Sustainable data centers and energy conversion technologies

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Abstract

Thermally mediated energy conversions create waste heat and have a limited efficiency because thermal gradients cannot be fully used mainly due to convective and conductive thermal resistances. To improve computer cooling thermal resistances were reduced tenfold against excellent predecessor technologies. With this a twofold improved datacenter energy efficiency and zero carbon footprint was demonstrated at large scale. Reduced thermal resistances enable high concentration photovoltaic thermal systems with reduced system cost, and electrical efficiencies beyond 30%. 90ºC waste heat is used for heat driven cooling and thermal desalination improving efficiency to 80%. Excellent conductive thermal contact and mass transport in adsorption heat pumps enable a much higher efficiency. The innovation is about materials with improved adsorption isotherm, reduced cycling time, and improved mass and thermal transport. This allows efficient heat use from datacenters and solar concentrators for cooling and a “thermal transformer”. The technologies allow smart combined grids and help to reduce dissipation of non-usable heat with its effects on global warming.

Keywords: Thermal resistance, dataccenter, photvoltaic-thermal, CPVT, adsorption heat-pump, sustainable, energy, efficiency, conversion

1. Introduction

In the past we focused on getting access to energy from fission and chemically stored solar energy (coal, oil, gas) and later to low cost, low efficiency solar technologies but lost ~75% of primary energy to non-usable heat. With the energy turnaround the focus shifts to improving efficiency because of risks for human survival (nuclear or climate catastrophes). For the electrical sector mature technologies for which efficiencies have improved over decades allow well-balanced production and consumption of electrical energy with no kWh intentionally rejected. But the thermal sector is much less mature, here we do not even object that TWhs of heat are thrown away! For this reason breakthrough innovations are needed involving efficiencies of all thermally mediated energy conversion processes as well as information and communication technologies (ICT). Investment into ICT efficiency and reduced carbon footprint has a twofold value since the energy consumption is reduced directly and investment of ICT “energy” provides a strong leverage: In some sectors 10 fold higher savings are possible [1].

The ICT industry massively improved computer cooling because huge power densities have to be transported at lowest thermal budget. Since 2007 a change in transistor scaling led to a 20% per year growth of areal power density from 1 to 100 W/cm^2 (0.01 to 1 MW/m^2) at a gradient of <20ºC. Volumetric power density in computers is currently moderate (<0.1 W/cm^3) but with a dense computing effort we can massively improve efficiency when system-level power densities can be increased to 100-1000 W/cm^3 (0.1-1 GW/m^3) – a power density more than

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100 times higher than in the working volume of a piston engine (10 W/cm^3). Current thermal conversion processes lose efficiency mainly due to thermal resistances: Heat driven heat pumps have an exergetic efficiency of 25-30% because of losses in absorbers, desorbers, condensers, and evaporators. Solar photovoltaic (PV) installations have efficiencies at elevated operation temperatures around 15% while 85% of the energy is emitted as non-usable heat. Concentrated PV (CPV) systems have a 30% efficiency at these conditions and still dissipate 70% non-usable heat. Even steam engines with up to 45% efficiency lose ~50% of the theoretically available energy in thermal resistances in the boiler and condenser. In the past lost heat was considered harmless but more recently – with growing world-wide energy demands – rejected heat and unnecessary CO_2 emissions add to local and even global warming in particular when heat cannot escape to space due to the growing greenhouse effect.

2. Use of datacenter waste heat for thermally driven heat pumps

Data centers account for ~2% of global electricity consumption with annual growth rates of 4% [2,3]. On average, one-third of data center power consumption is attributed to server cooling [4]. Direct liquid cooling allows for higher coolant temperatures compared to air cooling, as the thermal resistance between the microprocessor and a liquid-cooled microchannel heat sink is reduced by a factor of 10 compared to conventional air-cooled heat sinks [5]. For a microchannel heat sink with a thermal resistance of ~0.1 Kcm^2/W, a 200 W/cm^2 microprocessor chip with maximum chip junction temperature of 85°C can be cooled with a 65°C coolant to provide heat directly for space heating [6]. However, district heating networks are not always available near data centers, and space heating demand is projected to decrease due to improvements in building insulation.

