15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

# Low-Grade Heat-Driven Adsorption Heat Pumps

Bruno Michel[a*], Silvan Suter[a], Erich Rütsche[a], Xavier Daguenet[b], Jonas Keller[c], Maurus Caduff[d], and Massimo Giusti[e]

[a]Thermal Transformer AG, CH-8088 Pfäffikon, [b]Fachhochschule OST, CH-8640 Rapperswil
[c]Konvekta AG CH-9015, St.Gallen, [d]Willers AG, CH-8048 Zürich, [e]Burckhardt Compression CH-8404 Winterthur

**Abstract**

Innovative thermally driven rapid thermal swing adsorption (RTSA) heat pumps use abundant lowest-grade waste or renewable heat and benign working fluids to provide heating and cooling with high efficiency. Adoption of adsorption heat pumps was slowed by inefficient adsorbents and heat exchangers that result in large system volumes and capital cost. This paper shows how RTSA heat pumps may be improved via novel higher performance materials and shaping methods in terms of performance, sustainability, and cost. Low thermal and mass transport resistance and high-capacity adsorbent coatings on heat exchanger fins are studied with a novel temperature jump system (TJS). Using these results adsorption heat pump operation was calculated indicating that low thermal and mass transport resistances allow faster cycles and a larger active-to-dead-mass ratio. The concept is demonstrated for 10 kW cooling systems in scenarios with applications for datacenters and compressors. The TJS extension model is applied to two case studies: (1) In datacenters, waste heat as low as 45°C from graphics processor units (GPUs) is converted into cooling to reduce the electrical energy demand. (2) 75-90°C heat from compressors that is converted into suction gas cooling to improve compression efficiency. The case studies show that our new industrial heat pump driven with 200 kW heat provides cooling with a $COP_{th}$ close to 1. Leveraging high specific cooling power and a reduction in electrical energy consumption for cooling by > 95%.


Selection and/or peer-review under the responsibility of the organizers of the 15th IEA Heat Pump Conference 2026.

*Keywords: Adsorption; Low-grade heat; temperature swing; waste-heat; data center; compressor; suction cooling*

## 1. Introduction

In the past focus was on getting access to fossil and later to renewable energy while ~75% of primary energy was lost as waste heat. Now, the focus shifts to improving efficiency but the thermal sector is less mature than the electrical sector. Therefore, innovations are needed involving efficiencies of thermally mediated energy conversion. With the spread of artificial intelligence (AI), electricity consumption for data centers will double to reach 945 TWh by 2030, or 3% of total electricity consumption. From 2024 to 2030, it will grow 15% per year [1]. With accelerating climate change, more focus on improving cooling is needed since 30% of data center power use is attributed to server cooling [2]. Water with its 4000x better heat capacity and 30x better thermal conductivity than air in microchannels with hierarchical branched manifolds enables hot water cooling. Parallel to that filling materials/gaps with percolation and necking improve the thermal conduction [2].

Thermally driven solid sorption heat pumps suffer efficiency losses due to the coupling of adsorber beads or beds to heat sources and sinks. Reducing thermal gradients within the adsorbers massively improves thermal efficiency. However, the thermal transport is coupled to mass transport and the ad- / desorption process in solid sorbents. A **Temperature Jump System (TJS)** quantifies transient temperature and adsorption profiles [2, 4, 17] to distinguish between heat and mass transport limitations. TJS helps to enhance the heat rate per unit volume to increase the power density and efficiency of adsorbers. Table 1 provides an overview of applications

[*] Corresponding author. Tel.: +41 79 247 99 62
*E-mail address:* bmi@thermaltransformer.ch

of solid sorption technologies. and a context for applications of solid sorption technologies and ongoing advances in material sciences. Ultimately, this leads to the question, how advances in material sciences can be translated into a real-world application solving the need for large amounts of cooling capacity by valorization of low grade waste heat. Innovative models for datacenter integrated energy systems and new and sustainable adsorbent materials incorporated in a **Heat and Mass EXchanger (HEX-MEX)** help to actively engage in the interaction between computing networks and power grids / heating networks [3,17].

