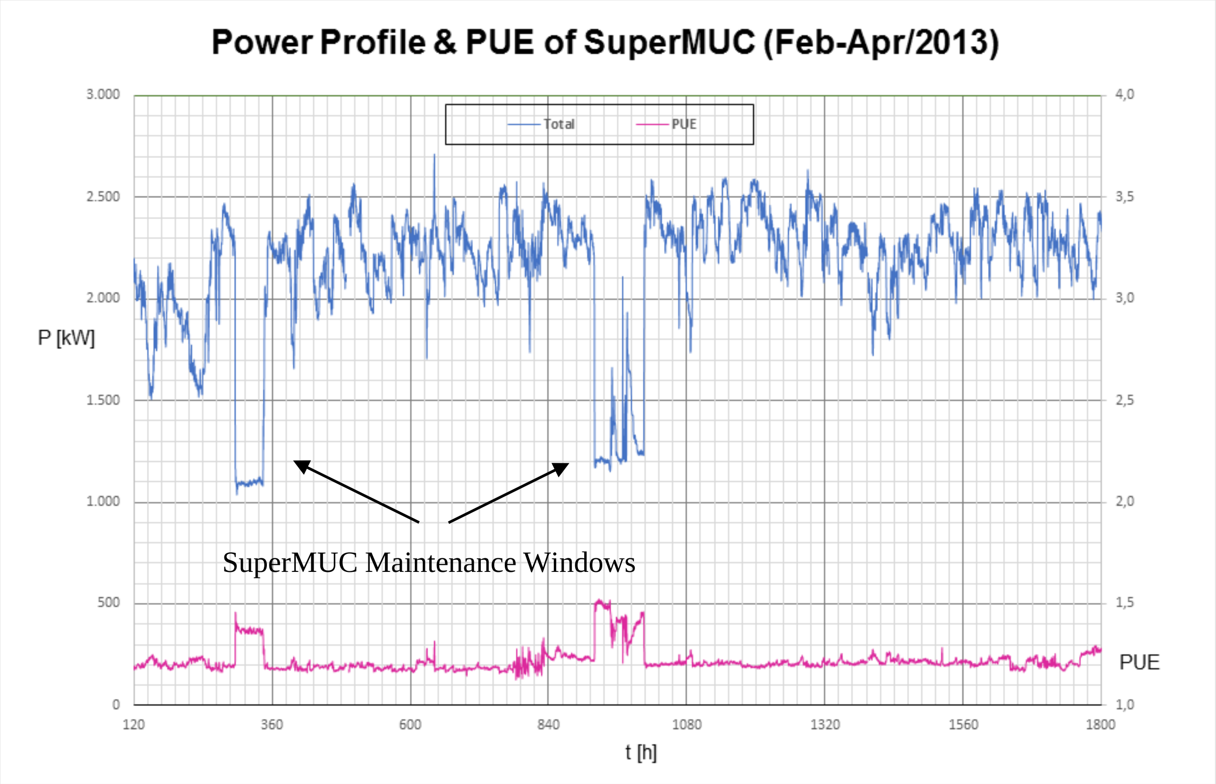
PUE

- Good to assess overall data center overhead

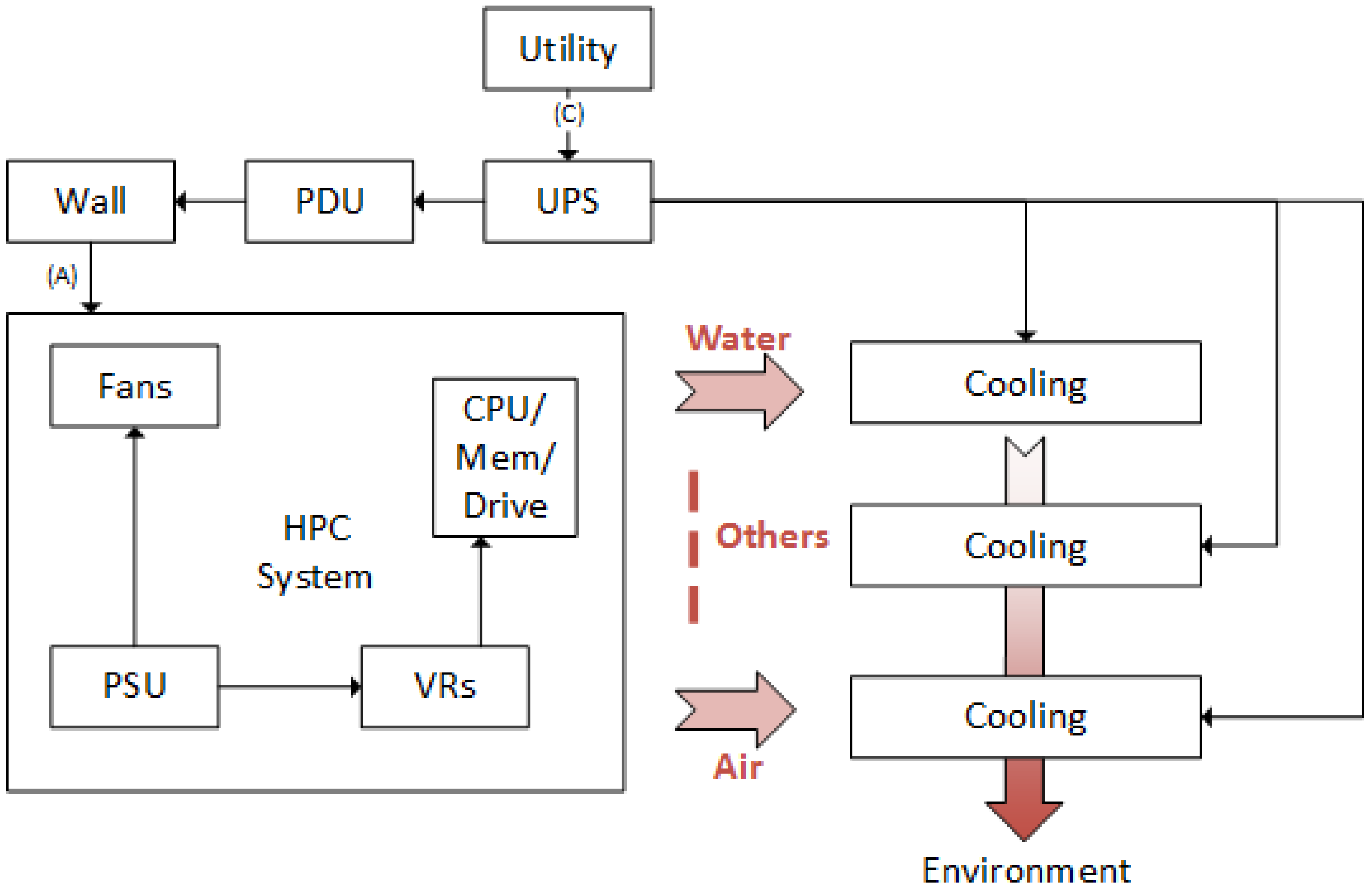
$$PUE = \frac{\sum P_i}{P_{IT}}$$

i: [IT, electrical power distribution and conversion losses, infrastructure, …]

- Does not determine if the IT power is efficiently used by IT systems
- Worst case:
  - One can very effectively waste a lot of energy
  - PUE ≠ Efficiency (Costs)



Data Center Infrastructure



Optimal PUE and Sustainability

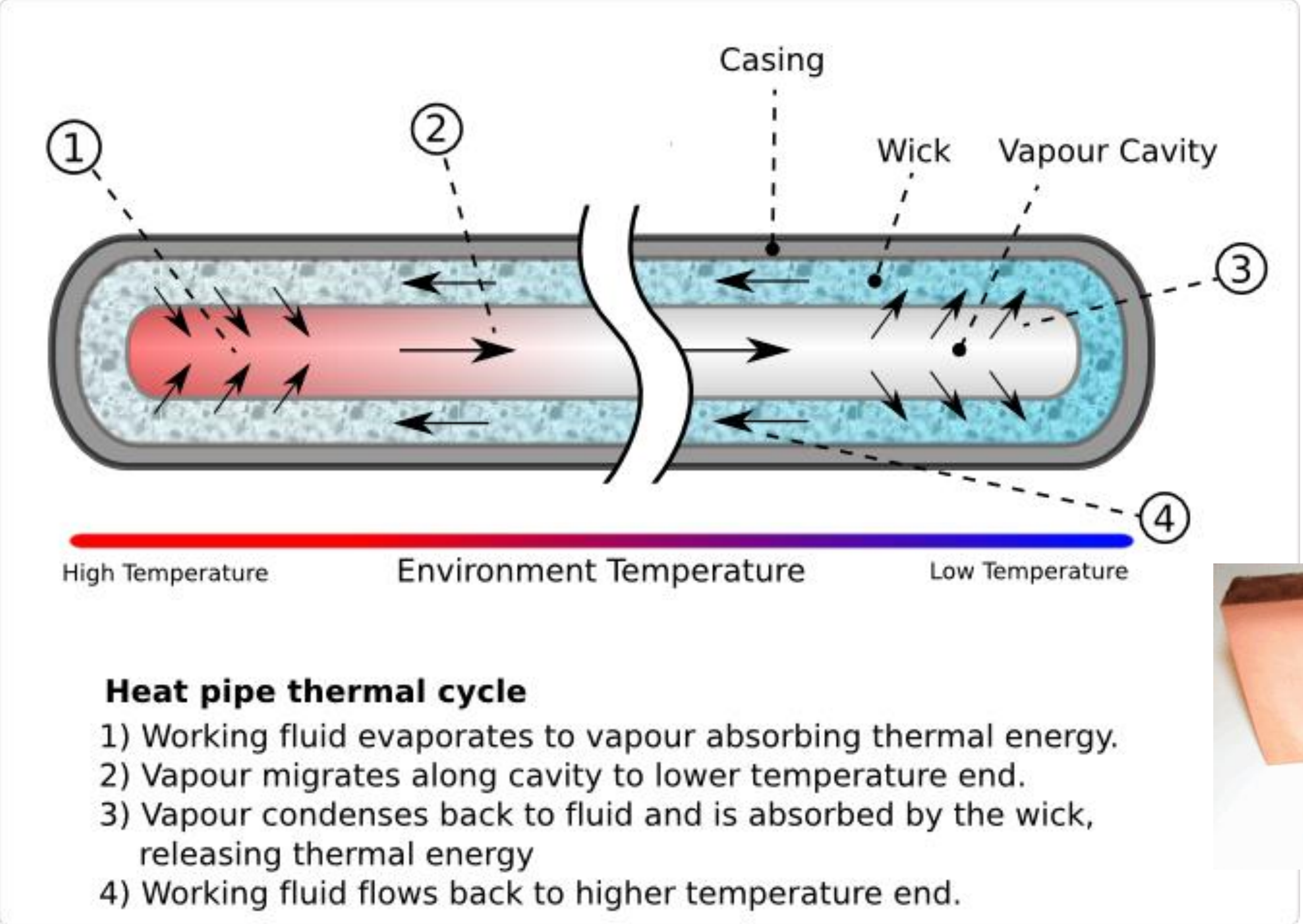
- No other power consumption than P_{IT}
  - Dark center, or only natural lighting