The direct use of server waste heat to operate thermally driven chillers has been demonstrated with a high-performance computing cluster (iDataCool [7]) combined with an aluminophosphate/water adsorption chiller to provide cooling for a GPU cluster. Later, in the largest combined server/adsorption chiller installation to date (CooLMUC-2 [8]), the 60°C server waste heat was used to operate silica/water adsorption chillers that provided cooling for data storage servers. These installations found considerable reduction in the electrical power consumption of the data center cooling infrastructure.

Utilizing waste server heat to drive adsorption chillers for data center cooling is mainly motivated by a reduction in electrical power consumption. Direct liquid cooling with low thermal resistance is a prerequisite for recovering server heat at sufficiently high temperatures to operate adsorption chillers. The reduction in electricity spent on cooling infrastructure is evident from basic data center modeling (Fig. 1), but the energy savings must be carefully balanced against the increased server power consumption at higher operating temperatures. Care must be taken to use meaningful metrics to quantify energy savings in the datacenter. Reduced leakage power of servers and enhanced adsorption heat pump performance at low driving temperature should be pursued to further reduce the overall power consumption of data centers with direct liquid cooling.

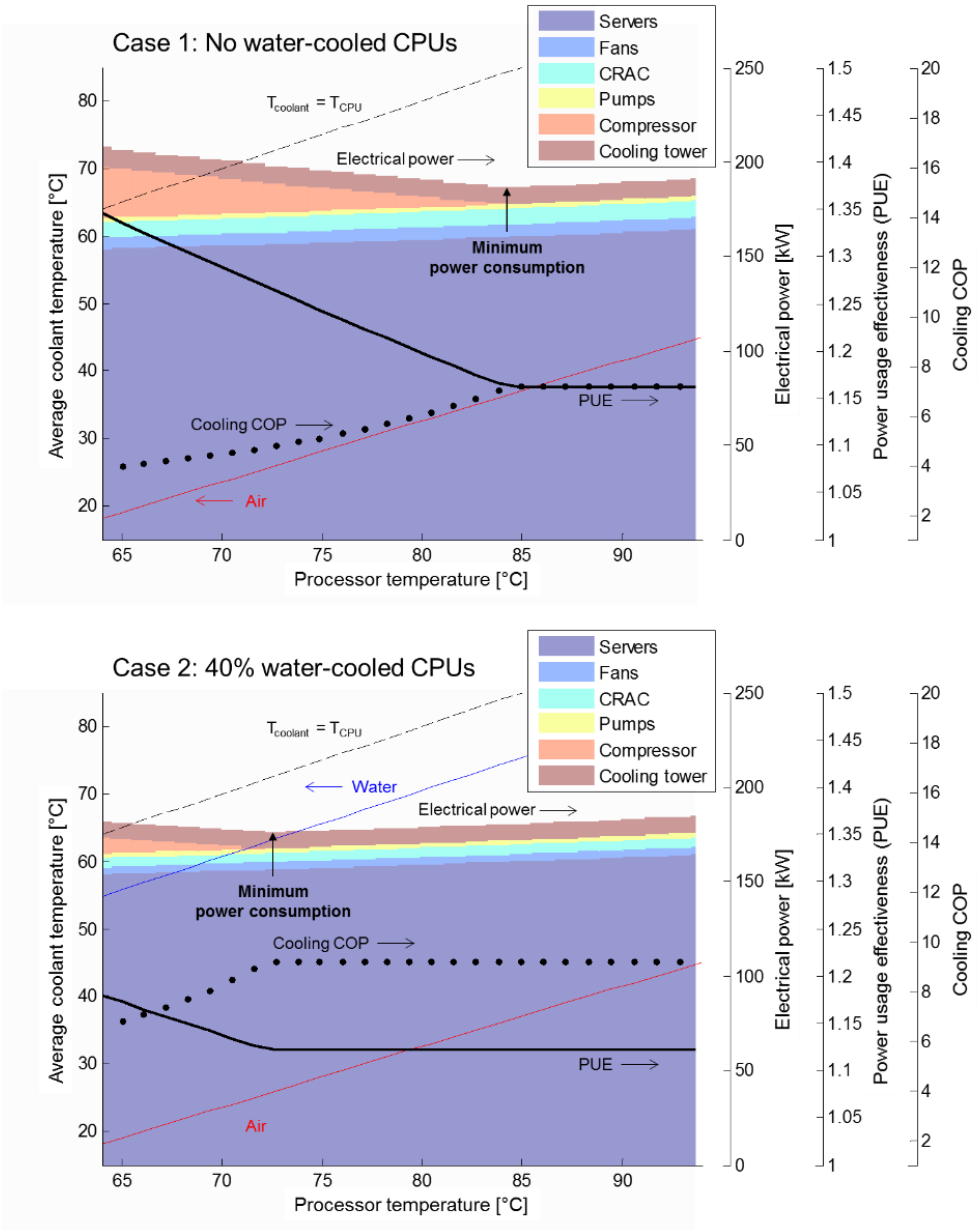

Fig. 1. The effect of cooling medium and processor temperature on the electrical power consumption, cooling COP and power usage effectiveness (PUE) of datacenters with only air-cooling (Case 1, upper scheme) or hot-water cooling for 40% of processors (Case 2, lower scheme) where the recovered heat is used to drive an adsorption chiller to replace compression cooling load.