Table 1: State of the art applications of solid sorption technologies

| **Coating (mm)** | **Geometry** | **Temperatures [°C] Cooling Cap. [kW]** | **Key Performance Indicators (KPI's) (SCP = Specific Cooling Power, EER = Energy Efficiency Ratio)** | **Source** |
|---|---|---|---|---|
| LiCl silica gel beads | Annular finned tube | 50/30/23<br>50/24/23 | SCP = 102.35 W/kg, VCP = 7.47 kW/m$^3$<br>SCP = 200.86 W/kg, $COP_{th}$ 0.49 | [5] Cui 2024 |
| MIL100(FE) | Flat-tube lamella | 50/26/18<br>8.5 | Therm. Efficiency 0.53-0.6<br>EER > 20 | [6] Velte 2024 |
| Simulation | Simulation | 55/29/18 + 63/30/18 | EER increase >122% | [7] Asadov 2021 |
| N.A. | N.A. | 30-60/20-35/5-15<br>1750 | Electrical heat pump upgrades Direct Cooling (DC) waste heat; Carbon emission red. 10% | [8] Bai 2025 |
| CAU-10-H | Crystallization on Aluminum | 45-75°C Swings<br>26 mbar | High Metal-Organic Frameworks (MOF) loading, Mc 250 g/kg | [9] de Lange 2015 |
| Al-fumarate 0.14-0.61 | Binder-based coatings | 60/30/20<br>cycle time 9-78s | 1.3 – 14 kW/kg, 0.2-0.7 kW/l<br>$COP_{th}$ 0.47-0.57 | [10] Laurenz 2021 |
| AL-fumarate MOF | Annular finned tube | 40°C/-/- | Thermal cond. = 0.07 W/(m K), Linear Driving Force (LDF) time constant = 0.1-3 1/s | [10] Laurenz 2021<br>[10] Laurenz 2021 |
| Review | Review | 40-80°C | Efficiency increase, Mitigation of environmental aspects | [11] Yuan 2023 |
| Silica Gel | Round tube-Al fins | 56/31/21$COP_{th}$ 0.48<br>86/30/11 $COP_{th}$ 0.51 | Solar driven heat pump for datacenter waste heat | [12] Pan 2021 |
| Adsorbent grown on fins | Annular finned tube | 40-55/25/15 | Efficiency increase vs. mechanical chiller = 2x<br>50°C: $COP_{th}$=0.5, $COP_{el}$ = 13.5 | [13] Wilde 2017 |

## 2. Methods

Innovative thermally driven adsorption heat pumps use abundant lowest-grade waste or renewable heat and benign working fluids to provide heating and cooling at optimal temperatures with high exergetic efficiency. Electrical energy consumption and carbon emissions are massively reduced compared to electrically driven heating and cooling. Adoption of adsorption heat pumps was so far hindered by inefficient adsorbents and **Heat Exchangers (HEX)** that result in large system volumes and capital cost. We address this challenge improving technical and economic incentives for widespread adoption of adsorption heat pumps as a sustainable heating and cooling technology. Measurements were conducted with materials (3.1), and shaping methods (2.2) applied to novel higher performance heat exchangers (2.1). Results were used to design a system (3.2) in terms of performance, sustainability and cost for two case studies (4).

### *2.1. Heat Exchangers*

Finned tube HEX with a unique design having headers on both sides were employed (*Fig. 1a and b*). These HEX allow a cross-counterflow and thus a large overlap of the leaving fluid and gas temperatures with small approach temperatures. This is a prerequisite for achieving high energy efficiencies (heat recovery coefficients and thermal resistance) allowing minimal HEX volumes for a given power, which saves space and cost in the **Adsorber / Desorber (A/D)** unit. The employed HEX enables scalable heat-driven RTSA heat pumps, as their use allows excellent efficiencies to be achieved in limited spaces. HEX are build in small dimensions for demonstrators for 0.5 kW heat exchange, (*Fig. 1c*), in medium dimensions for the 100 kW heat-driven chiller product (*Fig. 1d*) and in very large dimensions of 150 x 200 x 60 cm for engineered MW-scale systems. The use of stable and thick lamellas (*Fig. 1a*) results in a good connection to the water carrying copper tubes. In combination with a small pitch, the thermal resistance is lower as the state-of-the art used in adsorption chillers after having received a thick low thermal and mass transport resistant coating with adsorbent as shown below.

