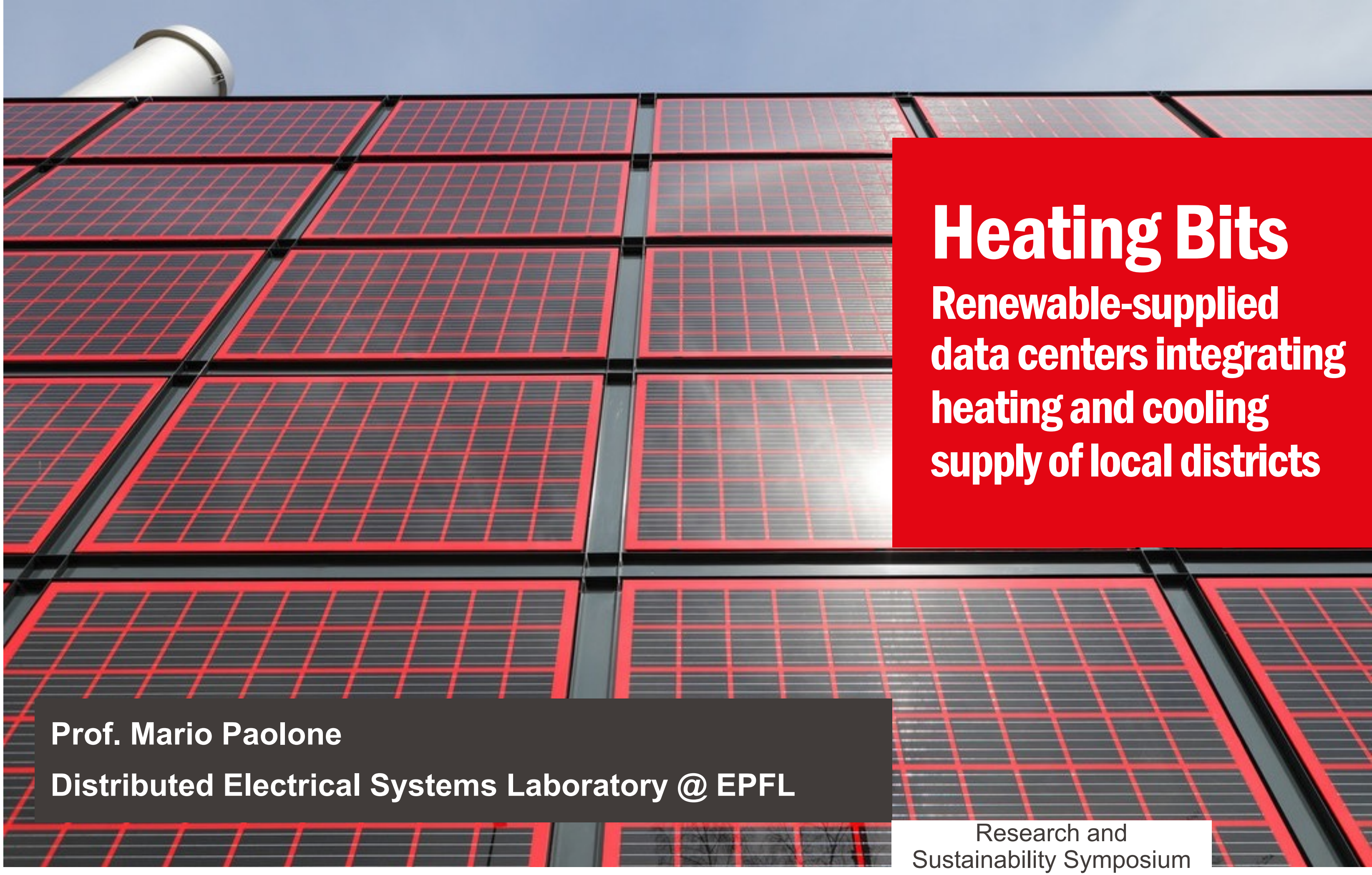


Heating Bits

Renewable-supplied data centers integrating heating and cooling supply of local districts

Prof. Mario Paolone

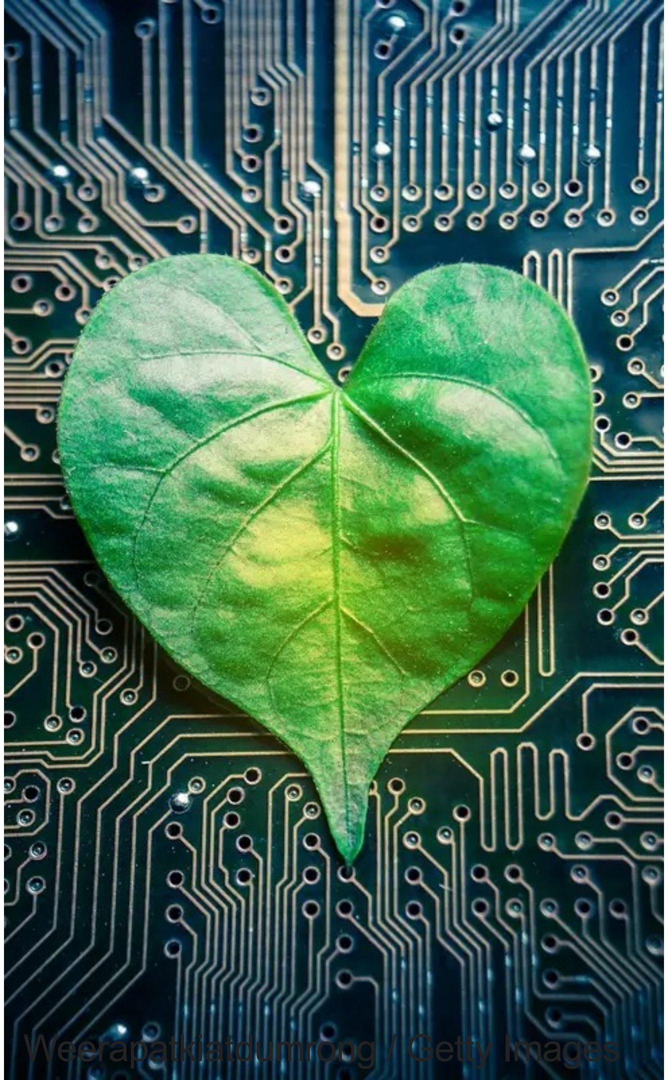
Distributed Electrical Systems Laboratory @ EPFL