Water cooling enables increased system level density of future computers and reduction of wire-length. Two approaches advance this new density roadmap: (1) top down miniaturization by size reduction of server main boards and use of systems on a chip [9], and (2) stacking of several layers of logic and memory in interlayer cooled chip stacks [10]. The ultimate density and orders of magnitude higher efficiencies are reached for densest systems that combine power delivery and cooling in one infrastructural element [11]. This strategy has the potential to replace the slowing Moore's law with another scaling law to keep the computer efficiency improving over the next 15-20 years. The decisive elements for this roadmap are reduced thermal and electrical resistances in ultra-compact three-dimensional form factors of these new computers.

3. Sunflower: High-concentration photovoltaic/thermal (HCPVT) system with heat recovery

Solar energy is converted either into electricity through PV mechanisms or collected as thermal energy but in current systems each approach only harvests a fraction of the available solar radiation. The co-generation of electricity and heat enables a more efficient use of the solar spectrum. The objective is to maximize the combined electrical and thermal output or the exergetic yield due to high receiver module temperatures. At 1500 suns concentration high-efficiency III/V semiconductor PV cells (GaInAs, GaInP, and Ge) provide the best economic output. Concentration reduces receiver cost but incurs higher cost due to the need for sun tracking structure and optics. Active liquid cooling is a major advantage since it allows thermal energy reuse at 80-95°C to drive subsequent processes such as space heating, domestic hot-water production, air-conditioning, refrigeration, desalination, or organic Rankine cycle-mediated electricity generation [12, 13].

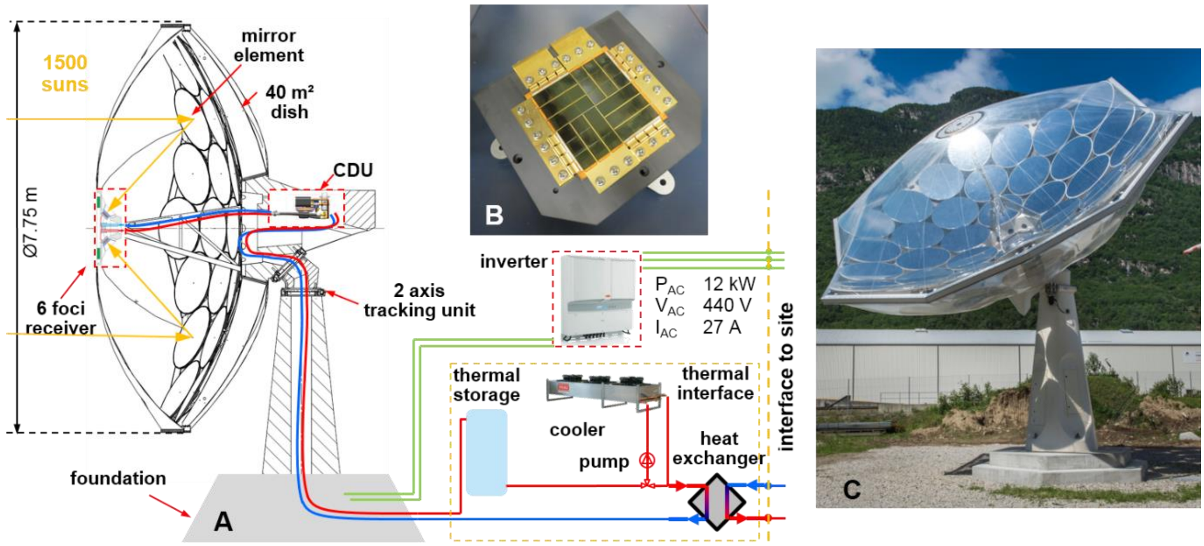

Fig. 2. Sunflower system overview showing the 2 axis tracking unit with the 40 m² concentrator and the thermal and electrical circuit to transform the solar radiation into electrical and thermal energy output (A). One of six receiver modules exposed to 1500suns in the focus where the energy transformation occurs (B). The Sunflower system with segmented mirror and 2 axis tracking system built in concrete (C).