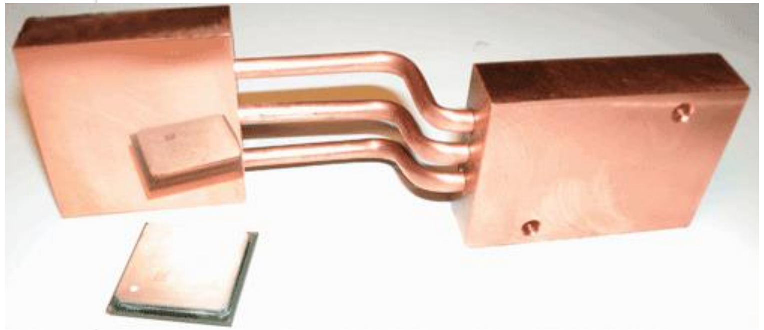
- No Electrical transmission losses
  - that’s hard, maybe super-conductors

- No power consumed by cooling system
  - Passive cooling

- No resource usage (carbon, water)
  - 100% renewable energy (challenging with only solar and wind power)
  - no water consumption (evaporative cooling)

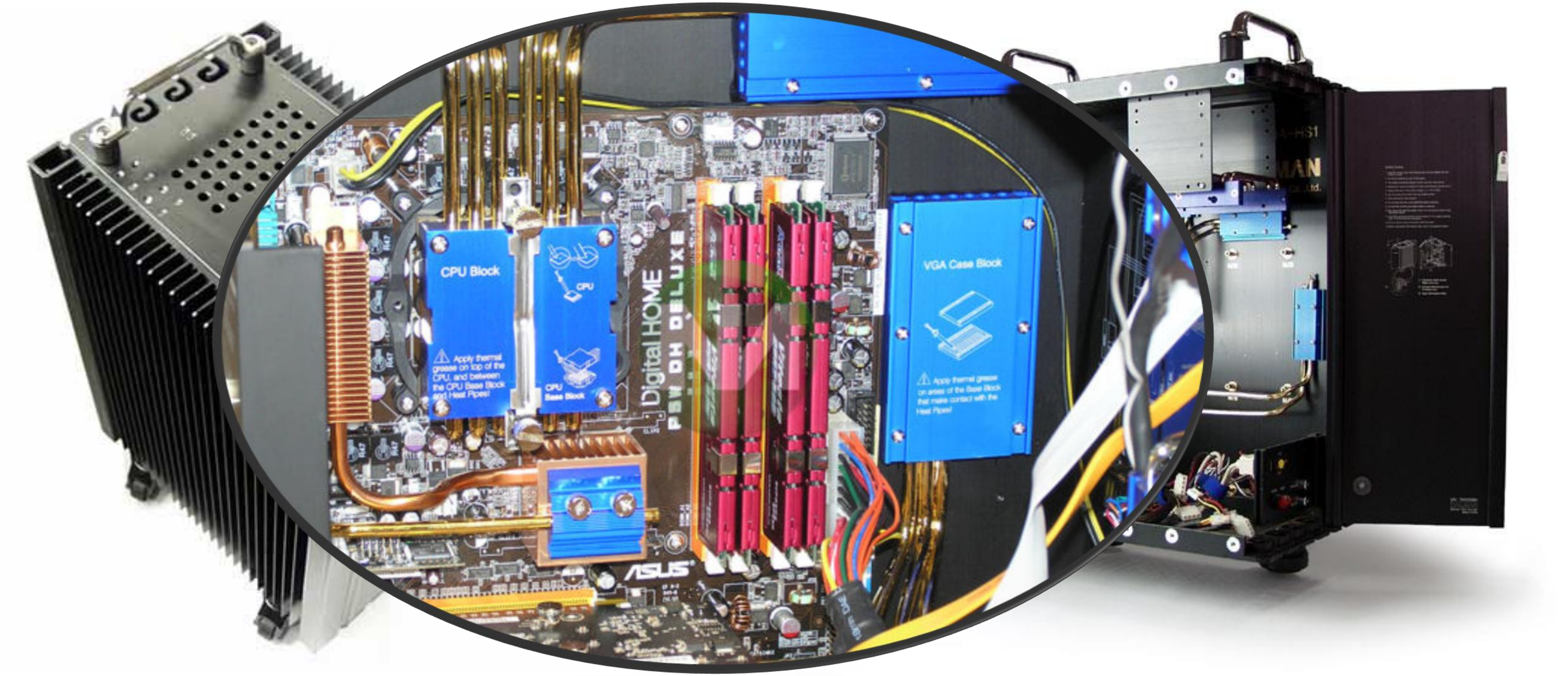
Heat Pipes





http://mmu.ic.polyu.edu.hk/mu_proj/2011/ME/ME08/1.html

Passive Cooled Data Center



Zalman TNN500A

LRZ Data Center 100% Solar Powered and Passive Cooled

- Solar Panels on roof and south side (20% efficiency, 200W per 1m^2):
  - South side: 70m x 33m = 2380m^2 => 476kW
  - Roof: 70m x 35m = 2450m^2 => 490kW
  - ~ 1MW

- Cooling area (4620m^2):
  - North side: 70m * 33m = 2310 m^2
  - West and east side: (35m*2) * 33m = 2310 m^2

- With 1m long fins in 1m intervals (9273m^2):
  - 1m*33m*141 = 4653 m^2

LRZ Cube With Heatsink on North, East, and West Side With 10K delta T

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Natural Convection Heat Transfer Coefficient Correlations (S.I. units)

1. With an isothermal vertical plane — Fluid = air

	Inputs			Calculations		
7	Fluid Temp, T_∞ =	20	°C	Temp Diff, ΔT =	10	°C
9	Surface Temp, T_w =	30	°C	Abs. Film Temp, T_f =	298	°K
11	Film Temp., T_f =	25	°C	Prandtl Number, Pr =	0,69	
12	[$T_f = (T_\infty + T_w)/2$]					
13	Area of Plate, A =	4620,0	m^2	Grashof Number, Gr =	4,09,E+13	
14	Height of Surf., L =	33,0	m			
15				Rayleigh No., Ra =	2,83E+13	
16	Fluid Density, ρ =	1,1	kg/m^3			
17				Correlation #1 (for all values of Ra):		
18	Fluid viscosity, μ =	1,87E-05	$N\text{-}s/m^2$			
19				Nu =	3291	
20	Fluid Sp. Heat, C_p =	1	J/g-°K			
21				h =	2,69	$W/m^2\text{-}K$
22	Fluid Sp. Heat, C_p =	1000	J/kg-°K			
24	Fluid Thermal			Correlation #2 (for RaL < 10^9):		
25	Conductivity, k =	0,027	J/s-m-K			
26				Nu =	1184	
27	Fluid Thermal					
28	Expans. Coeff, β =	0,003354	$°K^{-1}$	h =	0,97	$W/m^2\text{-}K$

NOTE: For the example shown, correlation #2 shouldn't be used, because Ra > 10^9.