### 2.2. Coatings with heat and mass transport enhancement

Thick coatings are essential for compact solid sorption heat-pumps because they improve the active to dead mass ratio for a given tube fin section (*Fig. 1g*). With a high active to dead mass ratio the size of the HEX-MEX and consequently the overall size of the system or the driving temperature gradient can be reduced. High performance thick coatings require low thermal and mass transport resistance which are challenging since they both increase with thickness. Maximizing active to dead mass ratio thus depends on the thermal and mass transport resistance within the thicker layer of sorbent. 1 mm beads show a good mass transport but have a bad thermal transport (*Fig. 1e*). Sorbent crystals directly grown on Aluminum fins have excellent kinetics but have a bad active to dead mass ratio (*Fig. 1f*). Necking, a process developed in context of thermal pastes in computers, can partially improve the thermal transport performance by allowing binder and additional smaller particles to accumulate at contact points. But necking is more effective to improve transport in 5-50 micron adsorbent particles formulated to thick layers on top of Aluminum fins (*Fig. 1h and i*).

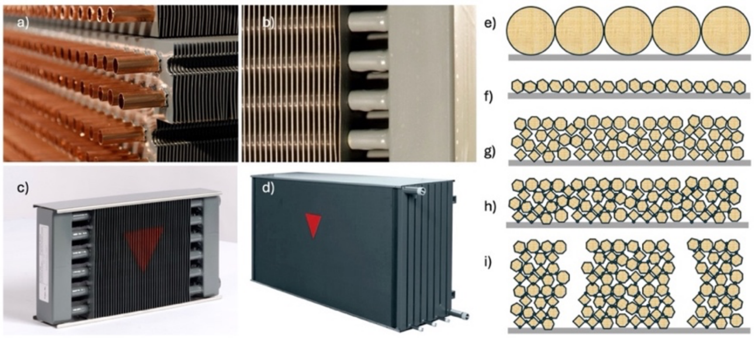


Figure 1: Heat exchanger structure (a, b), scalability (c, d) and coating approaches used for RTSA heat pumps (e-i).

Characterization and optimization of mass and heat transport in solid sorption RTSA heat pumps is improved with a novel experimental approach to discriminate between mass and heat transport in sorption processes. In this isochoric method, rapid temperature swings are applied to an adsorbent while mass transport is captured by the loading transient with pressure sensors and heat transport is quantified through the transient surface temperature with an IR-camera. The sorption equilibrium properties are measured in the same setup. The novel TJS System described in Ammann et al 2017 [14] identifies transport limitations and can accurately predict the performance of adsorption chillers which depends on the optimized thermal performance of the HEX, the **cycled mass (Mc)** for a given **temperature swing ($T_{cyc}$)** and kinetic parameters of the sorbent and the performance of the sorbent in the coatings.

Low thermal and mass transport resistance integration of high-capacity adsorbent coatings with HEX is confirmed using 1 $cm^2$ TJS samples that reflect a miniaturized HEX-MEX and can be completed quickly using small amounts of adsorbents and additives [2, references therein]. In addition, the exact process that takes place within the pumping cycle is executed in a miniaturized form. The result is the kinetics of heating and cooling at the surface of the sorbent layer with the IR temperature recording and the kinetics and equilibrium of sorption based on the pressure of the working fluid in a calibrated chamber. The kinetics is followed by a first order fitting to 2-4-8 minute swings to calculate **$M_c$/h - the maximal mass of working fluid that can be cycled** theoretically. Practically, the value is smaller depending on the cycle time. An effect that can also be measured with TJS is the relative mass transport improvement by the implementation of magnetically aligned pores.