The Sunflower system (Fig. 2) demonstrates the advantages and the economic viability of the co-generation of electricity and thermal energy. It comprises four sub components: the optical system, the mechanical tracking unit, the electrical and the thermal energy harvesting system. A 40m² primary mirror composed of segmented mirror facets concentrates the sun 1500-fold at six foci and a secondary optical element confines the solar radiation on the active area of the receivers. A 2-axis tracking system maximizes the illumination during the day, its mechanical elements are built of concrete to allow functional structures that host the different components and protect them from the environment with low material and process cost as well as long durability. The electrical system's core part is the receiver module (Fig. 2B) composed of a 6x6 array of triple junction (3J) PV 10x10 mm^2 cells that are attached to a silicon substrate. The PV cells on a module are interconnected in parallel in a quadrant and the 4 quadrants in series to provide higher output voltages and lower currents while handling the inhomogeneity of the radiation without reverse bias diodes. The module output voltages are converted by a DC/DC converter to 400V to feed a DC/AC inverter that interfaces the Sunflower with the electrical power grid. The thermal system is integrated in the silicon carrier where the 3J PV cells are mounted and ensures a minimal thermal resistance. This is done using micro channels where the flowing water efficiently collects the heat supported with a multilevel manifold system to achieve a minimal thermal gradient and a small temperature difference between inlet and outlet, allowing a high exergy recovery [14].

The receiver module cooling performance was characterized using coolers where the PV cells were replaced by a heater layer that dissipated 100 W/cm². A total power of 3.3kW was cooled with a ΔT of 4K for 20µm and 4.5K for 50µm channels. The cooled area was 33cm² having a maximal temperature variation on the surface of

<1K at 10 l/min. This was achieved with only 2.83W pumping power for the 20µm and 1W for the 50µm channels, respectively. This cooler cools PV cells with 85°C inlet temperature, extracting heat at 90°C [15].

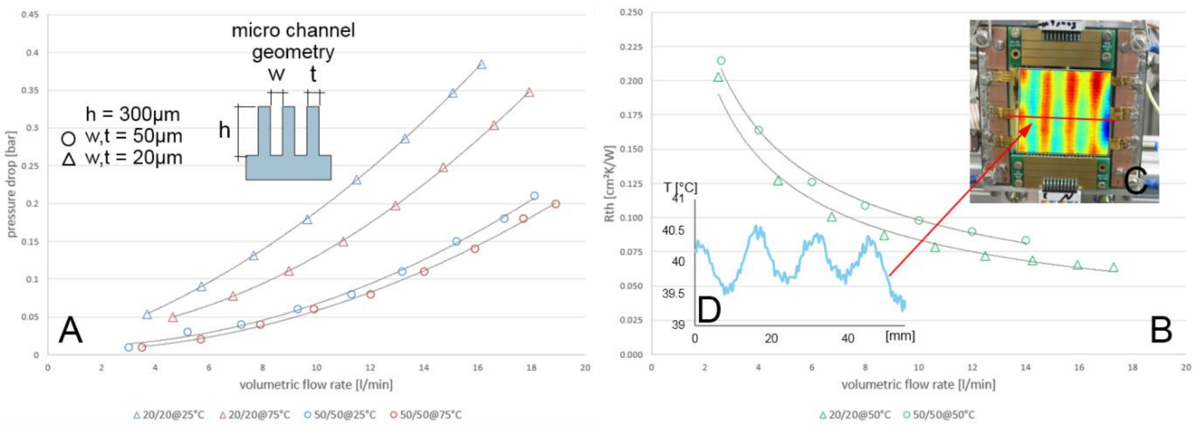

Fig. 3. Hydrodynamic (A) and thermal results (B) of receiver module integrated high performance cooler with an active area of 55x60mm² operated with deionized water at 25, and 75°C. Thermal image of cooler surface (C), overlay on test sample photograph) and temperature profile across cooler at an input heat flux of 100 W/cm² showing <1K variation (D).

