EBOOK

Powering Clean Energy Solutions

simulation success stories

COMSOL

Powering Clean Energy Solutions

Engineers and scientists are hard at work improving the practicality, cost-efficiency, and accessibility of green energy solutions, allowing us to reduce our dependence on fossil fuels. Several options have emerged as feasible alternatives, including solar, wind, tidal, and hydrogen power.

However, with new solutions and technologies come new challenges. Wind turbines, for instance, require protection from lightning, and their maintenance can be both demanding and costly, so it is crucial that components have a long lifespan. Additionally, many renewable energy sources, such as solar power, are intermittently available, necessitating the development of new battery technology. The creation of new technologies also warrants carefully assessing their environmental impacts to avoid also creating new problems.

As engineers and scientists face these challenges, simulation technology is there to help. Using modeling and simulation, designs can be evaluated in a virtual setting and optimized to meet specific goals. This ebook features six inspiring stories of engineers and scientists who harnessed multiphysics simulation to bring their innovative ideas to life, each contributing to the advancement of clean energy solutions and a greener future.

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PHYSIXFACTOR, NETHERLANDS

PRODUCING POWER, PROTECTING FISH WITH A DARRIEUS WATER TURBINE

The Netherlands employs coastal flood control structures that could also be used to harness tidal power. Strict national and European regulations drive new turbine designs that are inherently safe for fish passage. To develop such a rotor design for client Water2Energy, Physixfactor used simulation to adapt a Darrieus wind turbine for water use. Compared to conventional hydropower turbines, experiments show that the Water2Energy vertical-axis design reduces fish mortality rates from 20% to less than 1%.

by **ALAN PETRILLO**

"Here in the Netherlands, we are pretty close to the sea," says Helger Van Halewijn, who then smiles at his understatement. The North Sea (*Noordzee*) and the Dutch are inseparable. From this intimate and turbulent relationship, the people of the Netherlands have learned to be resilient, and also flexible. Rather than fighting with the water, it has long been wiser to negotiate a wary truce. The famous Dutch landscape of dykes, canals, and polders does not stop the sea, so much as it redirects water flow into something manageable — and useful.

This resourcefulness lives on in modern Dutch infrastructure projects and in the people who make them possible. "We not only want to use our dykes for flood protection. We can also use them to address the need for energy and to protect fish and the environment," says Van Halewijn, the director of engineering design consultancy Physixfactor. To achieve these goals, Dutch company Water2Energy turned to Van Halewijn to support the modeling of their vertical-axis water turbine (VAWT) for use in flood-control structures. Using multiphysics simulation, he optimized the Water2Energy VAWT to produce more electric power while minimizing potential harm to sea life.

The technology of this tidal power project may be modern, as is its emphasis on environmental protection, but its roots run deep into the vulnerable (but carefully guarded) Dutch soil.

ZEELAND AND THE DELTA WORKS: PROTECTING A PRECARIOUS PLACE

If any region of the Netherlands can be considered closest to (and most affected by) the sea, it may be the section with "sea" in its name: Zeeland. The westernmost and least populated Dutch province is also a river delta, where the Scheldt, Meuse, and Rhine all flow into the North Sea. More than one third of Zeeland's total area is water. Its Latin motto of *luctor et emergo*, or "I struggle and emerge," is illustrated on Zeeland's coat of arms by a lion rising out of the waves.

Even by Dutch standards, Zeeland is especially vulnerable to North Sea storms, and the 1953 storm known today as *Watersnoodramp* permanently reshaped the region. A combination of winds, tides, and storm surge caused the sea level to rise more than 4 meters above average, breaching dykes and inundating 165,000 hectares of land. More than 1800 people were killed and tens of thousands were forced to flee the area. The Netherlands responded by building a sophisticated system of dams and barriers throughout the delta region.

In the Dutch tradition, these *Deltawerken*, or Delta Works, did not completely wall off the sea from the land. The need for protection against periodic storms had to be balanced against the region's everyday needs, including fishery and river access to the major ports of Rotterdam and Antwerp, Belgium. Therefore, the Delta Works combined some fixed barriers with other semiopen structures, closing only when there is a threatening storm surge.