Research and Sustainability Symposium
May 16, 2024

EPFL

Motivation

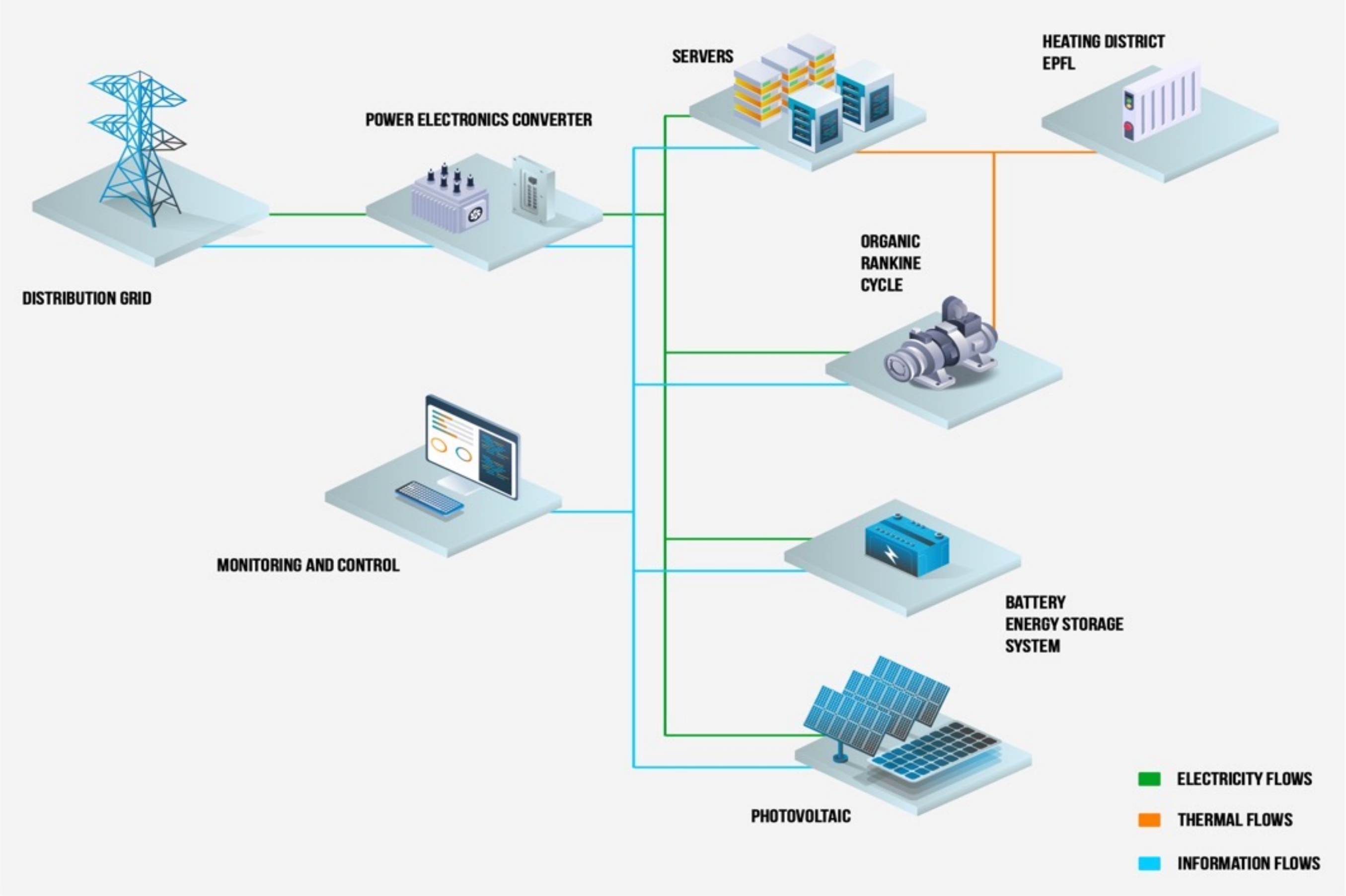
- Data centers (DCs) use **2% of global energy and will reach 10% by 2030**.
- Switzerland is one of the European countries with the **highest number of DCs (77).**
- IT and energy supply represents today **44% of the EPFL CO2eq emissions.**
- The DCs expansion is associated with key energy and climate-related challenges:
  (a) impact on the power grid;
  (b) inefficient energy usage;
  (c) electricity-end-use carbon footprint.



Goals of the project

- Develop a solution to **improve DCs' energy efficiency** while **reducing their carbon footprint** with special focus on the new EPFL DC
- Validate this solution in a **first-of-its-kind demonstrator benefiting the entire EPFL campus leveraging EPFL research and tech transfer towards our startups.**
- **Scale up** through the EPFL EcoCloud to industry-grade DCs operated by Amazon, Google, Microsoft, Meta.

Overview of the proposed system



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Activity 1: heat recovery and heat-derived electricity generation (PowerLab)

Aim: innovative on-chip cooling technology to efficiently remove heat from data center CPUs by flowing liquids on the chips, much closer to their hot spots providing:

a) **large cooling capacity**

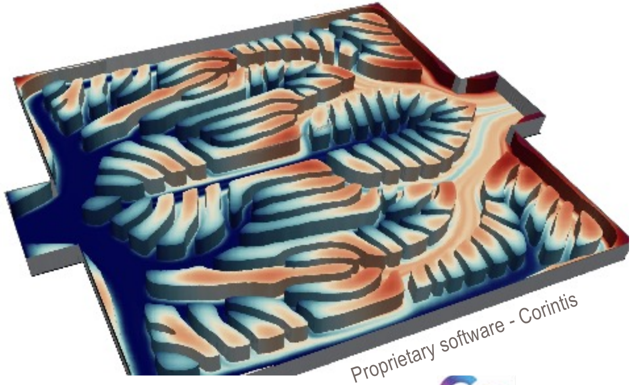
b) **high temperature coolant (75°C)** for subsequent energy recuperation.