* For an Excel spreadsheet that can be downloaded to calculate the density of a gas with known molecular weight and specified temperature and pressure, see:
"Excel Templates for Venturi and Orifice Flow Meter Calculations," at:
http://www.brighthub.com/engineering/civil/articles/83825.aspx

Equations for Natural Convection - Isothermal Vertical Plane

$$Nu = \frac{h\,L}{k} \qquad Pr = \frac{\mu\,C_p}{k}$$

$$Gr = \frac{L^3 \rho^2 g\,\Delta T\,\beta}{\mu^2}$$

$$Ra = Gr\,Pr$$

Dimensionless Numbers used in Natural Convection Heat Transfer Coefficient Correlations

Correlation #1:

for all values of Ra:

$$Nu = \left\{0.825 + \frac{0.387\,Ra^{1/6}}{[\,1 + (0.492/Pr)^{9/16}\,]^{8/27}}\right\}^2$$

Correlation #2:

Slightly better for laminar flow (Ra $\le 10^9$):

$$Nu = 0.68 + \frac{0.670\,Ra^{1/4}}{[\,1 + (0.492/Pr)^{9/16}\,]^{4/9}}$$

Q= 124391 W

http://www.brighthubengineering.com/hvac/92660-natural-convection-heat-transfer-coefficient-estimation-calculations

Capacity:

125 kW

LRZ Cube With Heatsink and Fins (1m Distance, 1m Long) On North, East, and West Side With 30K delta T

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Natural Convection Heat Transfer Coefficient Correlations (S.I. units)

1. With an isothermal vertical plane — Fluid = air

Inputs			Calculations		
Fluid Temp, T_∞ =	20	°C	Temp Diff, ΔT =	30	°C
Surface Temp, T_w =	50	°C	Abs. Film Temp, T_f =	308	°K
Film Temp., T_f =	35	°C	Prandtl Number, Pr =	0,69	
[$T_f = (T_\infty + T_w)/2$]					
Area of Plate, A =	9273,0	m²	Grashof Number, Gr =	1,19E+14	
Height of Surf., L =	33,0	m			
			Rayleigh No., Ra =	8,23E+13	
Fluid Density, ρ =	1,1	kg/m³			
			Correlation #1		
Fluid viscosity, μ =	1,87E-05	N-s/m²			
Fluid Sp. Heat, C_p =	1				
Fluid Sp. Heat, C_p					
Fluid Thermal			…RaL < 10⁹):		
Conductivity, k =					
			Nu =	1545	
Fluid Thermal					
Expans. Coeff, β =	0,…245	°K⁻¹	h =	1,26	W/m²-K

NOTE: For the example shown, correlation #2 shouldn't be used, because Ra > 10^9.

* For an Excel spreadsheet that can be downloaded to calculate the density of a gas with known molecular weight and specified temperature and pressure, see:

"Excel Templates for Venturi and Orifice Flow Meter Calculations," at:

http://www.brighthub.com/engineering/civil/articles/83825.aspx

Equations for Natural Convection - Isothermal Vertical Plane

$$Nu = \frac{h\,L}{k} \qquad Pr = \frac{\mu\,C_p}{k}$$

$$Gr = \frac{L^3 \rho^2 g\,\Delta T\,\beta}{\mu^2}$$

$$Ra = Gr\,Pr$$

Dimensionles…

Natur…

$$\left\{ 0.825 + \frac{0.387\,Ra^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}} \right\}^2$$

Correlation #2:

Slightly better for laminar flow (Ra ≤ 10^9):

$$Nu = 0.68 + \frac{0.670\,Ra^{1/4}}{\left[1 + (0.492/Pr)^{9/16}\right]^{4/9}}$$

Q= 1063455 W

http://www.brighthubengineering.com/hvac/92660-natural-convection-heat-transfer-coefficient-estimation-calculations

It is possible to run a 100% passive cooled 1MW HPC system ☺

Capacity:

1 MW

How About a “Water Cooled” Data Center?

Submarine Typhoon Class:

length: 175m (574 ft 2 in)

draft: 12 m (39 ft 4 in)

volume displacement: 33,270 long tones = 1164450 feet^2 (1 lt = 35 feet^2)

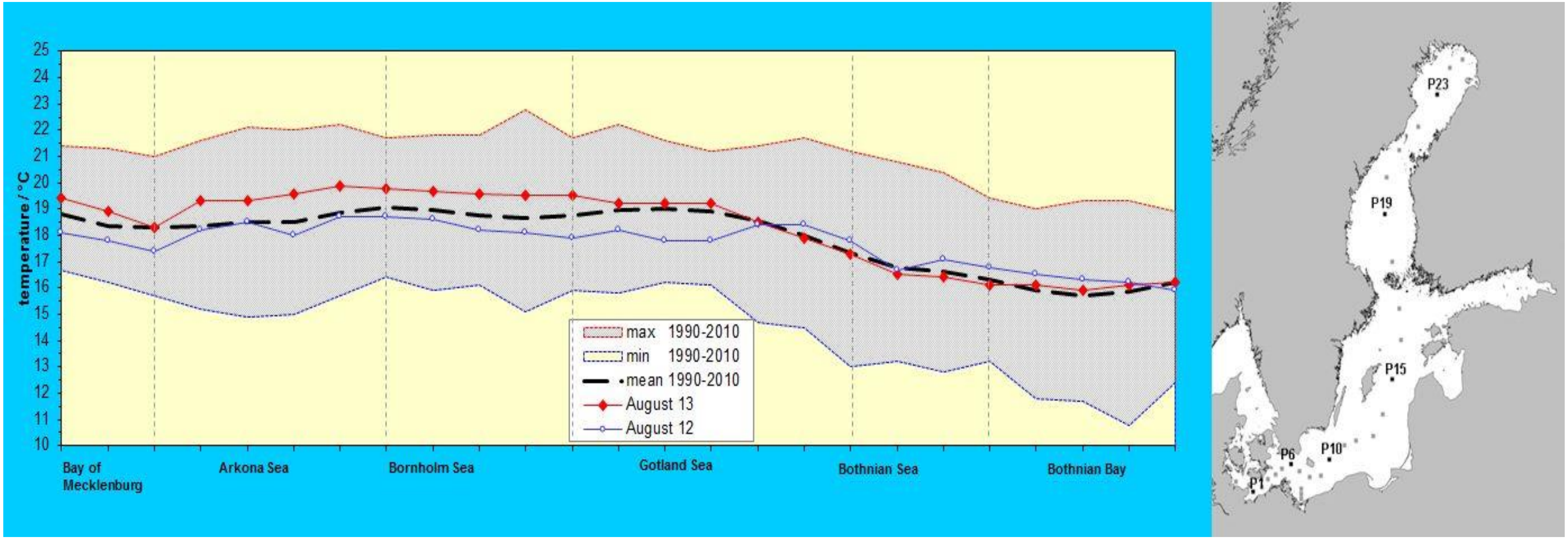
hull material: titanium

reactor: two OK-650 reactors (each 190MW)

surface area estimate*: 67914 feet^2 (6309 m^2)

* According to the technical development document for Phase I Uniform National Discharge Standards for Vessels of the Armed Forces, Naval Sea Systems Command, US Department of the Navy: SA = 1.7*(L)*(D) + (V) / (D)

Baltic Sea Max Surface Temperature



Source: http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/hydrography

Submarine Hull (6309 m²) heat transfer (30°C Hull temp -> 20 °C water temp)

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Als US-Dollar, Euro oder andere Währung formatieren.

Natural Convection Heat Transfer Coefficient Correlations (S.I. units)

4. With an isothermal horizontal cylinder — Fluid = water

Inputs			Calculations		
Fluid Temp, T_∞ =	20	°C	Temp Diff, ΔT =	10	°C
Surface Temp, T_w =	30	°C	Abs. Film Temp, T_f =	298	°K
Film Temp., T_f =	25	°C	Prandtl Number, **Pr** =	5,43	
[$T_f = (T_\infty + T_w)/2$]					
			Grashof Number, **Gr** =	6,36,E+13	
Cylinder Diam., **D** =	11,1	m			
Cylinder Surface, A =	6309	m²	Rayleigh No., **Ra** =	3,46E+14	
Fluid Density, ρ^* =	995,7	kg/m³			
Fluid viscosity, μ =	7,980E-04	N-s/m²			
			Nu =	9201	
Fluid Sp. Heat, C_p =	4,179	J/g-°K			
			h =	503,90	W/m²-K
Fluid Sp. Heat, C_p =	4179	J/kg-°K			
			Q =	31790980	W
Fluid Thermal Conductivity, **k** =	0,609	J/s-m-K			
Fluid Thermal Expans. Coeff, β =	3,03E-04	°K⁻¹			

* For an Excel spreadsheet that can be downloaded to calculate the density of a gas with known molecular weight and specified temperature and pressure, see: "Excel Templates for Venturi and Orifice Flow Meter Calculations," at:
http://www.brighthub.com/engineering/civil/articles/83825.aspx

Equations for Natural Convection - Isothermal Horizontal Cylinder

$$\mathrm{Nu} = \left\{ 0.60 + \frac{0.387\,\mathrm{Ra}^{1/6}}{\left[1 + (0.559/\mathrm{Pr})^{9/16}\right]^{8/27}} \right\}^2$$

$$\mathrm{Gr} = \frac{D^3 \rho^2 g\, \Delta T\, \beta}{\mu^2} \qquad \mathrm{Nu} = \frac{h D}{k} \qquad \mathrm{Pr} = \frac{\mu C_p}{k}$$

$$\text{for } \mathrm{Ra} \le 10^{12} \qquad (\mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr})$$

Natural Convection Heat Transfer from an Isothermal Horizontal Cylinder

Water properties taken from:

- http://www.engineeringtoolbox.com/water-thermal-properties-d_162.html
- http://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html

Cylinder estimation:

- d = 11,122m
- h = 175m
- A= 6309 m2

Good news:

31.8MW (submerged)

http://www.brighthubengineering.com/hvac/92660-natural-convection-heat-transfer-coefficient-estimation-calculations

LRZ System PUE SuperMUC

Unbelievably Good PUE'S

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Facebook Prineville:	2014 - 1.07
Yahoo Lockport, New York:	1.08 (no official measurement data)
Apple Viborg, Denmark:	1.11 (planed)
Google:	2014 – 1.12 over all data centers
Microsoft: (nothing concrete)	latest data center claim 1.13 to 1.2

Hyperscale Data Center – How They Do It

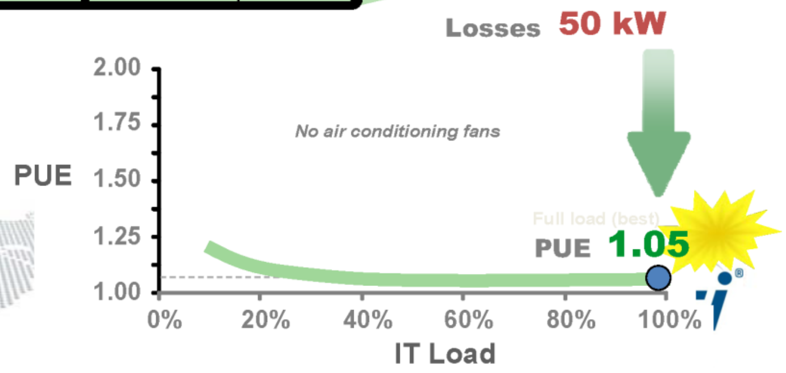
PUE 1.05? … Running the numbers

1 MW data center at 100% load

Step-by-step trimming of infrastructure

Scenario	kW losses	PUE
Traditional physical infrastructure	520	1.52
No chiller, add 100% water-side econ'r	330	1.33
UPS on bypass with 415V distribution	220	1.22
Air-side economizer, no UPS	140	1.14
No environmental conditioning fans	50	1.05

TARGET:
50 kW losses



Slide taken from: PUE Hype - Setting realistic expectations by Dennis Bouley , Strategic Research Analyst, Data Center Science Center, APC by Schneider Electric

PUE Advantages for Hyperscale Data Centers

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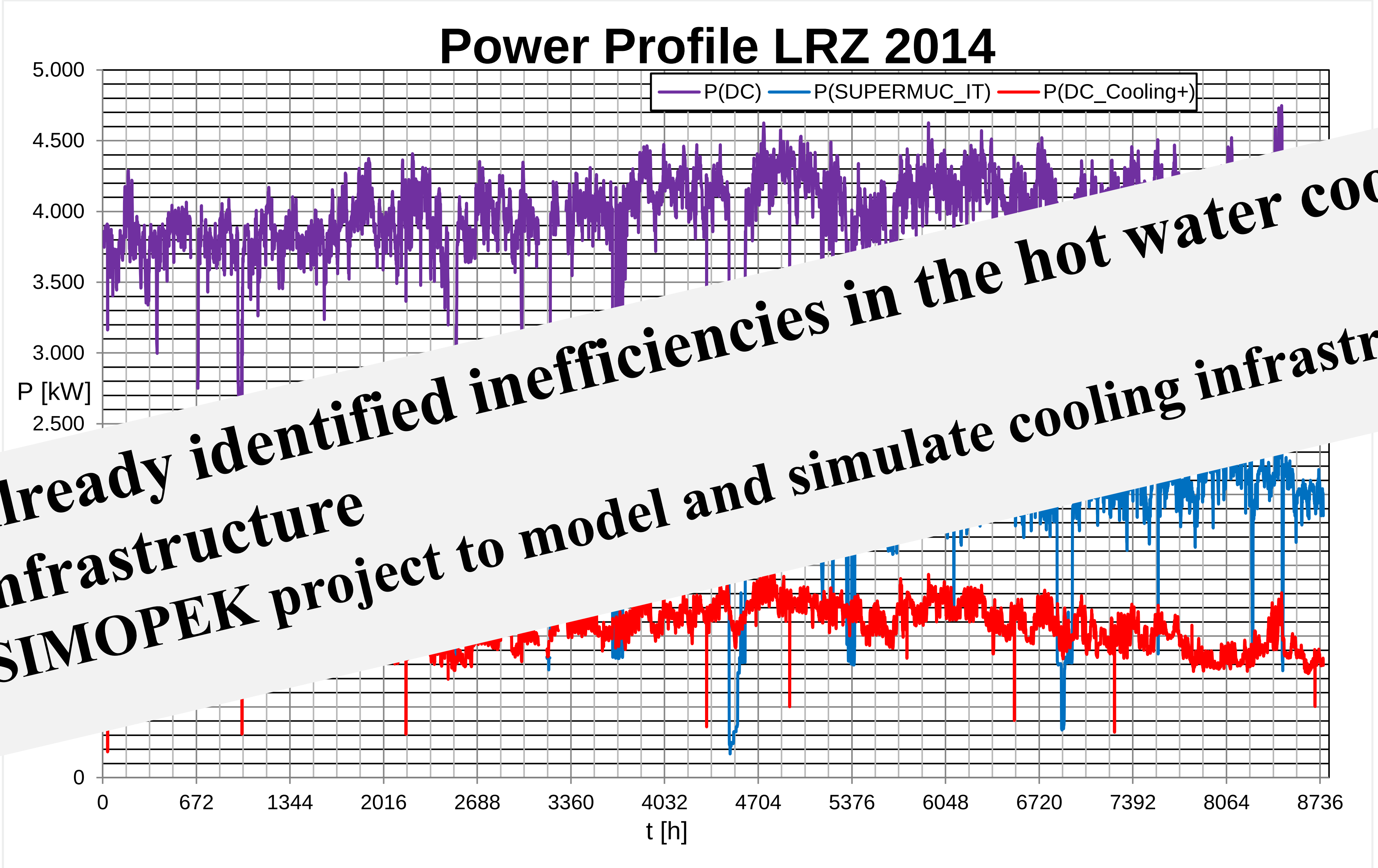
$$PUE = \frac{P_{IT} + P_{PDCL} + P_{Cooling}}{P_{IT}} = 1 + \frac{P_{PDCL}}{P_{IT}} + \frac{P_{Cooling}}{P_{IT}} = 1 + Overhead_{PDCL} + \frac{P_{Cooling}}{P_{IT}}$$

- By moving to cooler climates $P_{Cooling}$ is reduced (no chillers)
- Low power density (5-12kw per rack *) is optimal for air cooling (SuperMUC Phase1 20kW per rack, SuperMUC Phase2 25kW per rack)
  - Power consumption of air cooling equipment (fans) in racks count as P_{IT}
  - Increasing air inlet temperatures for IT equipment reduces $P_{Cooling}$ and increases P_{IT}
- Control over full data center and specialized use-case allows hardware redundancy to move to software redundancy, reducing $Overhead_{PDCL}$
- Using full load condition for PUE calculation maximizes P_{IT}
- All this allows for a leading PUE of less than 1.1 (Side note: besides Google, nobody explained in full detail how PUE is measured)

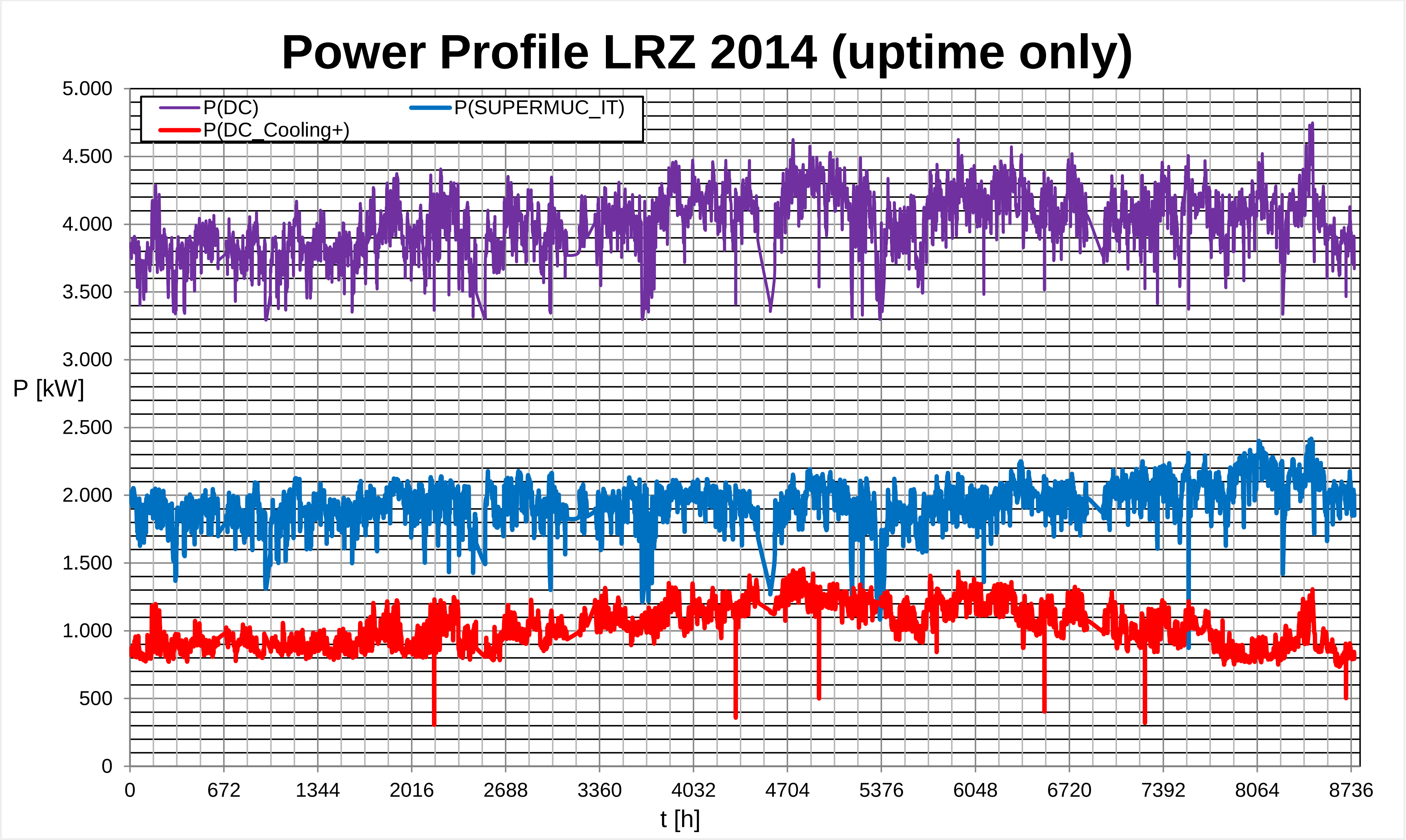
* http://www.opencompute.org/assets/open-rack/Open_Compute_Project_Open_Rack_v1.0.pdf

