Towards Integration of Carnot Batteries in Data Centres: Design Optimisation and Global Sensitivity Analysis under Techno-Economic Uncertainties

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Objective

Designing a Carnot battery integrated into a real data centre and coupled to a PV array to maximise its self-sufficiency ratio and to minimise the final cost of electricity.

Thermal Integration in Data Centres

From a thermodynamic point of view, **data centres are massive exergy destructors**: they convert electricity into **low-grade heat** (i.e. cooling water is typically **below $25°C$**), and there is an extra power consumption due to the associated cooling system. **Carnot batteries** (CB) and PV arrays can be integrated into data centres: they **recover** the **waste heat**, **reduce** the **cooling duty** and increase the **independence** from the **grid**.

This work proposes:

- to **optimise** the **design** of a **CB** and the **size** of a **PV** array towards integration into a $\sim$**100 kW data centre** (see fig.);
- to maximise its **self-sufficiency ratio** and minimise the final **cost of electricity**;
- and to **quantify the uncertainty** on economic figures.

Case Studies and Method

Two **integration scenarios** are considered:

- recovery of the **$25°C$** cooling water from cooling packages and cooling down to $15°C$ (current **air-cooled** facilities);
- recovery of the **$60°C$** cooling water from servers and cooling down to $50°C$ (future **water-cooled** data centres) [1].

A **semi-empirical operational model** is used to simulate the behaviour of the whole system based on **time series** from an existing facility (1h resolution). An **economic model** is used to assess economic figures. Details about the models and **power management strategy** can be found in our earlier work [2].

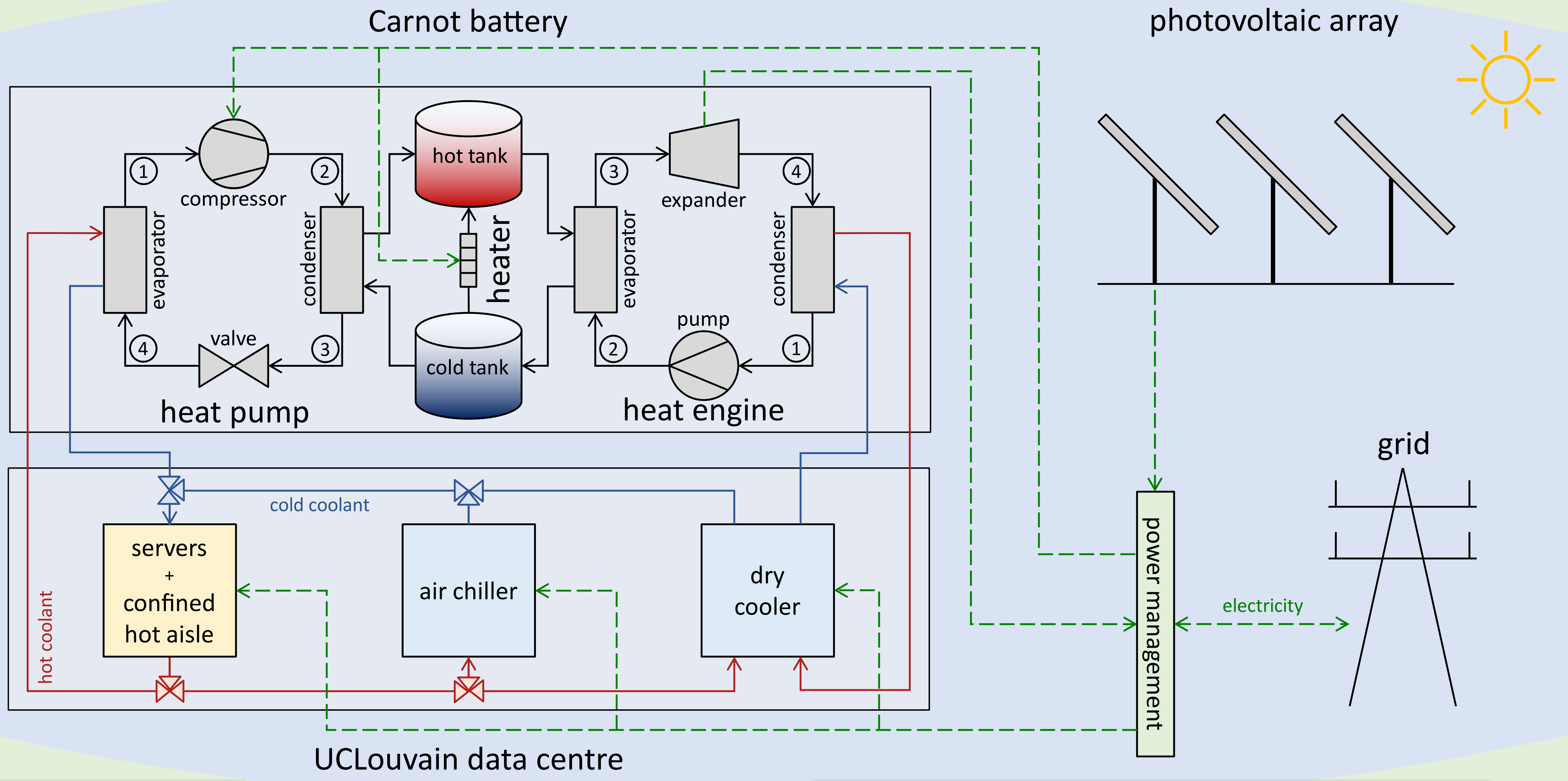
Multi-criteria optimisation and global sensitivity analyses are carried out with the RHEIA package (**genetic algorithm** and **polynomial chaos expansion**) [3].