Heat map of the CPU

High heat flux regions

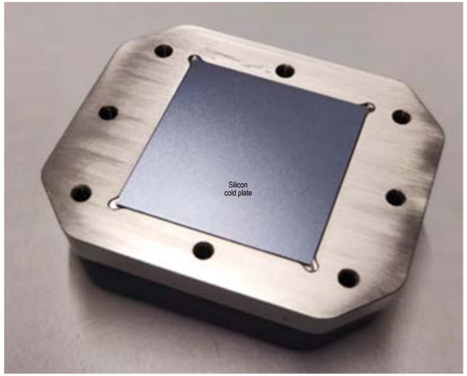
Low heat flux regions

Optimized microfluidic cold plate



corintis

Packaging

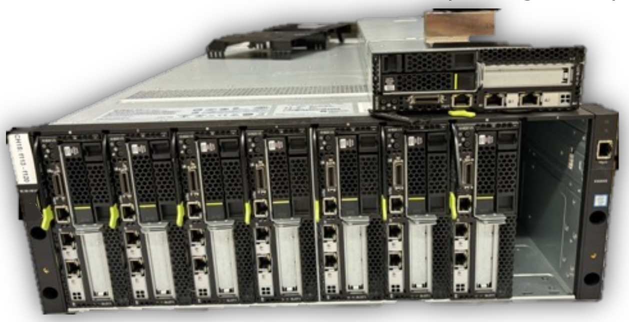


Activity 1: heat recovery and heat-derived electricity generation (PowerLab)

Ongoing activities:

- **power map** measurement and topology optimization of cold-plate
- benchtop evaluation of **microfluidic cooling for a single CPU**
- **blade- and rack-level** cooling circuit design and integration

Benchtop setup (being built)



Rack for integrating tests

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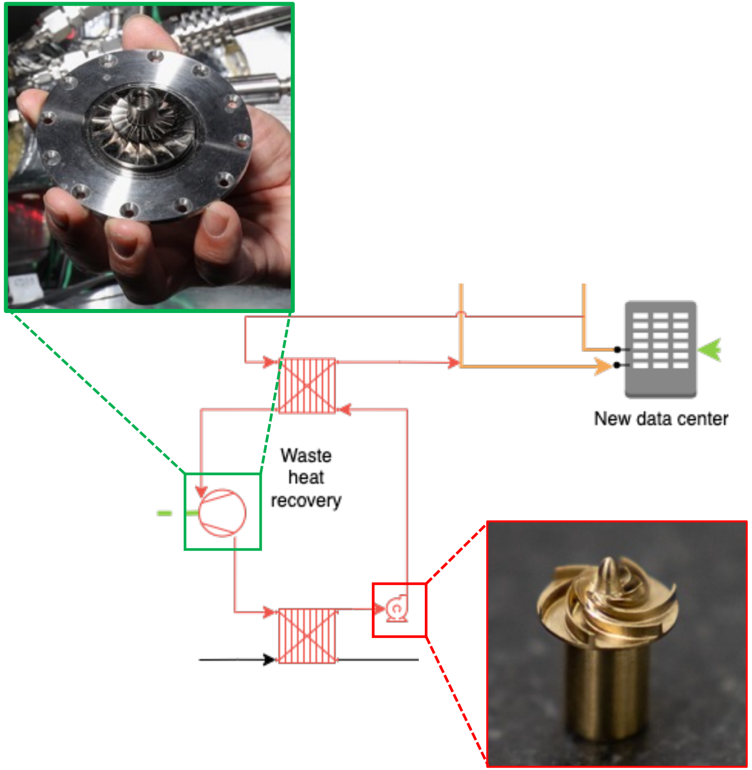
Activity 2: Waste heat to electricity (LAMD)

Aim: generation of **power from the heat extracted from CPUs** with the use of thermodynamic potential via power cycle (Organic Rankine Cycle)

First fully oil-free small-scale ORC:

- Operational **4-5kW oil-free ORC** (vs state-of-the art oil-lubricated volumetric ORC)
- with **gas-bearing supported turbine** and
- **single-stage turbopump** able to operate on wide part-load range



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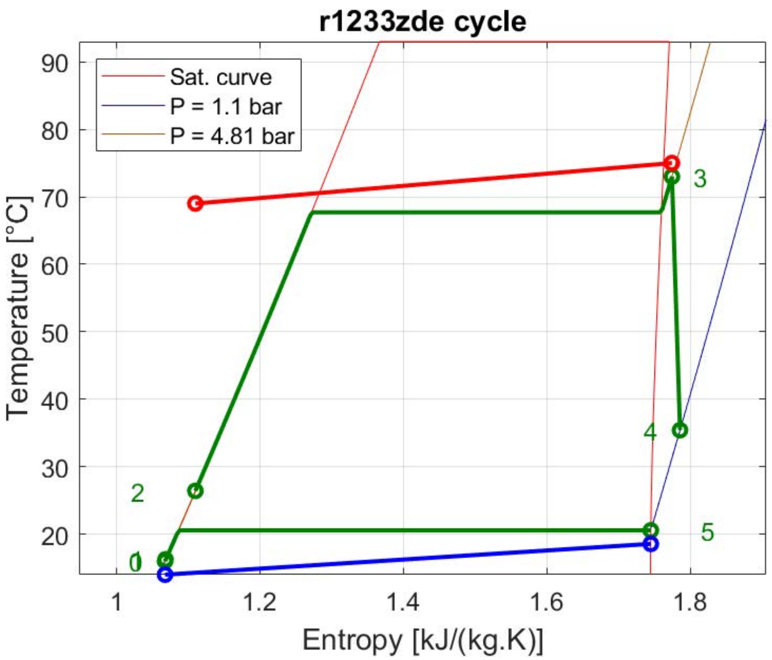
Activity 2: Waste heat to electricity (LAMD)

Organic Rankine Cycle (ORC) design and optimization

- **Working fluids (pure & mixtures)** studied to optimize efficiency & respect environmental and safety criteria.
- **Cycle output power maximized** for data center requirements
- Optimization shows **R1233zd(E)** (GWP=1) is optimal fluid:
  - Net power output ~4.7 kW
  - Thermal efficiency ~9%
  - Exergy efficiency ~60%



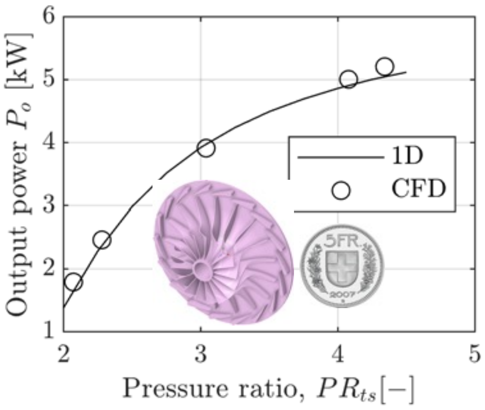
Activity 2: Waste heat to electricity (LAMD)

Turbine 1D optimization

- **Optimized turbine** maximizes power output for varying data center load
- **Fast 1D model** validated against CFD

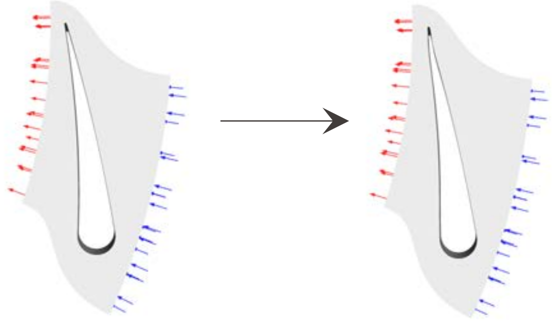
Pressure ratio [-]	T in [°C]	P in [bar]
4.1	71	4,56