LRZ Complete Power Profile 2014

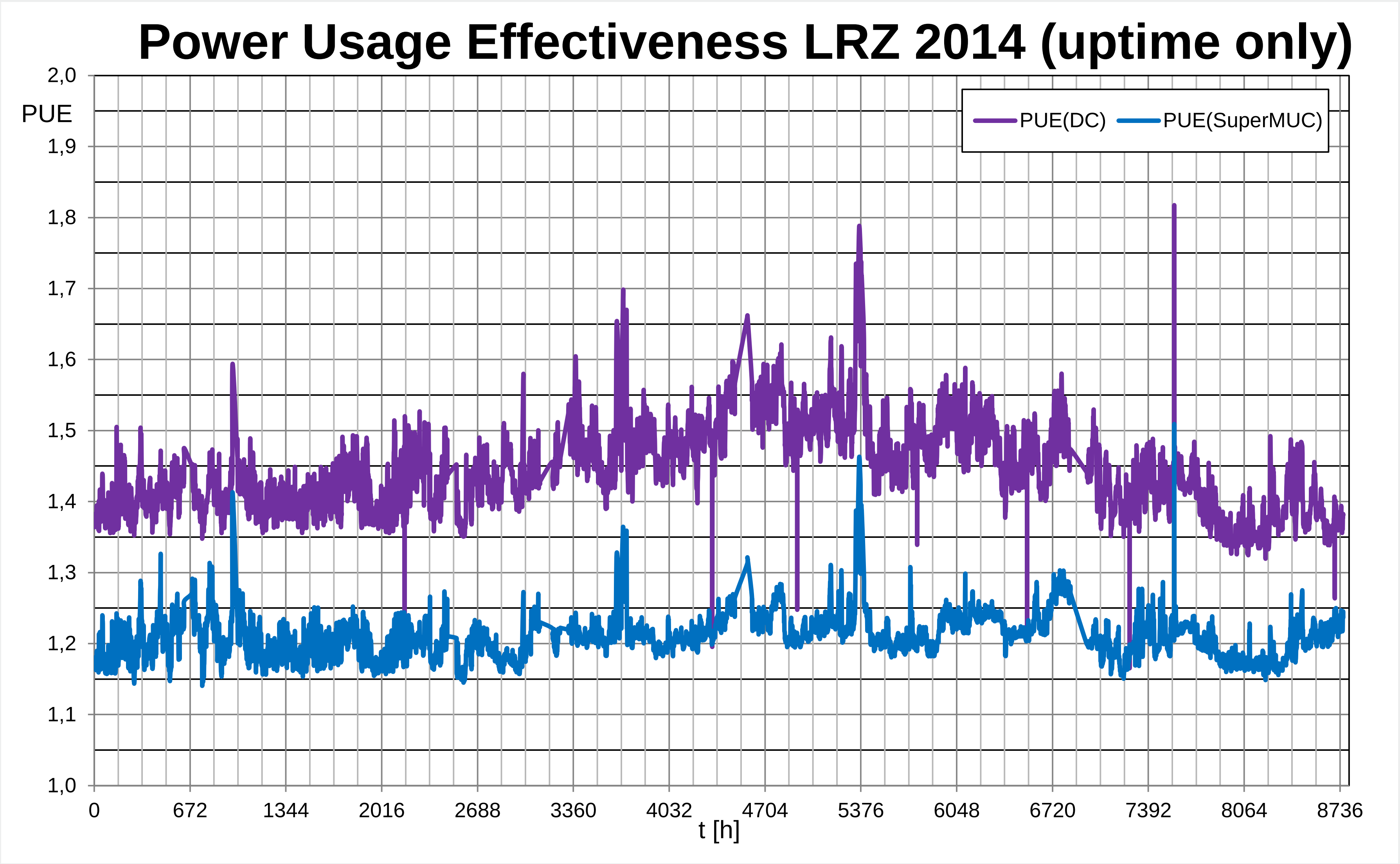


- Already identified inefficiencies in the hot water cooling infrastructure
- SIMOPEK project to model and simulate cooling infrastructure