Design variables

- ☐ compressor swept volume
- ☐ compressor volume ratio
- ☐ expander swept volume
- ☐ expander volume ratio
- ☐ storage hot temperature
- ☐ storage temperature spread
- ☐ tanks volume
- ☐ PV array peak power
- ☐ electric heater max. power

Parameters

- ☐ fluid: R1233zd(E) (HP/ORC)
- ☐ pinch point: 3K
- ☐ p. drops in exch.: 50 mbar
- ☐ max. isentropic eff.: 72.5%
- ☐ pump internal eff.: 55%



Uncertainties

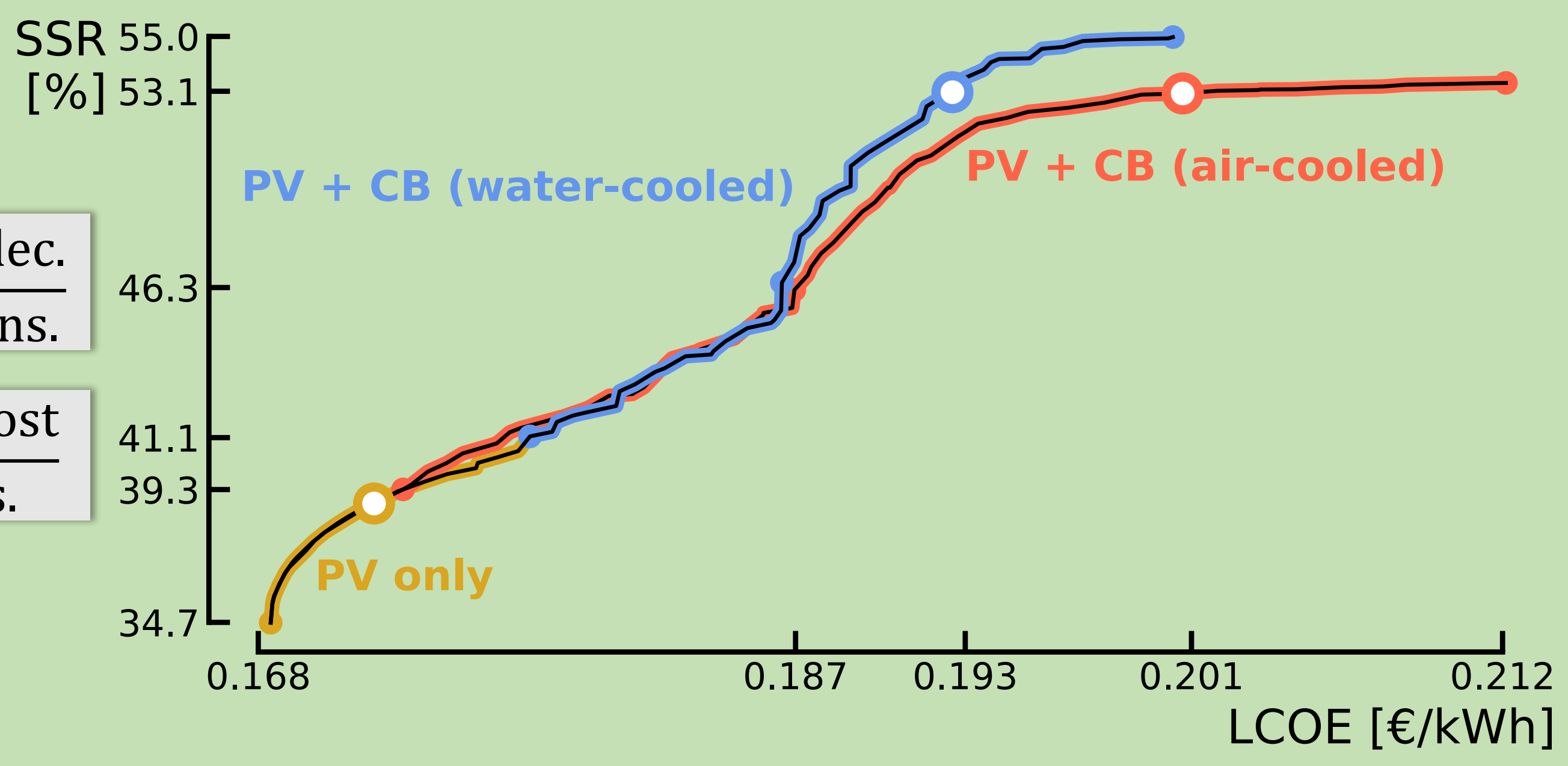
- ☐ max. isentropic efficiencies
- ☐ pump internal efficiency
- ☐ pinch points in exchangers
- ☐ pressure drops in exchang.
- ☐ time series:
  - servers power
  - sun irradiance
  - ambient temperature
- ☐ CAPEX and OPEX:
  - heat pump
  - organic Rankine cycle
  - storage tanks
  - PV array
  - electric heater
- ☐ price of electricity