$\dot{m}$ [gr/s]	N [kRPM]
226	53,6



Turbine 3D optimization

- Maximizing power output for design and off-design requires **variable geometry nozzles**
- **Ideal nozzle design** identified through POD-based shape optimization



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Activity 3: DC power consumption and distribution prediction of applications running inside the VMs (ESL)

Aim

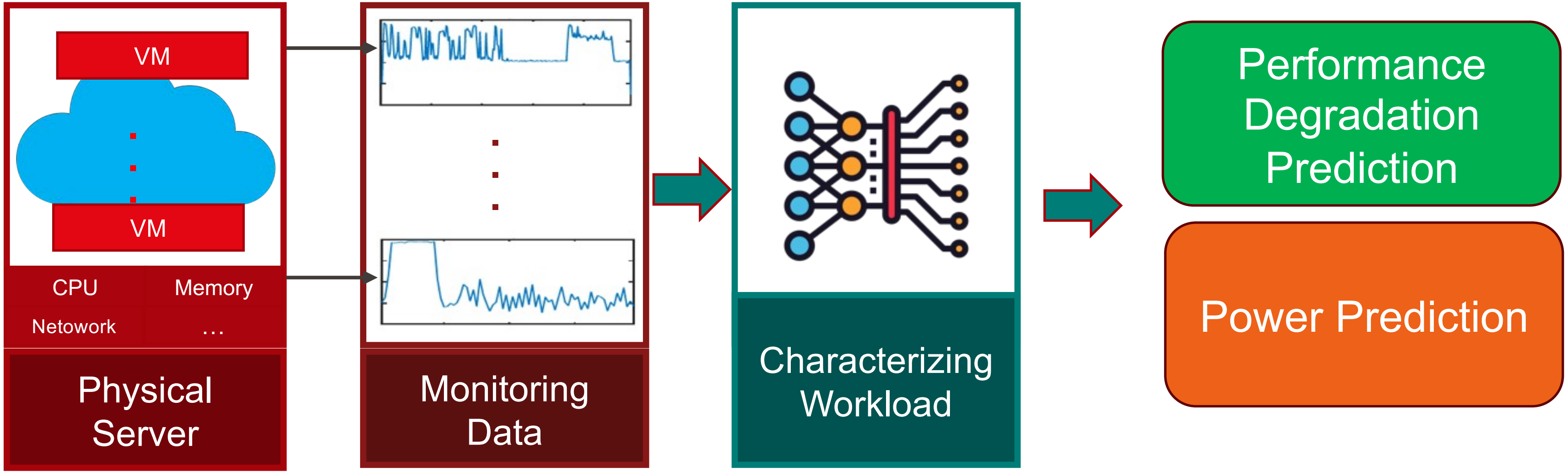
1. **Predict the workloads** of virtualized DCs to be executed
2. Develop new **hardware accelerators** use on reconfigurable hardware for EPFL key workloads

Expected outcomes

1. Maximize racks' **energy efficiency** and minimize DCs **carbon footprint** (target: 50% savings vs 2019)
2. **Recycle EPFL servers** to maximize DCs sustainability at EPFL (target: 7y vs. 3y)

Activity 3: DC power consumption and distribution prediction of applications running inside the VMs (ESL)

Workload Characterization



- Various Applications
- Various Workloads
- Various Scenarios
-

- VM Metrics
- Linux Perf
- Intel Top-down analysis

- Time-Series Analysis
- Transformer-based Models

Activity 3: DC power consumption and distribution prediction of applications running inside the VMs (ESL)

Performance Degradation Prediction

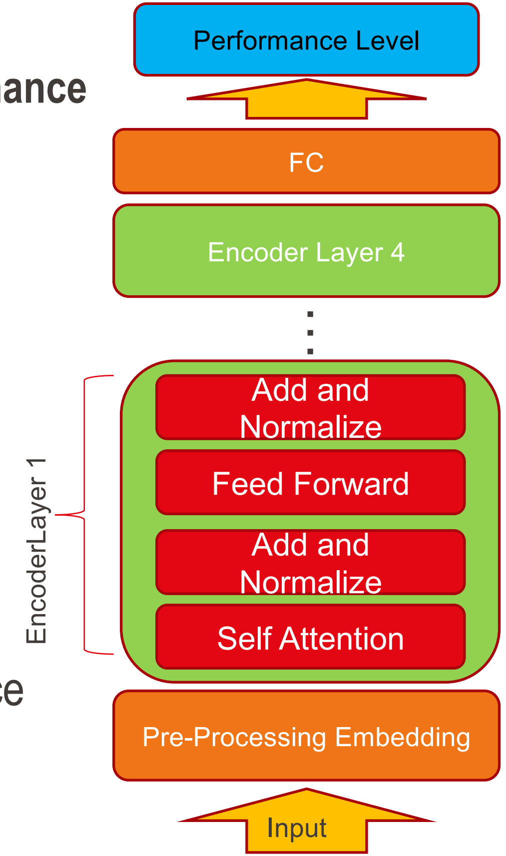
Leveraging the Workload Characterization to accurately forecast performance declines, addressing a variety of application scenarios effectively

Testing Framework:

- Seen Applications for familiar contexts.
- Unseen Applications for model's generalization capabilities across novel scenarios.

