

# New Engineering Thinking for a New Climate

Reducing carbon emissions is the engineering challenge of the 21st century. To meet it, mechanical engineers will have to find new approaches to familiar problems.

BY MICHAEL E. WEBBER

Everything we thought we knew about mechanical engineering has changed, thanks to the agreement that capped the 2015 United Nations Climate Change Conference in Paris last December. While the agreement is non-binding, the direction is clear: “a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.”

Simply put, we need to drive down net emissions of carbon before 2050. And by “we,” I mean mechanical engineers.

The Paris Agreement has, I believe, become the primary geopolitical context of the 21st century. Everything that the next generation of engineers will do professionally will be affected by the call to sharply reduce carbon emissions. And those reductions have to start with the power sector, which is responsible for a quarter of global carbon emissions and more than 30 percent of those in the United States.

Mechanical engineers have built up the power sector and now we have to reinvent it. Engineers will have to rethink the power system from top to bottom.

And to accompany this new approach to re-engineering the power sector, we must transform engineering education as well. Because climate change has put carbon emissions at the center of the global political discussion, we need to produce engineers who not only discover new solutions to enduring problems, but who can talk to multiple stakeholders from wide-ranging backgrounds.

Mechanical engineers have built the power sector and now we have to reinvent it from top to bottom.

That said, the rethinking isn’t something that only affects the next generation of mechanical engineers. It starts with all of us, and it starts now.

### the next transition

One place where teaching—and thinking—must change is how engineers grapple with sweeping, systemic changes, especially in energy technology. Too often, when we look to the past we constrain ourselves to searching for specific solutions that we can reapply. Instead, we need to think about largescale transitions, how they happened and, most importantly, why.

The widespread, global decarbonization of the power sector called for by the Paris Agreement won’t be the first time society has switched from one energy system to another. Over the last 200 years, we’ve transitioned from wood to coal to petroleum. Each transition was an improvement since each new fuel source was higher performing and less dirty and carbon-intensive than the one it supplanted.

Today we are on the cusp of another transition, as natural gas is poised to surpass petroleum as the dominant fuel in U.S.



## The Paris Agreement has become the primary geopolitical context of the 21st century.

energy consumption. And that follows the decarbonizing trend of the earlier transitions, since combusting methane releases less carbon than does burning coal.

The Paris Agreement calls on mechanical engineers to take the ongoing decarbonization trend and accelerate it. As mechanical engineers work toward that goal, we can't lose sight of the lessons from previous transitions.

To start with, shifts from one dominant fuel to the other have taken decades, so if we are going to meet the goal set for the second half of the century, we have to start today. It isn't just new power plants that must be built, but also an expansive logistical infrastructure that moves fuel and electricity from producer to consumer.

Next, the earlier transitions occurred because of performance—coal is easier to handle and more energy dense than wood; today natural gas use eliminates the fuel-handling and preparation requirements of a typical pulverized coal plant. As we develop low-carbon solutions, engineers have to make sure that new technologies have performance advantages, otherwise it

will be hard to convince industries to switch.

Today, for instance, utilities looking to add generating capacity don't need to have their arms twisted to opt for natural gas combined cycle power plants over legacy coal-fired thermal plants; such plants are twice as efficient, have about half the operations and maintenance costs, and can be built for just a fraction of the cost of a new coal facility. So many gas turbines (both simple and combined cycle) have been added to the U.S. grid in the last ten years that in 2015 power plants burning cheap natural gas were responsible for as much electricity generation as traditional coal plants. As recently as 2006, gas generated only half as much as coal.

And as we promote the next transition, we can't lose sight of the fact that today's solutions can become tomorrow's problems. The engineers who helped bring coal and oil to market actually solved some longstanding ecological problems related to deforestation and whaling. They may never have dreamed that their new technology would one-day be considered "dirty." Engineers need to examine the new energy solutions we

come up with to weed out any latent complications that may grow to become societal problems.

To see how those lessons come together, consider the possibility of a complete transition to wind and solar. By some measures, those renewables offer significant performance advantages over the conventional options—the wind and sun are essentially free and inexhaustible, and they obviate the need for fuel handling entirely. Plant operators won't need to worry about rising fuel prices or fret about fuel supply contracts. And contrary to longstanding concerns about the ability for renewables to scale up, the last few years have seen wind and solar power surging onto the U.S. grid, going from 55,000 GWh in 2008 to 240,000 GWh in 2015, according to Energy Information Agency.