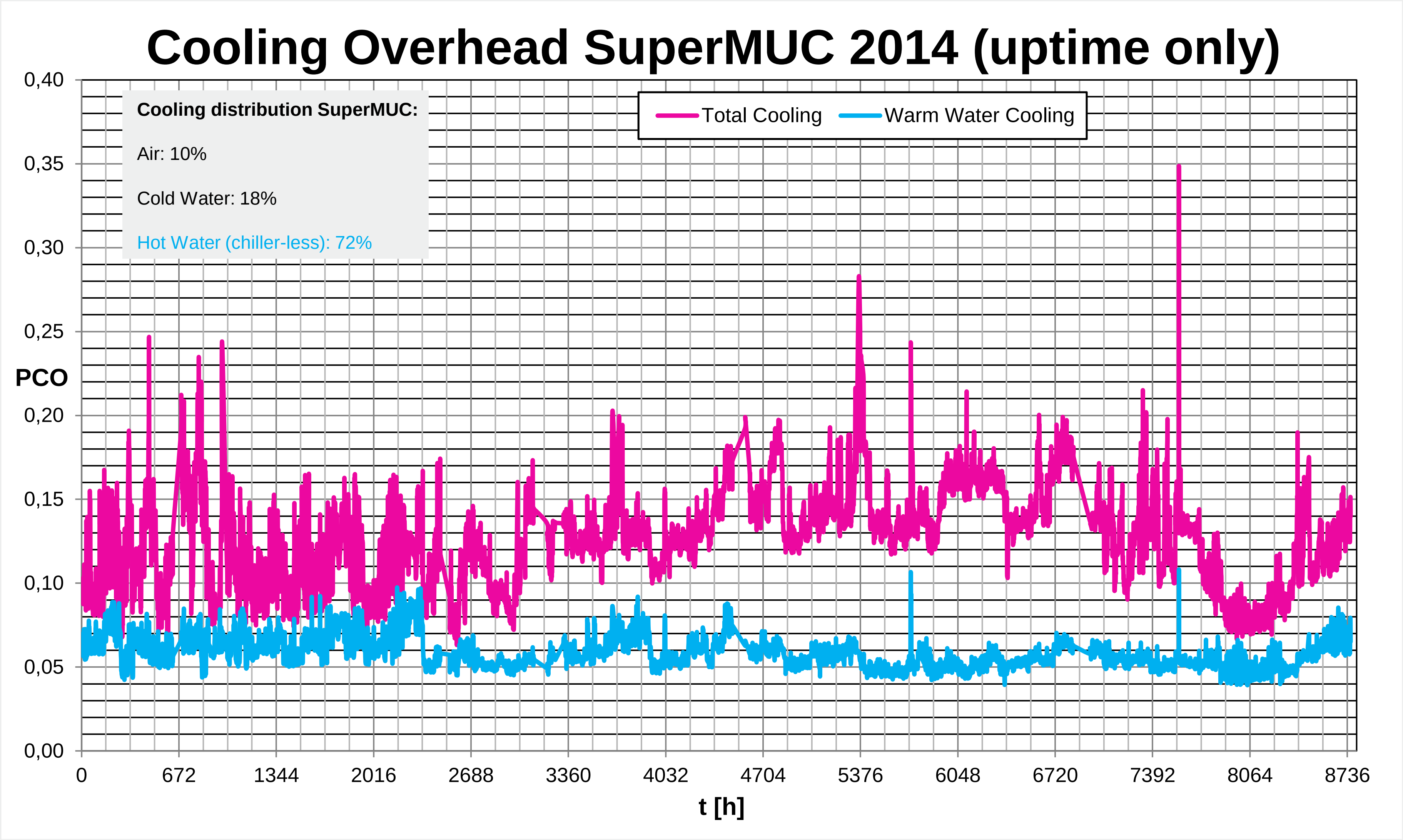
LRZ Uptime Only Power Profile 2014



SuperMUC Uptime Only PUE

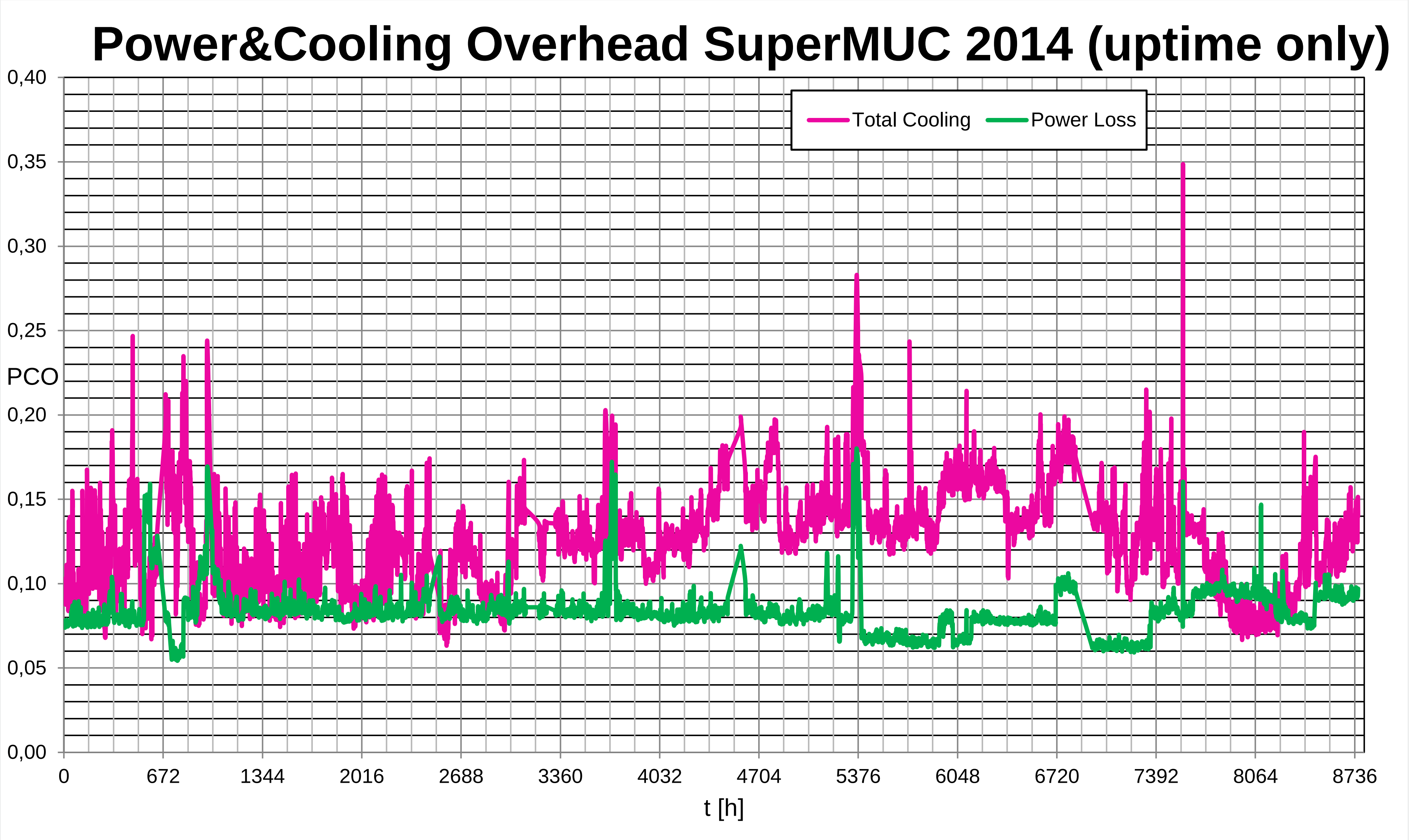


SuperMUC Colling Overhead Comparison (Total vs Warm Water)



lrz Fraunhofer SCAI SorTech AG IBM Johnson Controls GOHL GCS Gauss Centre for Supercomputing

LRZ Uptime Only Power and Cooling Overhead SuperMUC 2014



How To Do It The Hyperscale-Way?

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- Use “designed load” as P_{IT} for PUE
  - Restricting data to SuperMUC power consumption > 2.0 MW (could be as high as 3.6MW for Linpack ☺)
  - **SuperMUC PUE: 1.20**

- Remove all UPS equipment (can remove the 8% off power distribution overhead)
  - **SuperMUC PUE: 1.12 – very close to arctic data center PUE’s**

Sustainability – More Than Just PUE

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Sustainability – get work done without environmental impact and conserve natural resources

- CUE – 100% renewables ☑
- WUE – no evaporative chillers / cooling towers needed ☑
- Conserve natural resources – 100% ☒

Continuation on Sustainability

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120MW is 120MW - Is throwing away energy the best we can do?

- Data center needs to be located close to possible consumers
  - Heat requirement average single family home 150m^2 * 2.5m (http://www.haus-bau-blog.de/hausbau-planung/hausbau-deutschland-neubau-einfamilienhaus/)]
  - Outside -10°C (inside 20°C) 15.66 kW (https://de.trotec.com/tkl-mieten/infocenter/kapazitaetsberechnungen/heizleistung-berechnen/?tx_tklinfo_tklinfopi[action]=heating&tx_tklinfo_tklinfopi[controller]=Calculator&cHash=945e1742b4e0b6167df9f8d910f9083f)
  - SuperMUCs (2.4MW) waste heat would be sufficient to heat 153 single family homes under those conditions
  - **120MW == 7662 homes**
- Heat re-use with air cooling and low temperature water is hard

Benefits of Direct Hot Water Cooling

Data Center Technology Innovations

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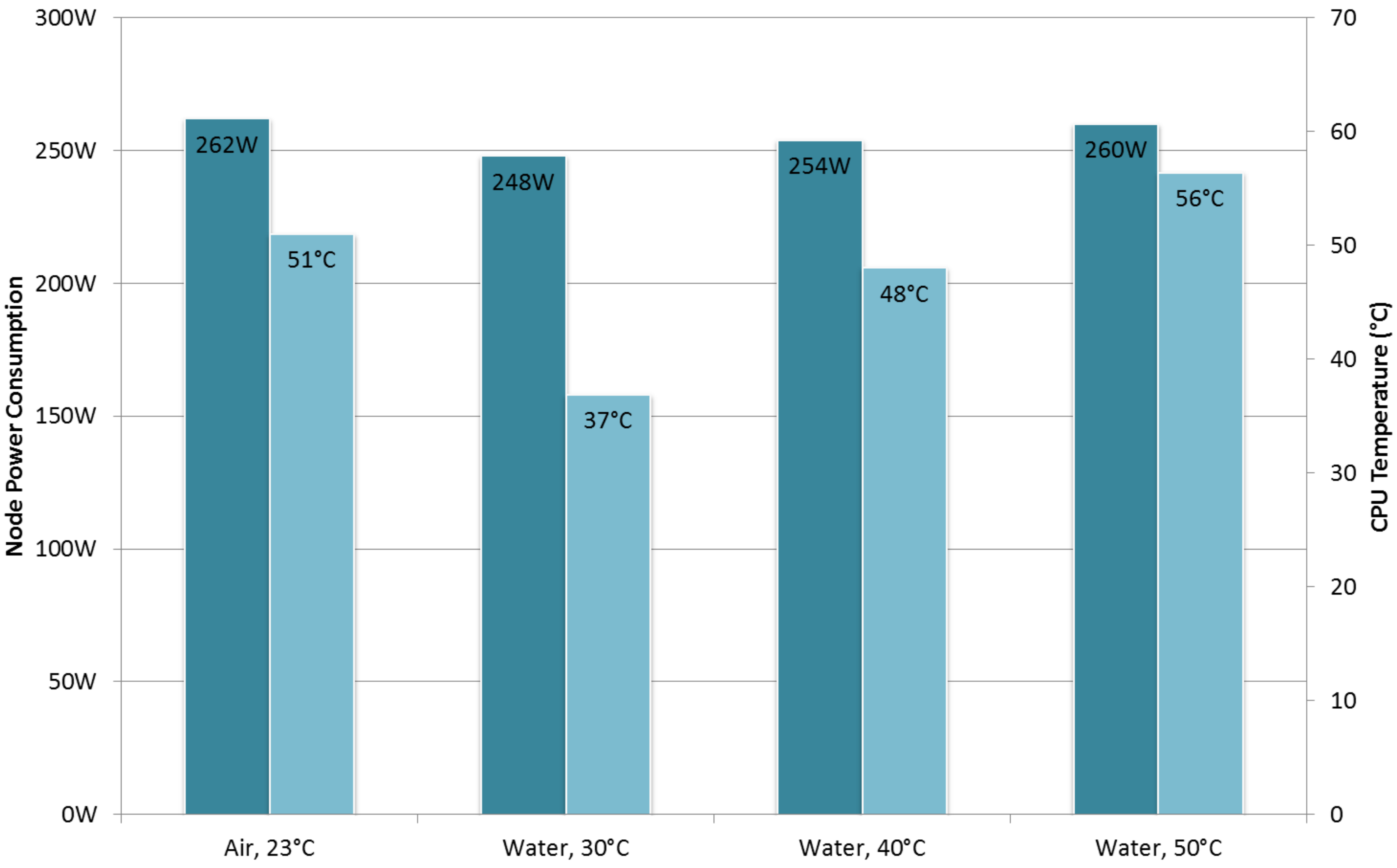
- Dan Reed (Monday key note) – expected benefit of CMOS shrinkage coming to an end (power linear)
- One improvement area slows – change directions, **data center and IT system cooling technologies**

- Look at power / energy consumption in an integrated way
  - (applications, CPU, systems, cooling infrastructure, to data center integration in smart city environment (re-use opportunities, not traditionally important for HPC data centers
- Data analytics
  - Complex data center instrumentation – traditionally only used for monitoring and operational support assuming a fixed optimal operating point
  - Moving to complex efficiency analysis and more complex command and control due to increased variability of the IT load and the hunt for energy proportionality over the full IT operating range
  - Machine learning to predict data center PUE based on multiple information sources (*Machine Learning Applications for Data Center Optimization, Jim Gao, Google*)

Air vs Direct Liquid Cooling



CooLMUC (178 nodes):

Measurement for single node

- two AMD Opteron 6128HE CPUs (MagnyCours) with 8 cores each
- 2GHz clock frequency
- 16GB RAM (eight 2GB DDR3 modules)

Characteristics will change with CPU and System architecture.