## 3. Results and Discussions

### 3.1. Selection of sorbents

Sorbents with a high Mc for a given temperature swing are crucial for compact RTSA heat pumps. Mc for water vapor has been measured with TJS for 20 and 50°C swings (*Fig. 2 a and b*). $M_c$ alone is not a sufficient measure for the suitability of a material for an adsorption heat pump. The best measure is Mc for a temperature swing and cycle time. This results in a complex characteristic since the best material for a short cycle time may not be the best one for a longer cycle time. A simplification is the use of a first order fit to the change of sorption during a 2-minute cycle time with identical times for sorption and desorption. The kinetic information is the average of first order fits to the adsorption and desorption phases and varies from 0.05 to 1 1/s. With both Mc and the average kinetic information, the $M_c$/h (in kg of adsorbent) is created. This cannot directly be used to calculate the cooling power since for a given $T_{cyc}$, $M_c$ and hence cooling power will be smaller.

Samples were analyzed for applications to provide 4, 12 or 18°C cooling with water vapor pressures of 5, 10, and 20 mbar, respectively (*Fig. 2 blue, magenta and green*). Silica gel A-D was analyzed with powder sizes from 100 to 5 micrometers. The analysis also included amine coated silica carriers (E), two different formulations of SAPO-34 (F, G), and Aluminum fumarate (H). The performance ($M_c$/h in g/kg sorbent*h) was analyzed with 50°C (a) and 20°C (b) thermal swing. The following conclusions can be drawn: SAPO-34 performs better than silica gels except when they are coated. Aluminum fumarate performs best for 50°C swings and 12°C cooling (10 mbar, magenta). Coated silica and SAPO34 performs best for 20°C swings and 20°C cooling (20 mbar, blue). Not only sorbents were varied but also particle sizes: Intermediate particles perform better than smaller or larger particles for all temperature swings and coolant temperatures. TJS results like, cycled mass and first order kinetics as well as thermal performance of heat exchangers are then used in subsequent calculations for chiller performance parameters like **Specific Cooling Power** (SCP), **electrical and thermal coefficient of performance ($COP_{th}$, $COP_{el}$)**, exergetic efficiency (%) and cost (€/kW).

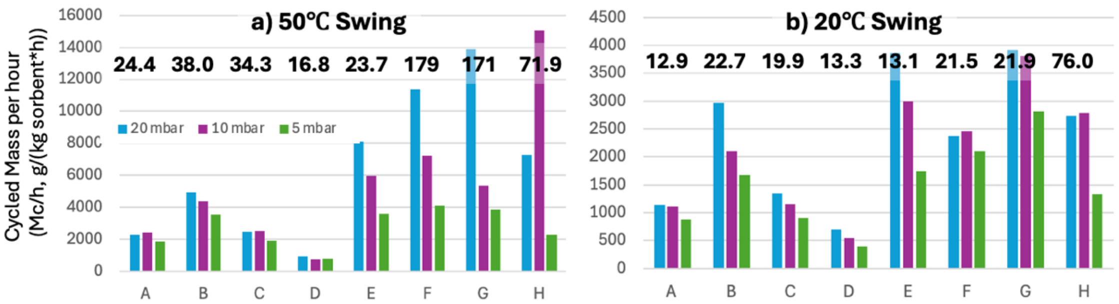


Figure 2: TJS Results for 75 and 45°C driving temperatures and 50 and 20°C temperature swings. Numbers are Mc at 10 mbar.

### 3.2. Modeling, design, build, and test of compact system

TJS results are used to design HEX-MEX, chambers, and temperature swing system in three stages: First, a HEX-MEX lab prototype is built and characterized (*Fig. 3a, and b*). Then, the same process will be repeated for a demonstrator with a single A/D chamber, followed by a complete 10 kW demonstrator (*Fig. 3d)*.

