and urban canyons also retain heat better into the night. In addition, the energy used in cities generates heat, which is negligible on a global scale but often important in urban areas. Urban heat islands are not typically included in climate calculations and are likely to worsen anywhere that urbanizes further, adding to the warming delivered by the climate system.

Although predicting the above factors is challenging enough, quantifying their impacts is even harder. Quantitative models of heat-affected natural and human systems, if used at all, are less advanced relative to the complexity involved than are weather and climate models. Meanwhile, climate change is creating conditions that lie outside the range of past experiences, limiting the reliability of empirical studies. Current impact models diverge substantially in the predicted impacts of climate changes (*14*) and almost surely suffer from systematic biases (*15*). Diverse impacts generally depend on the different aspects of heat events, devaluing any one-size-fits-all heat measure. We need to more rigorously quantify the links between meteorological forecasts and practical consequences.

Past studies do point to a couple of robust conclusions. One is that impacts will increase nonlinearly with mean warming, as extreme thresholds are crossed with rapidly increasing frequency (*8*). This highlights the need for strong emissions mitigation to keep warming to a level that we can cope with. The other is that although no one will be spared, the world's poor will be hit particularly hard (*11*). This highlights the need for low-cost adaptations and technologies as we seek suitable countermeasures to rising heat. ■

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PERSPECTIVE

Cooling our insatiable demand for data

Hyperscale data centers provide challenges and opportunities for energy use

By **Amy S. Fleischer**

The world is driven by constant access to information. We have the entire world at our fingertips wherever we are, and access to data in its various forms is ubiquitous. The ability to retrieve this information, much of it now stored in the cloud, is supported by data centers of various sizes and scales. Although instant access to data from anywhere is a benefit in many ways, part of the cost of this access is in escalating energy demands, much of it from the cooling infrastructure needed to support these data centers.

The widespread movement to cloud-based services over the past 14 years has transformed the data center industry. In 2006, 50% of all U.S. servers were located in small or medium-size data centers or in self-managed corporate data centers (*1*). These small data centers had an average processor utilization of only 10 to 20% and required a substantial energy investment because of high power demands. Inefficient cooling infrastructure for these servers, often located in closets or small rooms, led to a total data center annual energy demand of 70 terawatt hours in the United States in 2014 or about 1.8% of all U.S. energy usage (*1*).

The total energy demand of data centers includes both the energy demands of the IT equipment itself and the energy demand of the supporting infrastructure, the vast majority of which is for the cooling systems. A metric known as power usage effectiveness (PUE) represents the ratio of the total data center facility energy use to the energy use of the IT equipment. A data center with a PUE of 1.0 would use no energy other than that used to power the IT equipment. In 2007, when the metric was introduced by the Green Grid, the average data center PUE was 2.0, and this average value had not changed appreciably by 2016 (*1*). However, an increased focus on this metric in recent years has led to many advances in cooling technology.

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Notably, these improvements in cooling architecture are implemented mainly in hyperscale data centers and have coincided with a widespread shift away from small, local, on-site data centers. In 2010, 79% of all data center operations were executed in traditional data centers, including small on-site data centers, whereas in 2018, 89% of compute instances were executed in cloud computing facilities (*2*). The economy of scale in hyperscale data centers permits the use of advanced server designs and vastly improved cooling technologies, and PUE can now approach 1.1 to 1.2 (*1*). These massively scaled data centers have doubled in number in just the past 4 years, from just over 250 worldwide in 2015 to more than 540 today, with hundreds more in development (*3*).

Data center cooling technology has come a long way from the server rooms of yore. Traditional designs often relied on air cooling and the overprovision of room air conditioning, necessitating the use of a parka for technicians working in the space. Improvements in air-handling design thus were the first major steps forward in data center cooling. Raised floor designs with integrated air distribution plenums were implemented, with cold air distribution routed directly into the intake of the servers by using perforated floor tiles in front of each rack or cabinet.

Subsequent advances included arranging servers into "hot aisle"–"cold aisle" configurations to reduce the mixing of the exhaust from one server with the intake of another; detailed computational fluid dynamics analysis of the floor tile designs to optimize air flow and minimize pressure drop (*4*); and the implementation of advanced systems and component-level control strategies for air handling. The benefit of some of these techniques is that they are suitable for retrofit into existing legacy data centers (*5*) while also being relevant to new designs. Hyperscale data centers, which by nature have flexibility in their geographic location, can be located in cool and low-humidity climates in which both air-side economization and water-side economization can be used to reduce cooling costs. Air-side economization features the mixing of outdoor air into the conditioned air and brings the same benefits as opening the windows when cool outside. As such, the strategy is often referred to as "free cooling." Water-side economization reduces the demand on the chillers that cool the conditioned air in many data centers, again by using outside air. Evaporative cooling techniques can reduce the energy demand even further. By using such techniques, Google has dropped its average trailing 12-month PUE to 1.10 (*6*).