Heat Re-Use Possibilities

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Currently Running Three Hot Water Cooled Machines at LRZ:
CooLMUC at: 41°C IN – 50 to 60°C OUT (load dependent), *SuperMUC I*: 39°C IN – 41 to 44°C OUT, *SuperMUC II*: 40 °C IN – 43 to 47°C OUT

Industrial sector	Process	Temperature level [°C]
Food and beverages	drying	30 - 90
	washing	40 – 80
	pasteurising	80 – 110
	boiling	95 – 105
	sterilising	140 – 150
	heat treatment	40 – 60
Textile industry	washing	40 –80
	bleaching	60 – 100
	dyeing	100 – 160
Chemical industry	boiling	95 – 105
	distilling	110 – 300
	various chemical processes	120 - 180
All sectors	pre-heating of boiler feed water	30 – 100
	heating of production halls	30 – 80

European Solar Thermal Industry Federation: Key Issues for Renewable Heat in Europe (K4RES-H)
Solar Industrial Process Heat; http://www.estif.org/fileadmin/estif/content/policies/downloads/D23-solar-industrial-process-heat.pdf

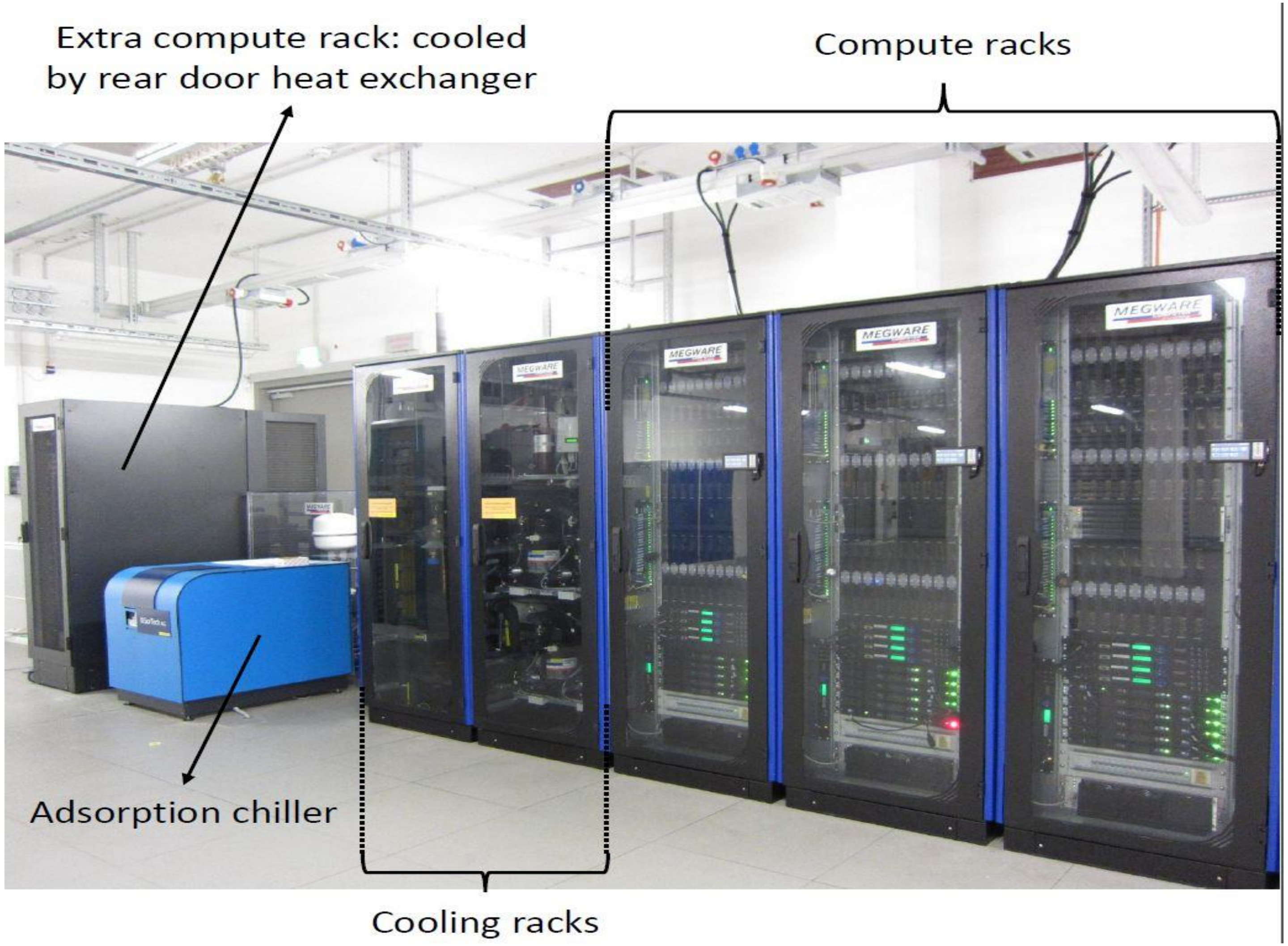
More Possibilities

- Ice-Cream production: 30-40°C
- Beer production: 7-76°C
- Oil production: 75-95°C
- Decaffeinated coffee: 22-100°C
- Surface treatment:
- anodizing 5-42°C
- plating cooper and copper alloys 20-70°C
- High temperature short time (HTST) pasteurization: 72-75°C

Dr. Vlasta KRMELJ, Dipl.Ing. : Selected industrial processes which require low temperature heat; Energy agency of Podavje, Slovenia

What To Do Inside the Data Center In the Summer ?

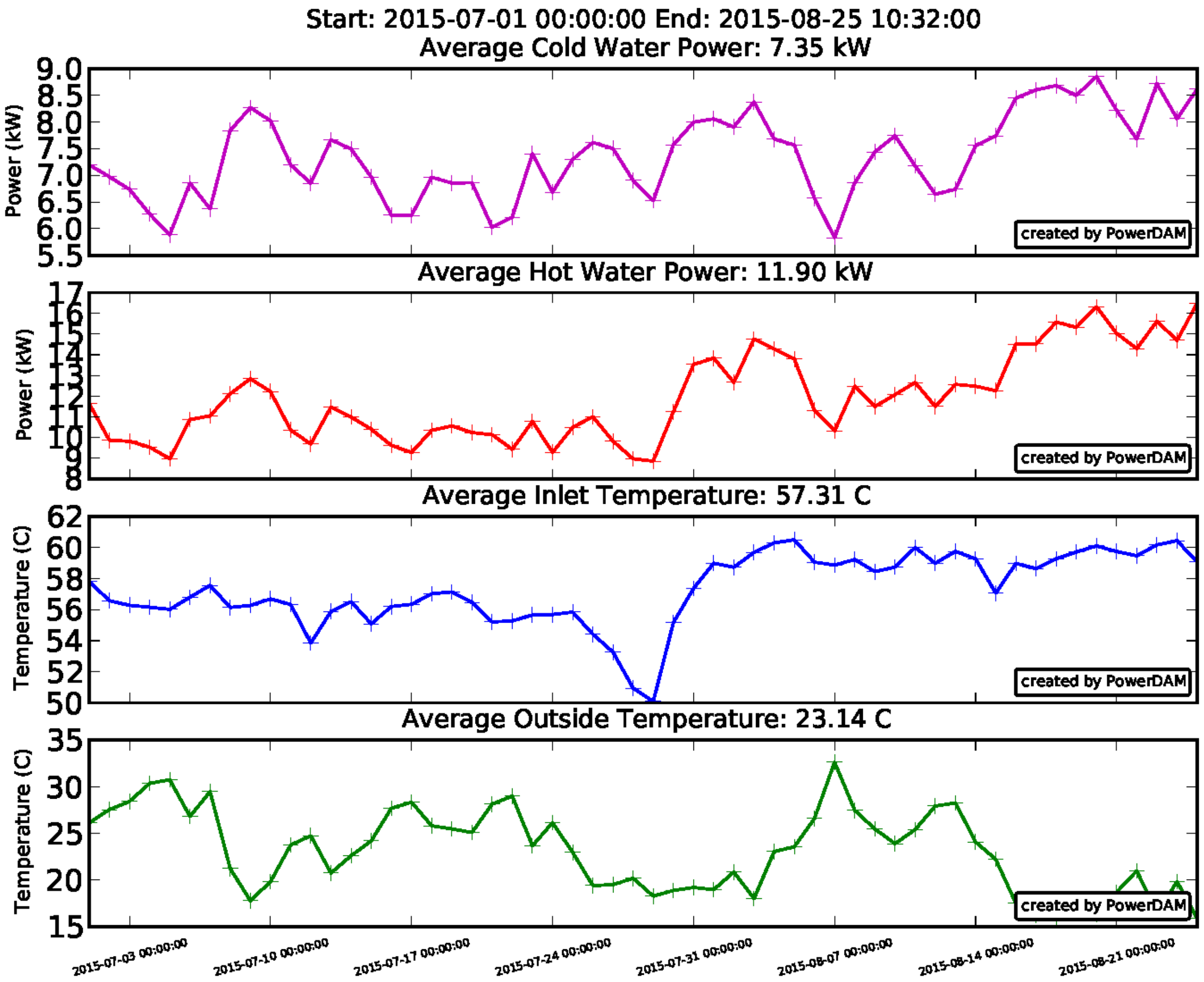
SIMOPEK



Adsorption cooling:

- Use hot water to generate cold water
- All year around

CooLMUC Adsorption Cooling Preliminary Data

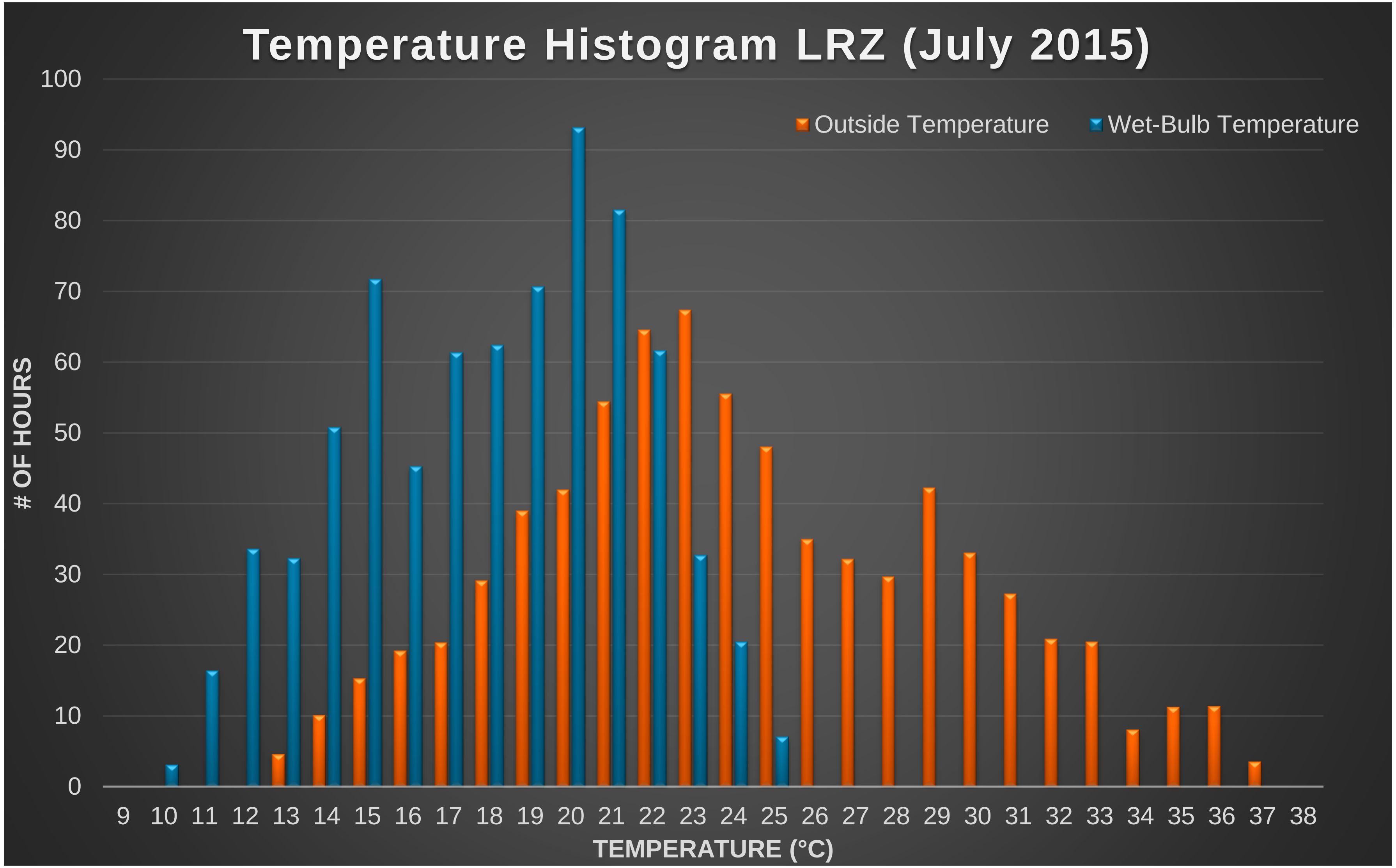


Disclaimer:

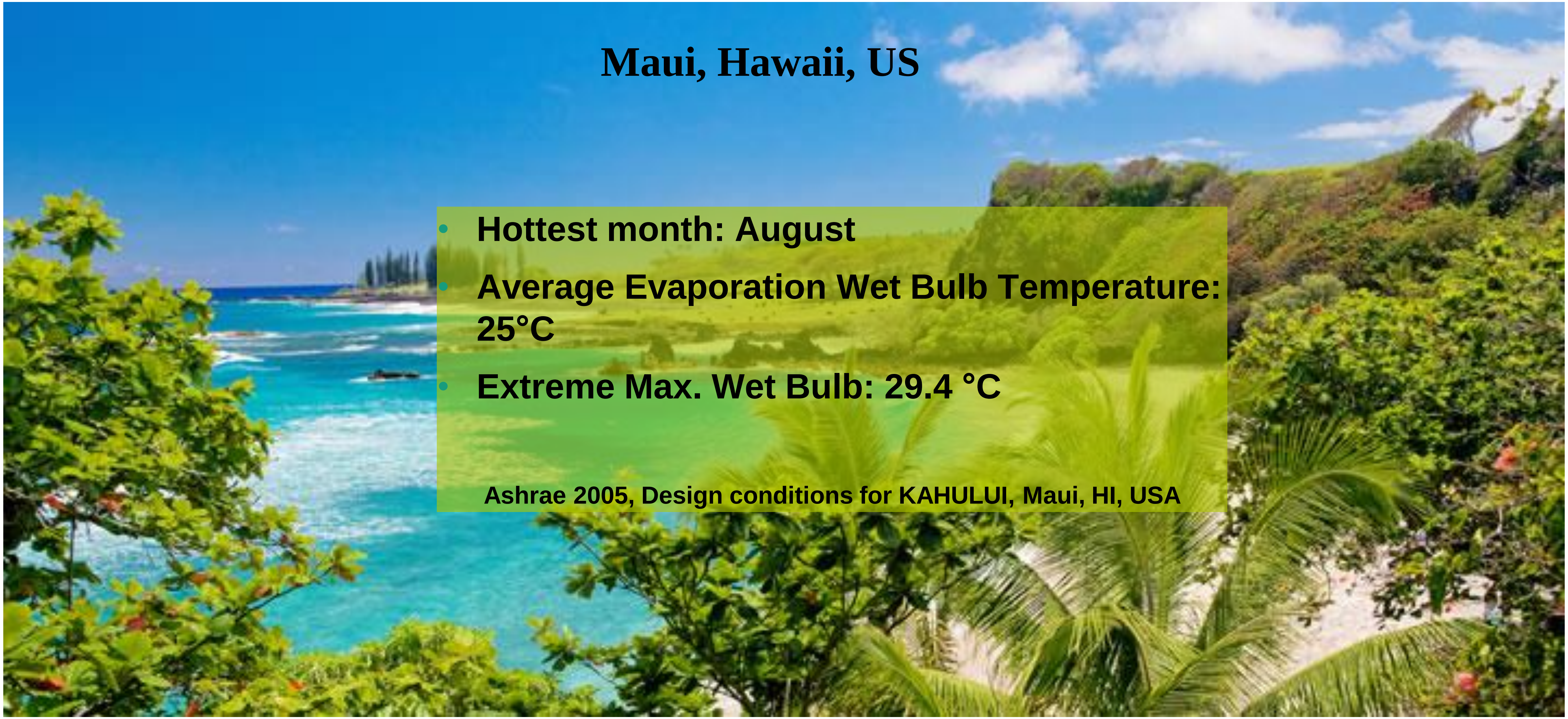
- Preliminary data
- Pending verification of SorTech AG

Bringing It All Together

Temperature Histogram LRZ July 2015 (close to temperature record)



If not the Artic, where else?



Maui, Hawaii, US

- Hottest month: August
- Average Evaporation Wet Bulb Temperature: 25°C
- Extreme Max. Wet Bulb: 29.4 °C

Ashrae 2005, Design conditions for KAHULUI, Maui, HI, USA

Or just staying home

Don’t Forget to Pack your Swimming Trunks!

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