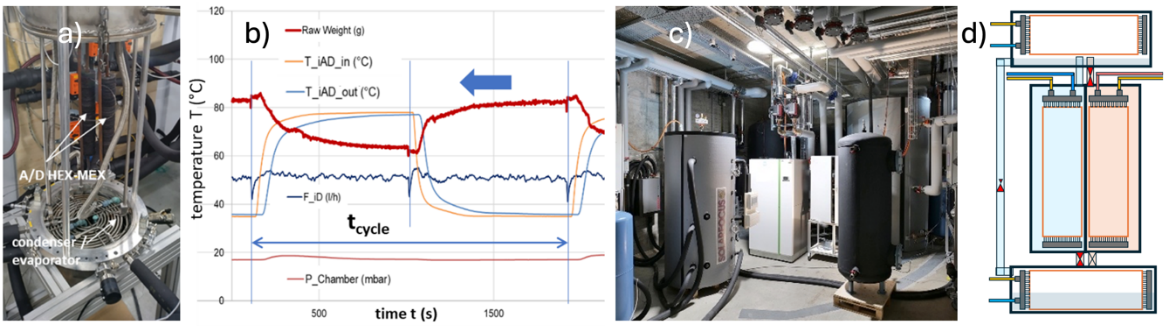


Figure 3a): open single chamber measurement setup for the characterisation of single A/D HEX-MEX. b): measurement data: adsorption and desorption cycle measurement - Raw A/D Weight (g), heat transfer fluid inlet (T_iAD_in) and outlet (T_iAD_out) temperature, heat transfer fluid flow (F_iD) and sorbent pressure P_Chamber in function of time t. c) hardware in the loop test rig. d) scheme of heat pump with two adsorber chambers, condenser, and evaporator.

The concept is tested in a hardware-in-the-loop test rig (*Fig. 3c*) and case studies are performed for application in a real facility. TJS results are used to calculate the mass of all involved materials of the coated heat exchanger. SCP is calculated using cycled mass and mass transport kinetics from TJS for a given cycle time. The COP is calculated using active and dead masses, sensible heat, and latent heat of sorption as well as heat recovery between the adsorption and desorption chamber during temperature swings. A dynamic model is under development that includes thermal spreading resistance in HEX fins and an analysis of the thermal transport in the sorbent coating. SCP and COP are calculated for all driving/rejection/cooling temperatures for the targeted case studies. TJS results and dynamic models also show that RTSA heat pumps have a high specific cooling power and reduced electrical energy consumption for cooling by >95%.

## 4. Case Studies for Applications

*4.1. Case study application to datacenters*

Power densities in **graphical processor unit (GPU)** racks reach 200 kW per rack or $m^3$. Direct liquid cooling allowed higher coolant temperatures of up to 65°C as the thermal resistance is reduced 10-fold [5, 2], direct space heating in winter, and conversion to cooling in summer [6, 2]. The server waste heat in CoolMUC-2 [8, 2] was used to operate silica/water adsorption chillers that provided cooling for data storage servers with reduced electrical power consumption. The reduction in electricity spent on cooling infrastructure must be carefully balanced against the increased server power consumption at higher operating temperatures. Consequently, there is a pressure to reduce direct liquid cooling temperatures in datacenters and GPUs from 65 to 45°C [16] which makes conversion to cooling in adsorption chillers challenging but was demonstrated using our case study that it can be handled using RTSA heat pumps (*Fig 4a*).