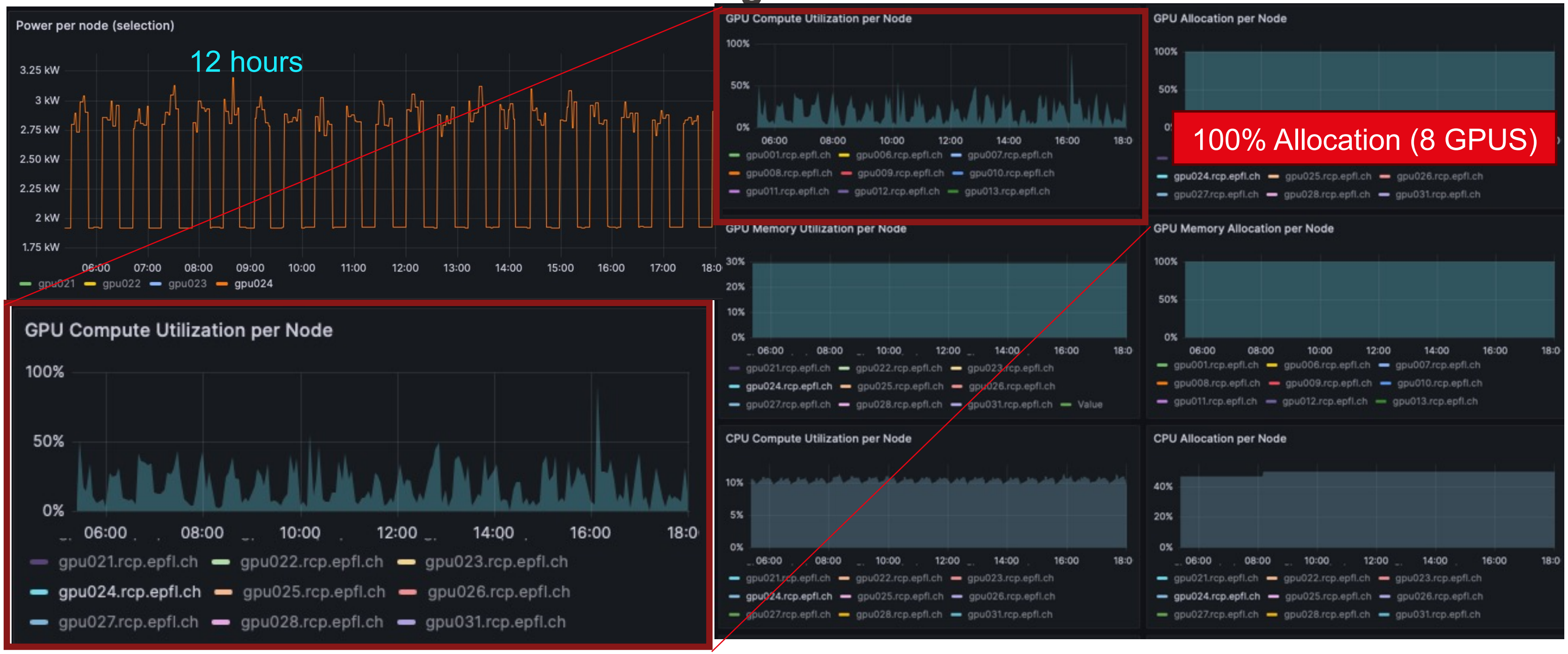
Test	Mean error (%)	Max error (%)	Avg Std (%)
Seen apps	3.64	66.97	3.51
Unseen apps	8.36	81.64	9.66

With **less than a 10% mean error**, the model reliably forecasts performance degradation across diverse application types, demonstrating robust predictive accuracy.



Activity 3: DC power consumption and distribution prediction of applications running inside the VMs (ESL)

Power Prediction & Management - EFPL RCP



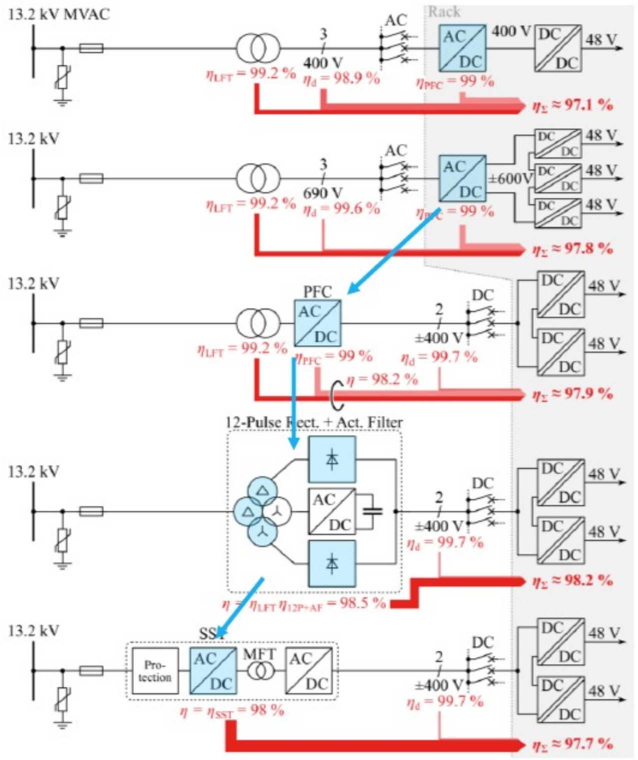
This case illustrates a **clear power and cost savings opportunity** through our workload characterization scheme, optimizing resource allocation and utilization.

Heating Bits

Activity 4: Power distribution and conversion architectures for DCs (PEL)

Aim: improve the efficiency and reliability of power delivery in the Data Centers by

- Moving from AC to DC distribution
- Reducing number of conversions
- Integrating devices operating in DC (e.g., batteries and PVs)