4. Advances in solid sorption heat pumps driven by low-grade waste heat

Thermally driven solid sorption heat pumps inherently suffer from exergetic losses due to the coupling of adsorber beds to external heat sources and sinks [16]. Reducing thermal gradients within the adsorber heat exchanger is important to reduce losses and improve thermal efficiency. However, the thermal transport is strongly coupled to mass transport and the ad-/desorption process in solid sorbents, thereby complicating the description of the system.

The concept of equivalent thermal resistances [17] was proposed to compare the relative importance of heat transfer and mass transfer in adsorber beds. An experimental method was developed to quantify transient temperature and adsorption profiles and applied to the adsorption of water on silica gel in a bead-type configuration (Fig. 4a). First, the equilibrium loading is measured as a function of adsorbent temperature and vapor pressure $w^*(T_{ads}, p)$. Then, in an isochoric adsorption experiment, a step-like temperature change is applied to the substrate and the surface temperatures of the substrate (T_s) and adsorbent (T_{ads}) are measured with an infrared camera following a calibration routine. At the same time, the vapor pressure p is measured with a capacitive pressure gauge. The actual adsorbed amount is calculated from the change in vapor pressure and the ideal gas law $\Delta w(t) = \Delta n(t) \cdot M_{w,H_2O,} = \Delta p(t) \cdot V \cdot M_{w,H_2O,} / (RT_{vapor}(t))$, whereby the experiment volume V is determined previously by means of a calibrated gas volume and T_{vapor} is equated to the wall temperature. During the experimental transient, the quantity $T_{ads} - T_s = \Delta T_{ht}$ is the thermal gradient which drives heat transfer. Further, during the transient, the actual loading is different from the equilibrium loading at the same temperature and pressure, $w(T_{ads}, p) \neq w^*(T_{ads}, p)$. Therefore, there is a virtual temperature difference ΔT_{mt} which accounts for the difference in loading so that $w(T_{ads} + \Delta T_{mt}, p) = w^*(T_{ads}, p)$. The quantity ΔT_{mt} therefore describes an equivalent thermal gradient which drives mass transfer in the adsorber. The adsorption end point t_{80} is defined as the time at which 80% of the equilibrium mass change for a given substrate temperature swing is realized, i.e. $\Delta w_{80} = 0.8\left[w^*\left(T_s^{t=\infty}\right) - w^*\left(T_s^{t=0}\right)\right]$. For the time interval until t_{80}, the average equivalent thermal resistances are extracted such that $R_{ht} = \Delta T_{ht} / \dot{q}''$ and $R_{mt} = \Delta T_{mt} / \dot{q}''$, whereby $\dot{q}''$ is the heat flux with respect to the adsorber heat exchanger surface area and is determined from the adsorption rate and the enthalpy of adsorption.

The experimental approach permits to quantitatively distinguish between the heat and mass transport limitations of the simple silica gel bead-type adsorber (Fig. 4). It can be seen that the heat and mass transport resistances are well balanced in this system, each resistance accounting for about half of the total transport resistance. The absolute transport resistances are reduced for smaller bead sizes due to the decreased diffusion length for water adsorption while the heat transfer path occurring predominantly through vapor is also reduced. The proposed method is useful for the optimization of adsorber transport rates and it is currently being employed to enhance the heat rate per unit volume to increase the power density and efficiency of adsorber heat exchangers.