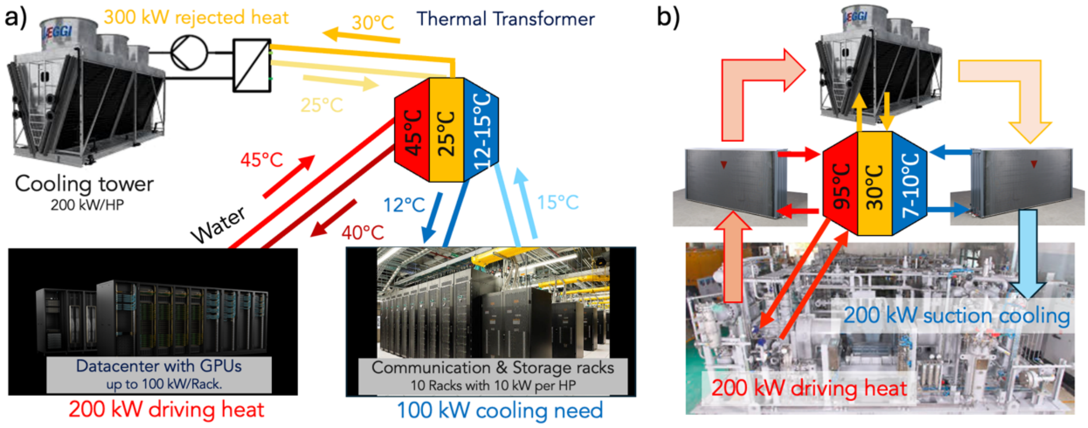


Figure 4: Application of RTSA heat pumps in Datacenter (a) and for suction cooling in compression (b).

*4.2. Case study application to compressors*

Compression requires a large amount of energy and rejects a lot of heat at the compressor exhaust. The performance is strongly affected by the suction temperature: The ability to regenerate the exhaust heat to produce pre-cooling for reduced suction temperature improves the compressor mass flow rate and the power per mass flow efficiency. Cooler, denser gas allows more mass to be drawn in per stroke, increasing volumetric efficiency, reducing power, compression ratio, friction heat, and wear, leading to a longer compressor lifespan. The impacts on different compressors were simulated showing a 5-10% mass flow improvement. In our case study we showed that the suction temperature can be reduced by 20-30°C compared to current cooling water systems (*Fig 4b*) using compression waste heat and RTSA heat pumps. Markets are gas processing in refineries, LPG, and ammonia transportation. Main new growing markets are LNG, $LH_2$ and ammonia tankers, energy applications for hydrogen economy for high and low-pressure markets (mobility, storage, pipelines), and $CO_2$ storage.

*4.3. Other applications*

Heat driven heat pumps thrive in many industries where low-grade heat is currently rejected and with a parallel demand for cooling in: Steel mills, refineries, power plants with gas separation / carbon capture, waste incineration. In addition, there is a large potential in the office- and residential building sector: Buildings emitted 15.4% of total GHG in Switzerland in 2024. Heat pumps can reduce the use of fossil energy sources. Another benefit is their use for both heating and cooling. However, a major challenge in temperate climates is the disparity between heating and cooling loads which bring challenges to correctly design and operate heat pumps. Combined RTSA adsorption and compression heat pumps provide the following benefits: (1) Improvement of operational characteristics of the compression heat pump due to smaller difference between heating and cooling demand (2) Reduction of noise emissions of the compression heat pump due to smaller load, (3) Reduction of installed electrical power by 20%. Identifying the right initial applications is an important task to allow a fast spread of the new heat pump technology and a good contribution to reduce $CO_2$ emissions.

## 5. Conclusions and Outlook

RTSA heat pumps are improved via novel materials and shaping methods in terms of performance, sustainability, and cost. Results from the TJS tool show that SAPO-34 performs best for higher cooling and driving temperatures while silica gel performs well for small and large swings when the layer is formulated optimally with the right particle size and porosity. Amine coated silica performs comparable to SAPO-34 for small temperature swings and higher cooling temperature. The low thermal and mass transport resistances enabled by good HEX, materials, and coating technologies allow faster cycles and a larger active-to-dead-mass ratio. This is used to demonstrate more efficiency and cooling power with 10 kW demonstrators for applications in datacenters and compressors. Low-grade 75-90°C heat from compressors and other sources is converted into suction gas cooling that enhances compressor efficiency, increases volumetric efficiency by reducing vapor specific volume and extending compressor life. A commercial industrial adsorption heat pump transformer may be driven with 200 kW heat to provide cooling with a $COP_{th}$ close to 1 and, based on results with the smaller test vehicle, will have a short payback period because of high specific cooling power and reduced electrical energy consumption for cooling >95% ($COP_{el} > 20$). Waste heat as low as 45°C from GPUs may be converted into cooling to allow installation of more GPUs for the same energy supply. A short payback period is possible because of the >10x reduced electrical consumption compared to electrical while investment cost is comparable, and maintenance is lower due to the absence of a compressor and use of "free" waste heat.