At the same time, wind and solar power still present challenges that have yet to be resolved. Each vary both seasonally and from minute to minute based on the weather and astronomical conditions. Those dynamic attributes create a lot of stress on the grid as other generating plants get used less (increasing their costs), yet are called on short notice to back up any changes in wind and solar output. While wind and solar power produce electricity, which is what utilities want, the production isn't tied to actual demand; for instance, a lot of wind power is produced in the middle of the night when no one is awake to use it. And even at moderate scales of deployment, renewables have had some unexpected environmental impacts—often on birds that fly too close—that have soured some on their expanded use. Those are all solvable problems, and mechanical engineers are part of the solution.

## multiple choices

**T**he challenge of the Paris Agreement differs from earlier energy transitions in an important way: This shift is being intentionally pushed along, rather than occurring accidentally as before. But we have to

**The success story of acid rain regulations should focus the thinking of mechanical engineers when we approach the much larger challenge of decarbonization.**

teach engineering students that responding to policy pressure isn't a new thing for the power sector.

A generation ago in the United States, for instance, the formation of acid rain from sulfur and nitrogen oxide emissions became an intolerable environmental problem and prompted a public policy solution. Regional limits were placed on NO<sub>x</sub> and SO<sub>x</sub> power plant emissions, and operators of non-compliant power plants had a few choices: They could retrofit, switch fuels, retire, or pay a fee for credits from cleaner power plants.

Operators of some power plants opted to install large-scale, very expensive scrubbers to remove the pollutants from flue gases. That approach kicked off a wave of innovation and gave engineering firms in the United States a competitive advantage, as environmental scrubbers became a multi-billion dollar export business. Other operators found it easier to switch fuels from Eastern, high-sulfur coal to low-sulfur coal from the West. Today Wyoming produces more coal than Kentucky and West Virginia combined.

But operators of some old, creaky, inefficient coal-fired power plants couldn't justify either of those moves. Instead, they shut them down and built new more efficient natural gas power plants in their place.

The multiple-prong approach worked. The acid rain problem, while not completely solved, has been dramatically improved. According to a 2004 assessment by the U.S. Environmental Protection Agency, dealing with acid rain took less time and money than anticipated—and provided \$40 billion of health benefits for every \$1 billion of investment in scrubbers and power plants. Along the way, grid reliability improved and electricity prices stayed level.

The success story of acid rain regulations should

focus the thinking of mechanical engineers when we approach the much larger challenge of post-Paris decarbonization. We must look hard at the existing technologies and energy sectors and apply our new thinking to the question of how much we want to retrofit and adapt by installing new scrubbers, and how much needs to be built from scratch so we can switch fuels entirely.

For example, even with the mandate of decarbonization, there could still be a place for coal. That fuel has considerable advantages—an abundant domestic resource, predictable pricing, and ease of storage in large piles on-site at power plants. But for coal to maintain its position, mechanical engineers will need to improve integrated gasification combined cycle power plants, which convert coal to gases that are then combusted in a gas turbine. A dry-cooled IGCC that separates CO<sub>2</sub> for sequestration would be cleaner and less water-intensive than a modern natural gas combined cycle power plant. But none of the demonstration IGCC plants built so far have been cost competitive, and the technology will remain on the shelf until it is economical.

If plant operators can't make new coal plants pencil out, they could turn to another familiar technology: Nuclear power. Massive, cheap, and reliable nuclear power plants have ably served baseload demand for decades, and new plants are springing up in Asia. But questions regarding public safety, waste management, and weapons proliferation still haven't been fully resolved. Also, since nuclear power plants are heavily dependent on water for cooling, they are vulnerable to derating as increasingly frequent and intense droughts and heat waves strain the availability of cool water.

To make nuclear power a bit more embraceable, mechanical engineers must work to develop advanced fuel cycles, small modular reactors, dry cooling, and passively safe designs.

And it will make sense to integrate nuclear power with water production systems so that waste heat is used for water treatment or desalination.

A bigger challenge is to find ways to enable nuclear power plants to operate more flexibly as renewables become an ever-larger part of the energy mix. Engineers will have to optimize designs capable of rapid ramping

and, critically, find ways to incorporate novel storage approaches. Thermal energy storage with molten salts, for instance, might be more appropriate for nuclear power, though many materials and heat transfer challenges remain.