400 V AC
$\eta_\Sigma \approx$ 97.1 %

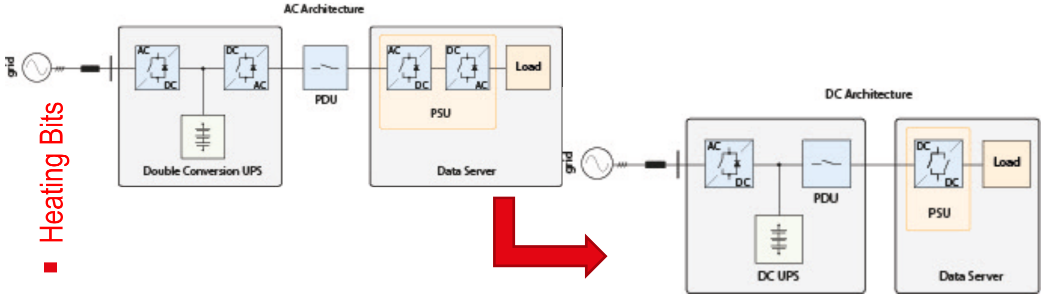
690 V AC
$\eta_\Sigma \approx$ 97.8 %

±400 V DC
$\eta_\Sigma \approx$ 97.9 %

±400 V DC
$\eta_\Sigma \approx$ 98.2 %

±400 V DC
$\eta_\Sigma \approx$ 97.7 %

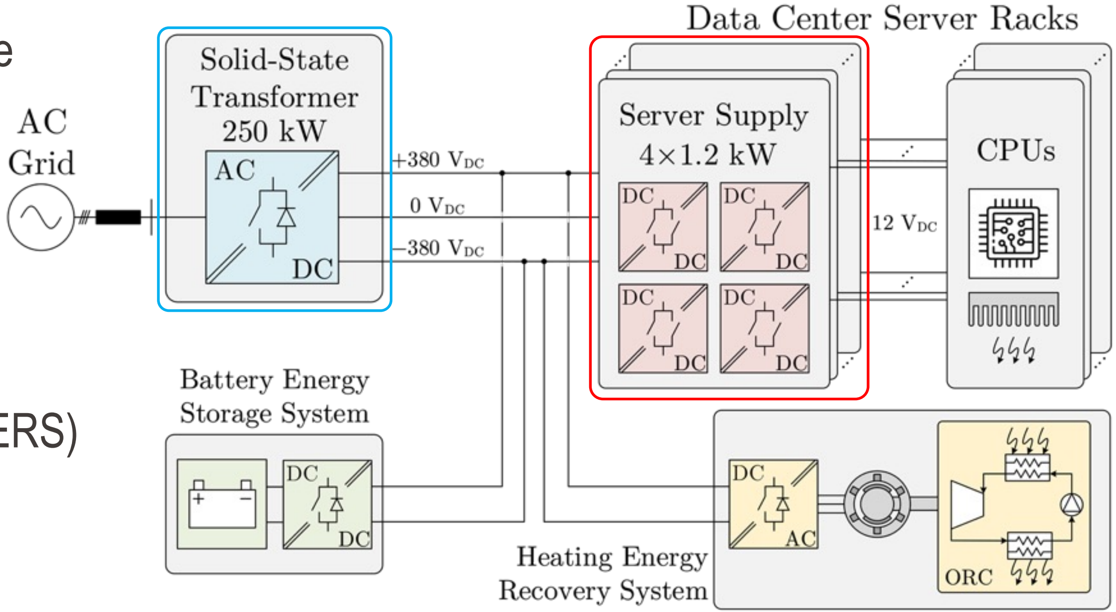
- Heating Bits



Source. J. Huber et al. PES, ETHZ

Activity 4: Power distribution and conversion architectures for DCs (PEL)

Future data denters will have a DC electric sistribution System



DC Distribution System

- ± 380 V_{DC} Distribution
- 760 V_{DC} pole-to-pole (interface of BESS and HERS)
- 12 V_{DC} for Point-of-Load

Role of PEL in the project:

- Design and realization of the main HVDC power distribution supply (AC/DC stage – Solid-State Transformer)
- Design and realization of the Server Supplies (DC/DC stages – 4 units × each server blade)

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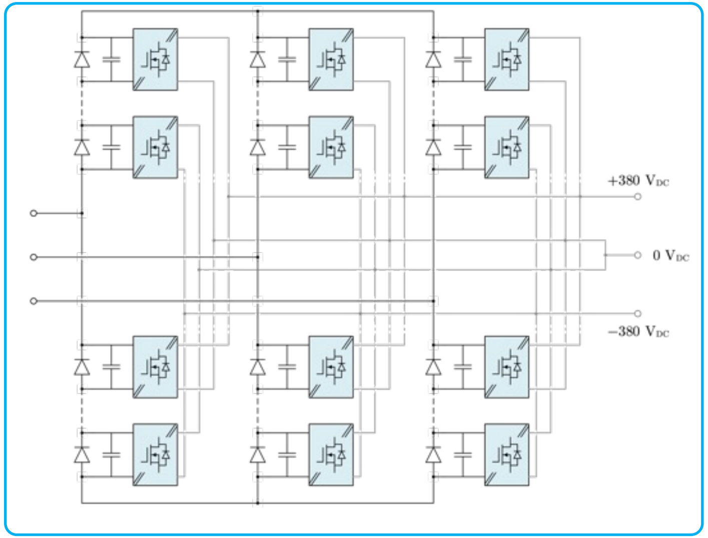
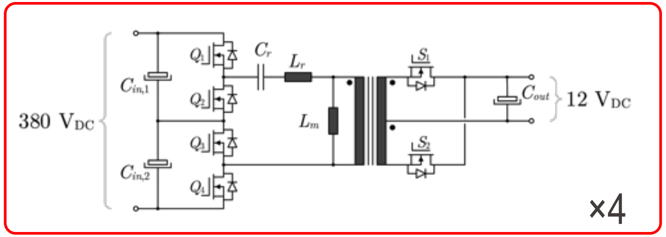
Activity 4: Power distribution and conversion architectures for DCs (PEL)

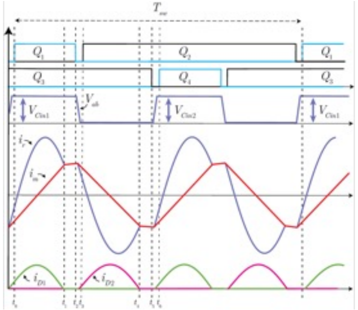
Modularized Bridge Rectifier Solid-State Transformer

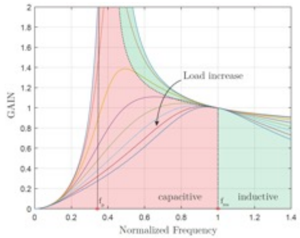


- Modular Design
- Galvanic insulation
- AC/DC conversion with DC/DC stages

Frequency-Doubling LLC Resonant Converter







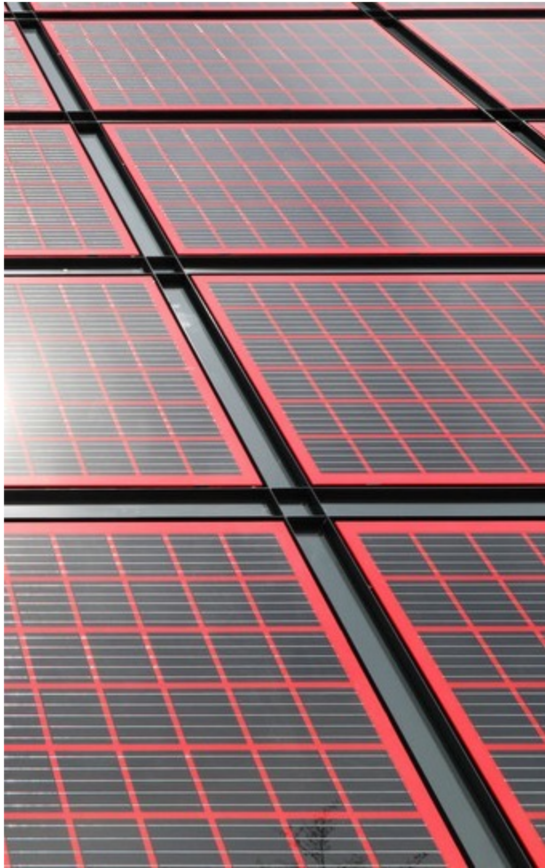
- Based on resonant converter topology
- High-frequency magnetic insulation
- Soft-switching capability

Heating Bits

Activity 5: Multi-energy system integration and CO_2eq content assessment (DESL-IPESE)

Aim: optimal system operation to supply **electricity, heating and cooling services** while **minimizing the overall CO_2 emissions**.