## References


[1] IEA Energy demand from AI https://www.iea.org/reports/energy-and-ai/energy-demand-from-ai (link tested Oct. 8, 2025)

[2] Ruch P., Ammann J., Paredes S., Wiik N., Lörtscher E., Meijer G.I., Michel B., "Sustainable data centers and energy conversion technologies", 12th IEA Heat Pump Conference (2017) K.4.5.1.

[3] Wang Y., et al., "Data center integrated energy system for sustainability", The Innovation Energy 1(1): 100014, February 26, 2024.

[4] Sadykov, I., Michel, B. et al, " Understanding rapid thermal swing adsorption of carbon dioxide with moisture-tolerant sorbent coatings", Chemical Engineering Journal (2025), 172104.

[5] Cui Z., Du S., Zhao T., Chen Z., Wang R., "High-power density adsorption chiller driven by data center waste heat using encapsulated composite as adsorbent", Energy 311 (2024) 13339.

[6] Velte, et al., "Utilizing waste heat from data centers with adsorptive heat transformation– Heat exchanger design and choice of adsorbent", Energy Conversion and Mgmt 310 (2024) 118500.

[7] Asadov N., Lindenberg K. J., Fischer T., Gohr F., Brandt S., Kriegel M., "Abwärmenutzung aus Kompakt-Rechenzentren mit Hot-Fluid-Adsorptionskälte-System", DKV-Tagung 2021, Dresden, RZ 04.

[8] Bai J., et al., "Combined space cooling/heating and domestic hot water supply driven by data center waste heat", Building and Environment 283 (2025) 113402.

[9] de Lange M. F., Zeng T., Vlugt T. J. H., Gascona J., Kapteijn F., "Manufacture of dense CAU-10-H coatings for application in adsorption driven heat pumps", Cryst Eng Comm, 2015, 17, 5911.

[10] Laurenz E., Füldner G., Velte A., Schnabel L., Schmitz G., "Frequency response analysis for the determination of thermal conductivity and water transport in MOF adsorbent coatings for heat transformation, Int'l J. Heat and Mass Transfer 169 (2021) 120921.

[11] Yuan, X., Liang, Y., Hu, X., Xu, Y., Chen, Y., & Kosonen, R. (2023). Waste heat recoveries in data centers: A review. Renewable and Sustainable Energy Reviews, 188, Article 113777.

[12] Pan Q., Peng J., Wang R., "Application analysis of adsorption refrigeration system for solar and data center waste heat utilization", Energy Conv. and Mgmt **228**, 15 January 2021, 113564.

[13] Wilde T., Ott M., Auweter A., Meijer G.I., Ruch P., Hilger M., Kühnert S., Huber H., "CoolMUC-2: A Supercomputing Cluster with Heat Recovery for Adsorption Cooling", 2017 IEEE 115, SEMI-THERM.

[14] Ammann J. et al., "Characterization of transport limitations in SAPO-34 adsorbent coatings for adsorption heat pumps" (2019) Int'l J. Heat and Mass Transfer 129, 18.

[15] Piccoli E., Civioc R., Galmarini S., Jobard X., Duret A., Daguenet X., Gantenbein P., "Optimized Adsorption Heat Pump for Efficiency Increase of District Heating Networks", Proc. EuroSun 2022.

[16] https://www.datacenterdynamics.com/en/news/vera-rubin-hot-water-cooling-reveal-triggers-hvac-share-drop/, "Vera Rubin hot water cooling reveal triggers HVAC share drop"

[17] T. Aziz, M. Engelpracht, P. Postweiler, et al., Enhanced infrared large-temperature-jump method for multi-layer adsorption kinetics estimation, (2024), Appl. Thermal Engineering pre-proof.