But much like the plant operators of the 1990s, we may have to face retiring and replacing large portions of the power sector. Fortunately, we have many viable alternatives. Clean and lean natural gas combined cycle power plants are ready today. And while mechanical engineers are under pressure to continue improving the efficiency, reliability, and durability of all renewable systems, wind and solar are growing in popularity even if they are not—yet—a complete solution. Indeed, in January 2016, wind and solar made up 100 percent of all new power plant installations in the United States.

## intermittency and beyond

---

Handling the influx of power from intermittent sources such as wind and solar is going to require mechanical engineers to rethink the transmission and distribution system. The amount of capital assets tied up in the T&D system—about \$4 trillion worldwide—approaches the \$6 trillion capital value in power plants, so building out a bigger, better, smarter grid is going to be a major challenge of its own.

Engineers will have to think differently about T&D to make this new grid work. Today's conventional approach to the grid uses a load-following mentality. That is, we turn our lights and appliances on and off all day long, which changes the load on the grid. Power plants are then dispatched up and down to follow the load and to balance the supply and demand. But that approach makes it difficult for operators to handle power from nondispatchable wind farms and solar plants.

Rather than expecting power plants to operate when we need them, we could instead schedule our demand to match the forecast supply of wind and solar. There are many operations—water heating, pool pumping, water treatment, noncritical data centers, and so forth—that can be performed flexibly over the course of

the day. Connecting machines and appliances to the Internet via smart meters could enable grid operators to remotely dial down demand as necessary and provide valuable reliability services.

But tomorrow's T&D issues go beyond intermittency. Adding renewables on a large scale requires long distance lines connecting cities to distant plains and deserts as well as new technology and innovative policies to address the impact on local distribution systems from rooftop solar panels. Some far-out concepts, such as the proposal from China's state grid operator for a global high voltage network, will require extending engineering and operational standards across sometimes adversarial borders. It's always windy or sunny somewhere, so building a large-scale grid will help bring that renewable energy from far-flung places to load centers in major cities.

Tomorrow's T&D system also will require grid-scale energy storage—and here's where some of the most significant engineering advances still loom. Recent government research and development for batteries has been welcome, but it needs to be extended to other forms of energy storage as well. Compressed springs, spinning flywheels, ultracapacitors, chilled water, molten salts, pumped hydroelectric, and compressed air energy storage all offer different performance tradeoffs. The expertise of mechanical engineers and materials scientists is sorely needed to help develop and optimize those storage concepts.

## building better engineers

**T**he Paris Agreement gives unambiguous direction to mechanical engineers: Develop better hardware, algorithms, and control systems to decarbonize the power sector. But the profession needs to do one other thing better. We need to build better engineers.

Because the scale of society's challenges have grown, the engineer of the 21<sup>st</sup> century will need to be more

## Decarbonizing the power sector isn't a job most mechanical engineers asked for, but it is the one we now have.

globally cognizant. And to work in an energy system that is more closely intertwined with policy frameworks, those engineers will need more policy (and political) savvy.

That means our educational approaches need to change to prepare those engineers for their careers. It seems senseless to use textbooks and chalkboards—tools we have used for hundreds of years, since before the advent of the modern engineering degree—instead of interactive, digital textbooks that could enhance problem-solving. We need more immersive experiences, more hands-on labs, and more exposure to real-world devices.

Just as importantly, we must provide multidisciplinary training and require graduating engineers to have the capacity to speak normal English to the array of stakeholders they will face. It won't be enough to just find the solutions; tomorrow's mechanical engineers will need to drive the conversation.

Decarbonizing the power sector isn't a job most mechanical engineers asked for, but it is the one we now have. In the process of accomplishing that task, there are a great many benefits that will certainly result from it: Generating electricity with greater efficiency, building a grid that is more robust and flexible, preparing engineering graduates to have a larger impact on society. If we energize the engineering community to embrace the challenge, then when engineers look back from decades from now, decarbonizing the power sector will have seemed an obvious outcome and improvement for society. And we will wonder why we didn't start it sooner. **ME**

**MICHAEL E. WEBBER** is an ASME Fellow and winner of ASME's Frank Kreith Award. He is deputy director of the Energy Institute at the University of Texas at Austin and author of *Thirst for Power: Energy, Water and Human Survival*, published in April 2016 by Yale University Press.