- Design level ➔ Definition of technologies' sizes and opportunities for services' provision.
- Operational level ➔ Development and demonstration of the strategic optimal system operation based on the CO_2 content forecast of the electrical grid.



Activity 5: Multi-energy system integration and CO_2eq content assessment (DESL)

Carbon-aware dispatcher: formulation

- **Day-ahead schedule** of the power at the grid connection point to minimize the expected carbon emissions (CE) caused by
  - consuming electricity from the grid (considering dynamic and stochastic carbon intensity, load, and PV generation)
  - using the battery (LCA based, considering the calendar and cycling aging of the battery)
- Subject to **operational constraints**
  - Battery state-of-charge
  - Battery efficiency

$$\min \; E(C_e^{pcc}) + E(C_e^{ess})$$

$$C_{\mathrm{e}}^{\mathrm{ess}} \geq \frac{T \cdot C_{\mathrm{i}}^{\mathrm{ess}}}{M} \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} (|\mathbf{P}_{\mathrm{ess}}^{\mathrm{charge}}[k][j]| + |\mathbf{P}_{\mathrm{ess}}^{\mathrm{discharge}}[k][j]|) + E_{\mathrm{ess}}^{\mathrm{rated}} \frac{W \cdot C_{\mathrm{e,\,LCA}}^{\mathrm{ess}}}{L_{\mathrm{ess}}^{\mathrm{calendar}}}$$

Activity 5: Multi-energy system integration and CO_2eq content assessment (DESL)

Carbon-aware dispatcher: results

- **Dispatch** the experimental facility in the CCT
  - Servers (50 kW)
  - Battery Li-Ion (60 kW, 100 kWh)
  - PV (58.5 kWp)
- **400 days simulated** (50+1 scenarios per day)

	Servers only	Servers, PV No dispatch	Servers, PV, BESS Dispatched
Average daily emissions [kgCO2eq]	53.82	40.51	38.97
Average emissions reductions compared to server only case [%]	-0	-24.7	-27.6

Activity 5: Multi-energy system integration and CO_2eq content assessment (DESL)

Carbon-aware ESS&PV sizing: formulation

- Scenario based **carbon and cost aware sizing of energy storage and photovoltaic** generation
  - considering dynamic and stochastic grid carbon intensity, load, and PV generation
  - subject to operational constraints
- **Minimize the objective function** F_{obj}, over user-selected typical days

$$F_{\mathrm{obj}}(P_{\mathrm{ess}}^{\mathrm{rated}}, E_{\mathrm{ess}}^{\mathrm{rated}}, P_{\mathrm{gen}}^{\mathrm{rated}}) = C_{\mathrm{e}}^{\mathrm{pcc}} + C_{\mathrm{e}}^{\mathrm{ess}} + C_{\mathrm{e}}^{\mathrm{gen}} + w(c_{\mathrm{ess}} + c_{\mathrm{gen}} + c_{\mathrm{el}}^{\mathrm{energy}} + c_{\mathrm{el}}^{\mathrm{power}})$$

Carbon costs	**Financial costs**
Emissions from grid electricity imports	Electricity bill
ESS equivalent emissions	ESS investment, operation and maintenance
Generation equivalent emissions	Generation investment, operation and maintenance

Table 1. Summary of the multi-objective function

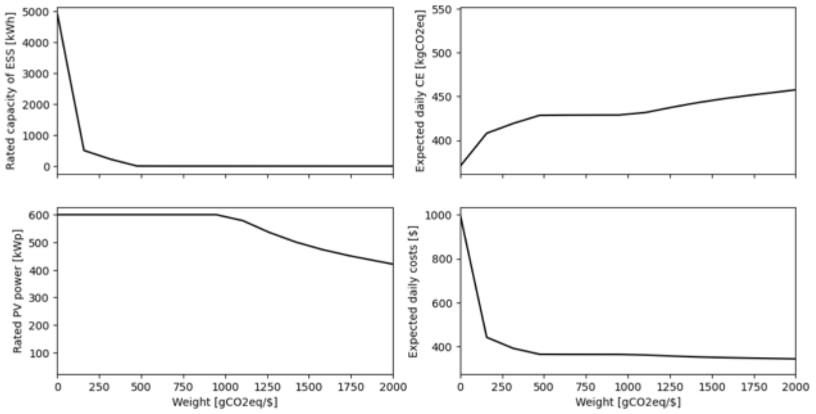
Note: the weight w [gCO_2eq/$] can be interpreted as the amount of CO_2 emissions for a CAPEX+OPEX increase of 1$. Or, $\frac{1}{w}$ [$/$gCO_2$eq] the economical value (CAPEX+OPEX) of one gram of CO_2eq saved.

Activity 5: Multi-energy system integration and CO_2eq content assessment (DESL)

Carbon-aware sizing: results

- **Sizing for a load** comparable to the CCT servers
  - Servers (500 kW)
  - Swiss case study (e.g., for electricity prices, carbon intensities, GHI, …)
- **28 typical days** (7 per season), **20 scenarios per typical day**
  - Expected daily CE of servers alone is 550 kgCO_2eq, expected daily cost is 300$.

Weight [gCO_2eq/$]	Optimal sizing: Expected daily CE [kgCO2eq]	Optimal sizing: Expected daily cost [$]
1	370 (-32%)	1000
315	420 (-26%)	390
1100	431 (-22%)	355
3000	540 (-9%)	308

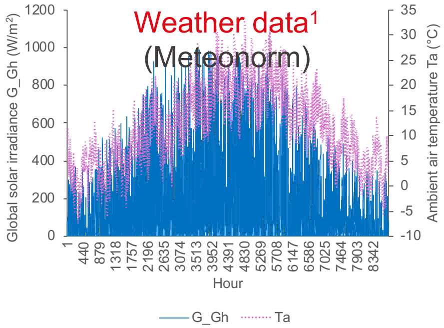


Activity 5: Multi-energy system integration and CO_2eq content assessment (IPESE)

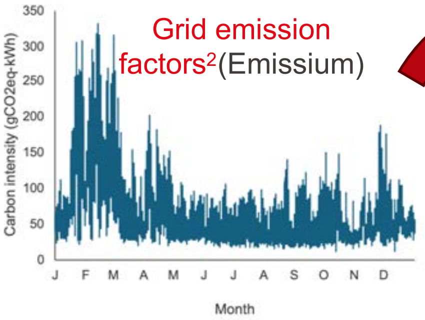
Energy services characterisation for EPFL campus