Future improvements in cooling strategies will come from a shift in focus from air-cooling strategies to a focus on embedded liquid and evaporative cooling techniques, which take advantage of inherently higher heat transfer coefficients. Direct liquid cooling features microchannel cold plates mounted directly on the heat-producing chips. Reliability concerns related to the integration of liquids in the server chassis initially affected the implementation of this technology, but increases in chip energy density beyond the capabilities of air cooling, coupled with technology advances such as optimized microchannel designs (*7*) and detailed failure mode analysis and mitigation (*8*), have led to wider adoption of embedded liquid cooling in hyperscale data centers over the past few years.

However, advances in integrated chip designs with three-dimensional architecture are creating energy densities beyond even that which can be controlled with direct liquid cooling. Thus, next-generation cooling research is investigating techniques such as flow and pool boiling (*9*) and even direct immersion of the chips in dielectric fluids with subsequent boiling at the chip interface (*10*). Thermosyphons, which feature gravity-fed liquid-vapor systems, are the focus of much attention (*11*), as they allow the high heat transfer possible with flow boiling while eliminating the reliability issues inherent with micropumps. In application, microevaporators are located directly at each chip, much like a cold plate; gravity-fed liquid feeds the evaporator, and the resulting vapor rises to a condenser located at the top of the server rack, where the loop begins again. Much two-phase flow research focuses on the use of environmentally friendly refrigerants such as HFC-245fa or HCFO-1233zd(E), adding the benefit that any leak will immediately vaporize, eliminating concerns around liquid leakage (*12*).

As the demand for data center capacity continues unabated, the demand on the power grid will continue to escalate. Thus, solutions for environmentally friendly and off-grid power production are of much interest. Some hyperscale data center operators are exploring sourcing their own sustainable power production using hydrogen fuel cells (*13*), and others are sourcing their energy from solar and wind farms. Future research trends will include a focus on advanced cooling techniques that feature energy recovery and reuse. Both liquid and two-phase cooling strategies produce a stream of heated liquid or vapor that can be used in various waste-heat recovery systems, including straightforward techniques such as hot water production and plant or district heating (*14*) and more complex systems such as absorption refrigeration or the organic Rankine cycle, which generates a source of electricity that can be fed back into the data center (*15*).

"As the demand for data center capacity continues unabated, the demand on the power grid will continue to escalate."

The current technical limitation is the low quality of the heat, and next-generation advances will require much attention to the integration of the cooling technology and the energy generation technique to meet the growing demands of our insatiable need for data. The past 5 years have shown incredible advancements in the technology used to cool data center equipment, but much work remains to be done to develop sustainable, environmentally friendly solutions to the energy demand required to power the cloud. ■

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PERSPECTIVE

Photon-engineered radiative cooling textiles

Personal thermal management offers a path to reduce climate control energy use

By **Po-Chun Hsu** *and* **Xiuqiang Li**

Take a few seconds to look around and list all the technologies that are indispensable for you. If your list does not include textiles, try to live a typical day without them. Textiles are arguably one of the earliest human inventions. Without textiles to cover the human body for warmth, our ancestors would not have been able to spread across the various climate zones of the Earth. Today, many textiles are made for social etiquette and aesthetic purposes, but the pressing threat of global warming has created demand for innovative textiles that help to better cool the person who wears them.

The rationale behind linking textiles and climate change is that wearing the cooler textiles for localized "personal thermal management" may reduce the demand for air conditioning. The impact of air conditioning is considerable, given that it is not only responsible for 10% of U.S. electricity consumption but that the refrigerants are also a source of high global-warming-potential gasses (*1*, *2*). Considering an indoor setting distinguishes the new generation of cooling textiles from textiles oriented for sports. On average, the metabolic heat rate of indoor light activities is 60 to 80 W/m^2, balanced by the heat flux from the skin to the environment. This flux occurs through all viable heat transfer pathways: conduction, convection, radiation, and evaporation. Because one of the criteria of thermal comfort is the absence of sensible perspiration, evaporation only accounts for ~5 W/m^2. Using the American Society of Heating, Refrigerating and Air-Conditioning

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Cooling our insatiable demand for data

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