Multi-Criteria Optimisation

- **PV only** provide **lowest LCOE** and SSR up to 39.3%;
- **PV + CB** in both case studies provide **similar LCOE and SSR** for **SSR up to 46.3%**;
- PV + CB achieves **higher SSR in water-cooled case** for same LCOE as in air-cooled case;
- SSR is constrained by maximum available PV capacity;
- In best cases, **CB** can **increase SSR** by up to about **15%**;
- In actual infrastructure, LCOE is 0.22 €/kWh so **PV + CB is always competitive**.

$$\mathbf{SSR} = 1 - \frac{\text{grid. elec.}}{\text{tot. cons.}}$$

$$\mathbf{LCOE} = \frac{\text{tot. ann. cost}}{\text{tot. cons.}}$$



Conclusion

In the two case studies, the data centre can achieve up to 55% self-sufficiency with PV + CB (of which about 15% is due to CB) while providing a lower final cost of elec. than in the actual infrastructure. The uncertainty on the final cost of electricity is also less sensitive to the price of electricity thanks to storage.

Acknowledgement

Time series corresponding to the data centre have been gratefully provided by the Center for High Performance Computing and Mass Storage (CISM) from UCLouvain.

References

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[2] A. Laterre, O. Dumont, V. Lemort, and F. Contino, “Design Optimisation and Global Sensitivity Analysis of a Carnot Battery Towards Integration in a Data Centre under Techno-Economic Uncertainties”, in *Proceedings of 5th SEE SDEWES*, Vlorë, May 2022.
[3] D. Coppitters, P. Tsirikoglou, W. D. Paepe, K. Kyprianidis, A. Kalfas, and F. Contino, ‘RHEIA: Robust design optimization of renewable Hydrogen and dErIved energy cArrier systems’, *Journal of Open Source Software*, vol. 7, no. 75, p. 4370, Jul. 2022.