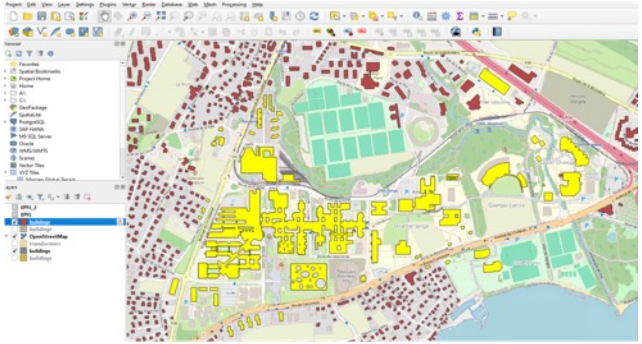
Input data

Weather data[1] (Meteonorm)



Grid emission factors[2] (Emissium)

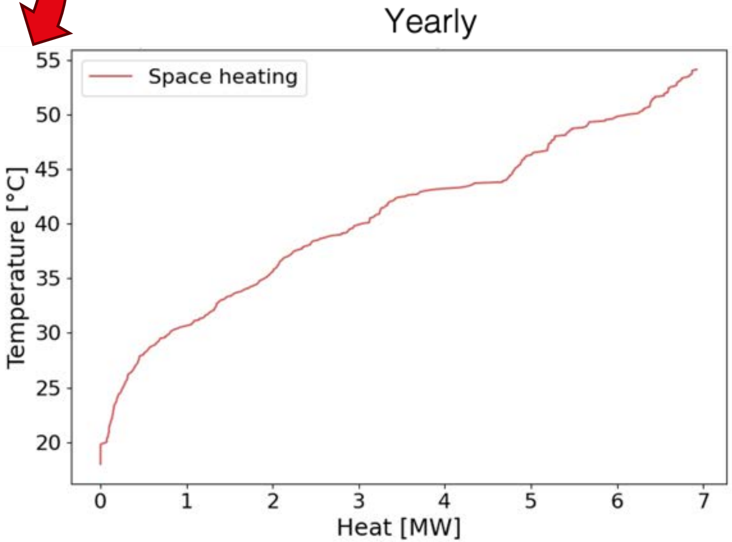




EPFL campus buildings data (Qbuildings[3]) + validation (CCT)

Typical periods evaluation (Clustering algorithm)

REHO BY IPESE



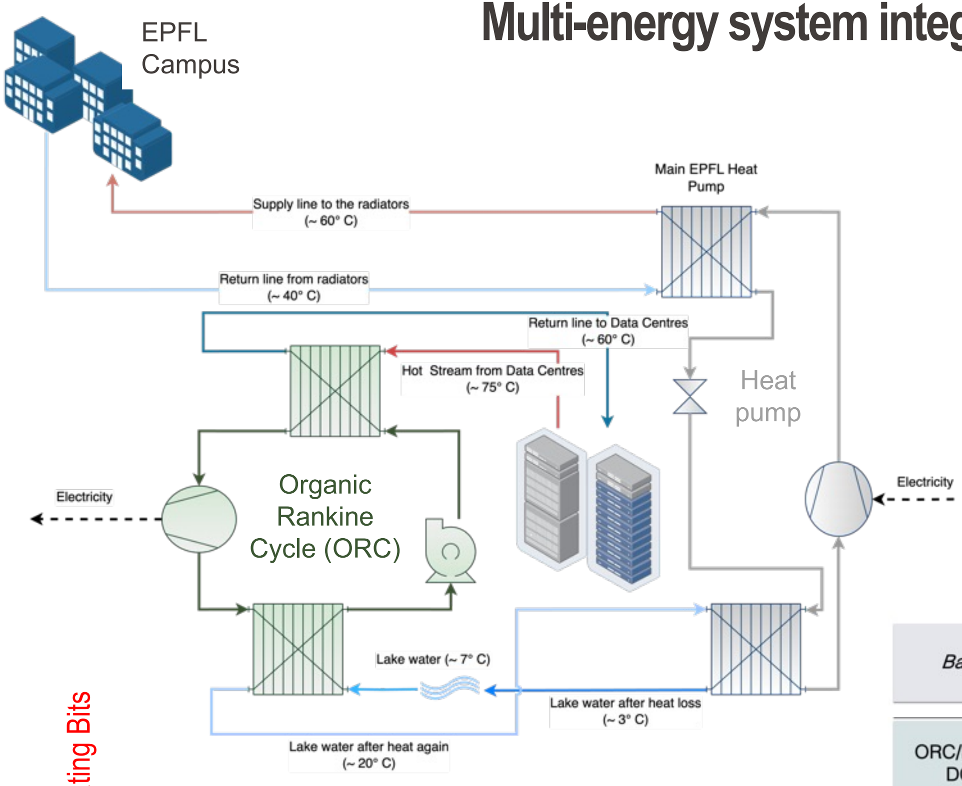
Composite curves per typical period ➔ Heating curves setpoints.

Heating Bits

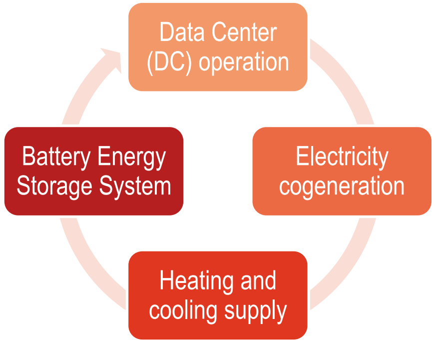
[1] https://meteonorm.com/
[2] https://www.emissium.io/
[3] https://ipese-web.epfl.ch/lepour/qbuildings/
[4] https://reho.readthedocs.io/en/main/

Activity 5: Multi-energy system integration and CO_2eq content assessment (IPESE)

Multi-energy system integration: ORC/HP + DC



Strategic optimal system operation ➔ Heating period and non-heating period



Preliminary assessment: Potential annual electricity consumption reduction

		Annual HP Electricity demand - EPFL (MWh)	Electricity produced by the ORC (MWh)	Avoided Electricity demand HP (MWh)*	Net annual electricity Consumption (MWh)	Percentage decrease in annual consumption*
BaU	Summer	0	0	0	9760	-
	Winter	9760	0	0		
ORC/HP + DC	Summer	0	25.4	0	9711	0.50%
	Winter	9752	15.74	8		

Heating Bits

EPFL

EcoCloud sustainable-computing experimental facility at EPFL's CCT

- **~100 m² of flexible space for experiments** on **sustainable computing**
  - Independent regulation of water flow per rack
  - Separate room for UPS, batteries, and direct current (DC) equipment
  - Monitoring of energy consumption
- **Server fleet with modern and decommissioned EPFL machines**
  - 200 nodes received from SCITAS
  - Can be used to install cold plates and run workloads