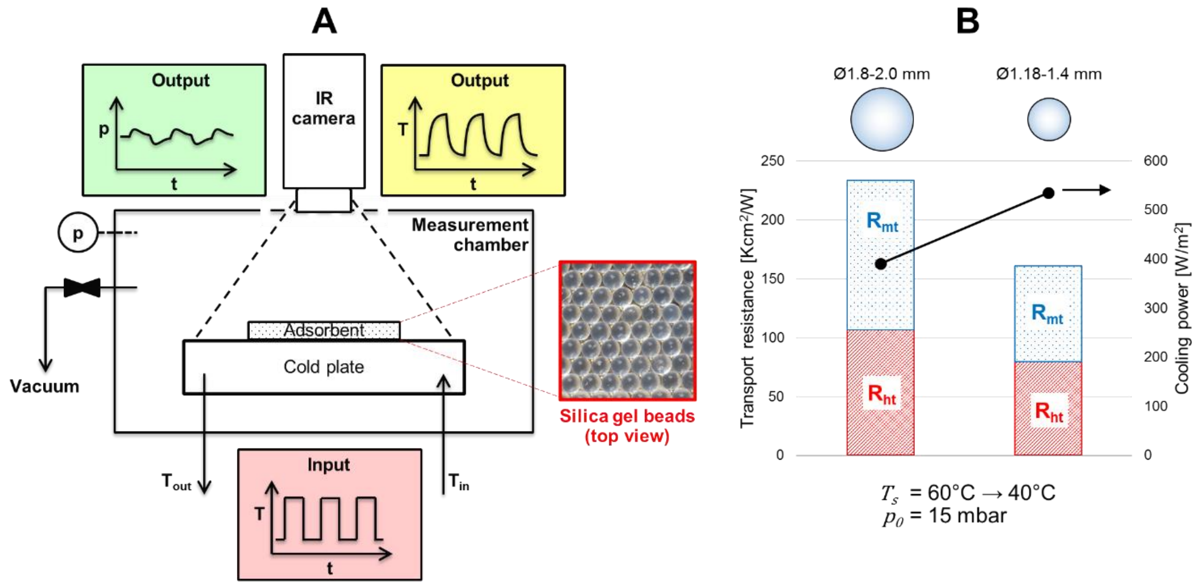

Fig. 4. (A) Experimental setup and water/silica adsorption system for determination of transport resistances, (B) comparison of equivalent thermal resistances for heat and mass transport extracted from the experiments on two different silica gel bead sizes.

5. Conclusions and Outlook

Water with its 4000 times better heat capacity and 30 times better thermal conductivity than air massively reduces thermal resistance. This is further reduced by high aspect ratio ultra-short microchannels with hierarchical branched manifolds that enlarge surfaces similar to the circulation system of our bodies. Consequent miniaturization and use of silicon structural material with good thermal conduction and absence of thermal interfaces reduces conductive resistances. Where interfaces are still needed filling materials/gaps with percolation and necking improve the thermal conduction. The first reason why this innovation happens now is the current confluence of energy and information technologies while earlier there has been no overlap between the two disciplines. The second reason is the current paradigm change in the ICT industry from performance focus to efficiency focus. Driven by these boundary conditions, we demonstrated a doubled efficiency of existing ICT equipment by reducing thermal resistances and also opened a new scaling roadmap for much larger improvements through densification. Solar system efficiency was improved from 15% to 80% with this technology. An exergetic analysis of a HCPVT power plant demonstrated reduced total average costs as fixed capital is deployed more efficiently [18]. The remarkable reduction in solar-panel costs triggered that low-efficiency, low-cost photovoltaics (PV) currently prevails over more complex, high-efficiency technologies. PV systems change the absorption properties so that less sunlight is reflected, three effects need to be considered: (1) global albedo impact, (2) regional atmospheric heat islands, and (3) locally heated surfaces [19]. This radiative forcing effect adversely affects building-integrated solar installations in warm urban climates, as more energy is required for cooling. Only when taking radiative forcing into environmental and economic considerations, solar-technology development will correct its trajectory toward high-efficiency installations with lower overall global warming potential (GWP) [20, 21].

Heat pumps with an exergetic efficiency >>40% due to reduced thermal resistances can have an economic impact as a thermal transformer in thermal grids – smart grids are not smart when they are only composed of electrical energy transfer – for an efficient overall energy supply we clearly need the inclusion of thermal grids. Low grade heat from the sources described above can be stored at lower cost than electrical energy, in regions without hydropower. To make this useful conversion processes are needed to convert lower-grade heat into electrical energy but Organic Rankine systems currently have too low efficiencies to make this feasible because of thermal resistances in the boiler and condenser. Our technology can make such systems feasible to allow smart grids to rely equally on thermal storage, transport, and conversion as on the electrical functions. Interestingly, 120ºC steam was used by Edison in Manhattan for energy transport. This was replaced by high voltage electrical energy transport after the invention of the electrical transformer. With a "thermal transformer" we can create a more balanced dual energy transport system and use sustainable high efficiency PVT and other low grade heat. With thermal demands exceeding electrical demands by a factor of 5 and the growing cooling demand in the Sunbelt our low thermal resistance technologies allow a faster transition to a low carbon economy and thus help to save our planet from overheating.

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