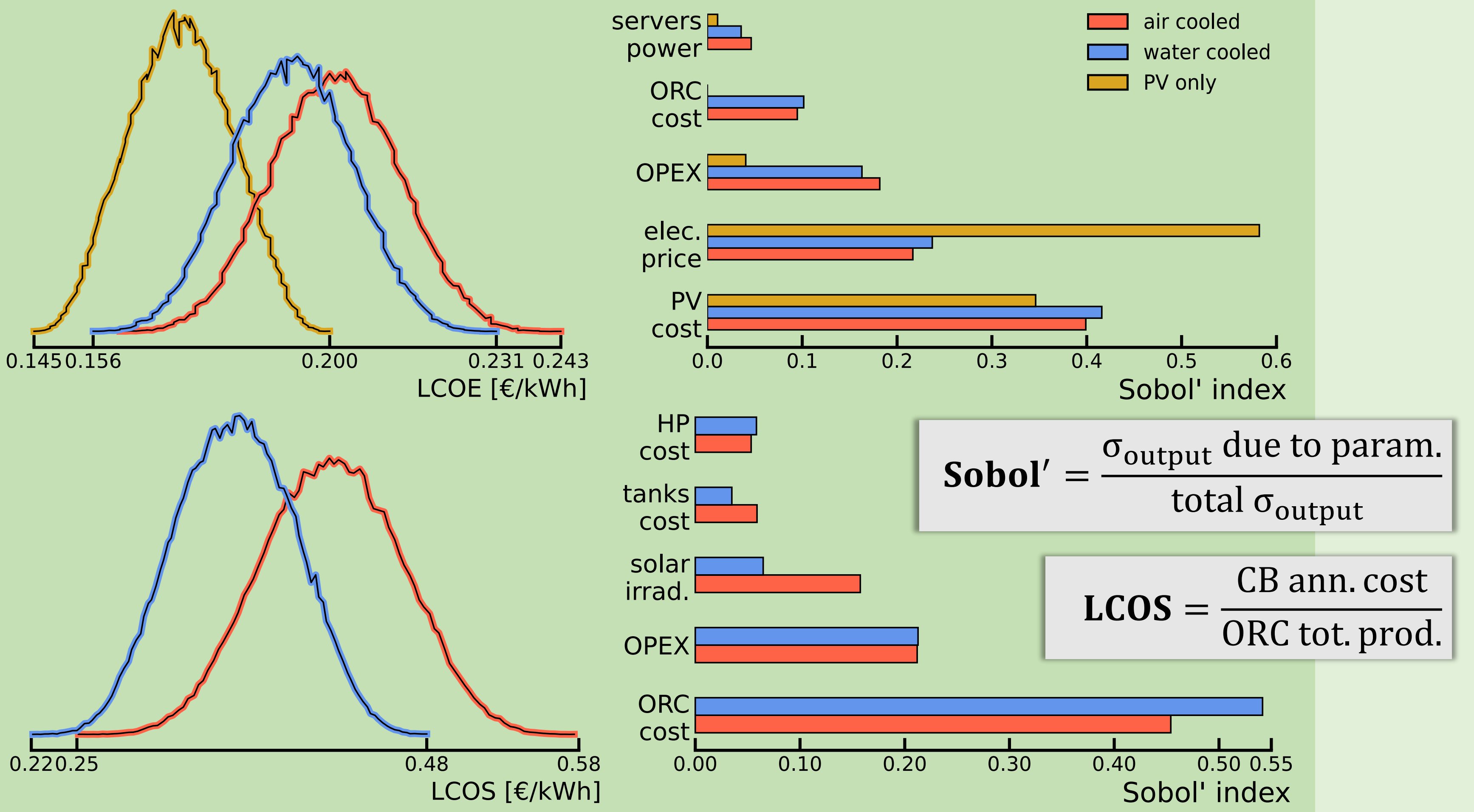
Global Sensitivity Analysis

Uncertainty on **LCOE**:

- **PV only** is **more sensitive** to **electricity price** and PV cost;
- **PV + CB** is **less sensitive** to elec. price thanks to **higher SSR**;
- **Storage** leads **to higher dev. on LCOE** due to uncert. on cost.

Uncertainty on **LCOS**:

- Driven by **ORC cost**, total **OPEX** and solar **irradiance**;
- **Narrower** for **water-cooled** than for air-cooled because it is **less affected** by solar **irradiance** (i.e. higher P2P efficiency).



$$\mathbf{Sobol'} = \frac{\sigma_{\text{output}} \text{ due to param.}}{\text{total } \sigma_{\text{output}}}$$

$$\mathbf{LCOS} = \frac{\text{CB ann. cost}}{\text{ORC tot. prod.}}$$

Figures of Merit

case	$\mathbf{T_{sto,hot}}\ [°C]$	$\mathbf{T_{spread}}\ [K]$	$\mathbf{LCOS}\ \left[\frac{€}{\mathbf{kWh}}\right]$	$\mathbf{P2P}\ [\%]$	$\mathbf{frac_{sto}}\ [\%]$	$\mathbf{tank}\ [\mathbf{m^3}]$
air-cooled	150	57.3	0.413	19.9	11.9	90.9
water-cooled	150	65.5	0.353	32.2	12.2	57.6