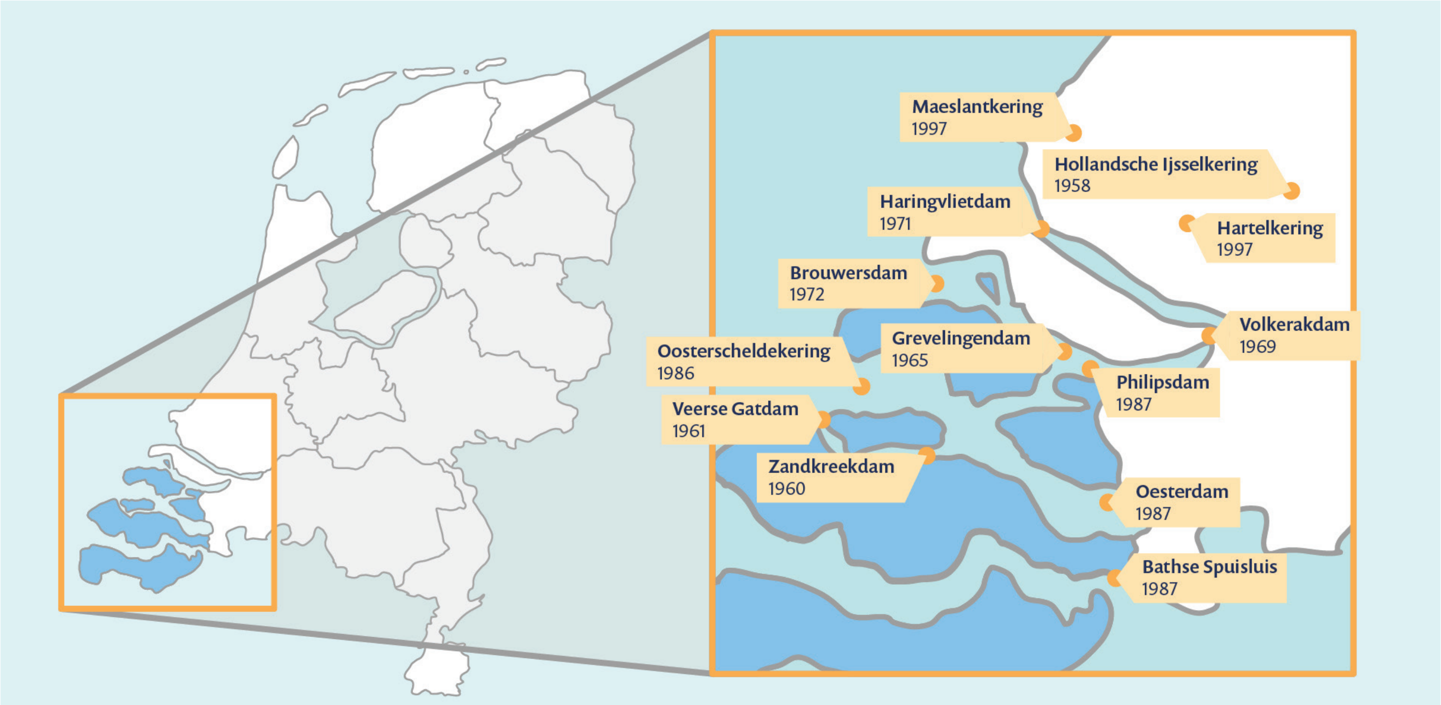


FIGURE 1 *The Netherlands, highlighting the province of Zeeland and its major flood control facilities. Original image of Zeeland in the Netherlands by TUBS, CC BY-SA 3.0, via Wikimedia Commons. The original work has been modified.*

FEEDBACK LOOP: THE EVOLVING PRIORITIES OF THE DELTA WORKS

As would be expected from such a large and complex project, construction of the Delta Works has lasted for decades (Figure 1). The project's priorities have continued to evolve over the 70+ years since it began. Along with providing protection from sea storms, the Delta Works have also changed the regional ecosystem — not always for the better. "In the 1950s and '60s, when the project was designed, it was completely new. Nobody in the world had done this type of waterworks before," explains Van Halewijn. "Concern for the environment was not like it is today."

Aside from the semiopen barriers mentioned above, the original Delta Works included dams that blocked off some estuaries. This created new boundaries between salty seawater and freshwater from the rivers. Behind the dams, areas that had previously been subject to tidal action instead became freshwater lakes. "Nowadays we see that was a mistake," Van Halewijn says. Since the 1970s, sluices have been installed in a number of dams. These controlled passages are kept open under normal conditions and are closed only during storms. By reintroducing tidal cycles to the basins behind the dams, the sluices have restored the salty conditions preferred by oysters, mussels, and other coastal sea life.

ENCORE AND WATER2ENERGY: RENEWABLE ENERGY FROM VULNERABLE PLACES

While Zeeland's circumstances are unusual, rising sea levels caused by climate change are threatening coastal regions worldwide. The infrastructural expertise of the Netherlands, learned from many centuries of bargaining with the sea, is more globally relevant than ever before. In this context, it is no surprise to see the Dutch lead cross-border initiatives like Energizing Coastal Regions with Offshore Renewable Energy (ENCORE).

A joint project funded through the Interreg 2 Seas program and led by marine renewable energy expert BLUESPRING, ENCORE recognizes the North Sea region's vulnerability to climate change, as well as its potential as a source of energy production. The project, with partners from the U.K., France, Belgium, and the Netherlands, affirms that 25% of European energy demand could be met with offshore renewable sources by 2050. Three participating companies are developing offshore solar power, wave energy technology, and a river turbine. The third company, Water2Energy, seeks to produce power from the tidal flows through Delta Works sluices.

THE DARRIEUS ROTOR: ADAPTING A WIND TURBINE FOR WATER

A place defined by the restless movement of water seems like an ideal setting for hydroelectric production. However, while tapping into the potential of tidal power seems simple, actual conditions present many challenges. Conventional hydroelectric technology (Figure 2) is not well suited to installation in Delta Works sluices. "The most common design for water turbines is the Kaplan-type rotor," explains Van Halewijn. "It looks like the propeller used to power a ship. It turns very fast and if you place it in a confined space, like the sluices in our dams, it could damage fish and other sea life," he says. To address these issues, Water2Energy has instead developed a vertical-axis water turbine (VAWT) that incorporates a Darrieus-type rotor (Figure 3).

FIGURE 2 *An example of a Kaplan turbine rotor. Image by Reinraum, CC0, via Wikimedia Commons.*

Named after Georges Jean Marie Darrieus, who patented the Darrieus rotor for wind turbine use in 1926, this design offers potential benefits for water applications as well. From Water2Energy's perspective, the most significant advantage of a Darrieus rotor is that its open structure and motion would be far less dangerous to fish than that of a Kaplan-type rotor. Would it be able to meet the ambitious power production goals of the ENCORE project? To balance the need to maximize electrical output while minimizing ecological harm, a number of challenges inherent to the Darrieus design had to be addressed.

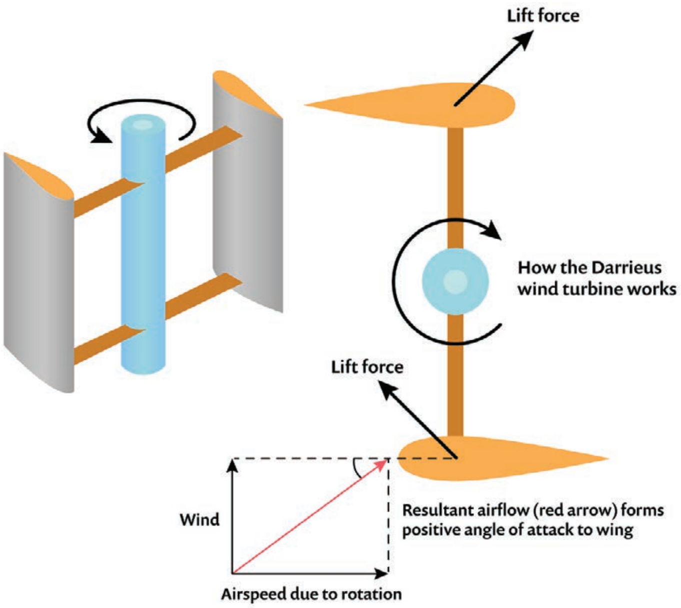


FIGURE 3 *A Darrieus rotor schematic. Image by Saperaud~commonswiki, CC BY-SA 3.0, via Wikimedia Commons. The original work has been modified.*

GO WITH THE FLOW: TURBINE BLADES SELF-OPTIMIZE THEIR ANGLE OF ATTACK

For Water2Energy's tidal power turbine, the most significant design decisions involved optimization of the rotor's vertical blades (Figure 4). By testing and refining both the design of the blades and a mechanism to adjust their angle, Van Halewijn tackled two technical challenges. First, a Darrieus rotor is not always self-starting, even in an environment where water flows continuously. The second challenge? A spinning turbine installed in a contained passage, such as a sluice through a dam, is subject to more turbulence than one that spins freely in open air or water.

Both of these challenges can be met by continuously adjusting the turbine blades' angle of attack. With the correct orientation toward water flow, a Darrieus rotor's blade will start moving even at very low water speeds. The problem is that the optimal angle for starting the blade will be inefficient once the turbine is already moving. Similarly, a blade's angle can be optimized to move smoothly past the wall of its enclosure, but that angle will be inefficient when the blade is at other points of its rotation. Van Halewijn used the COMSOL Multiphysics® software to model the effects of different blade positions on performance.

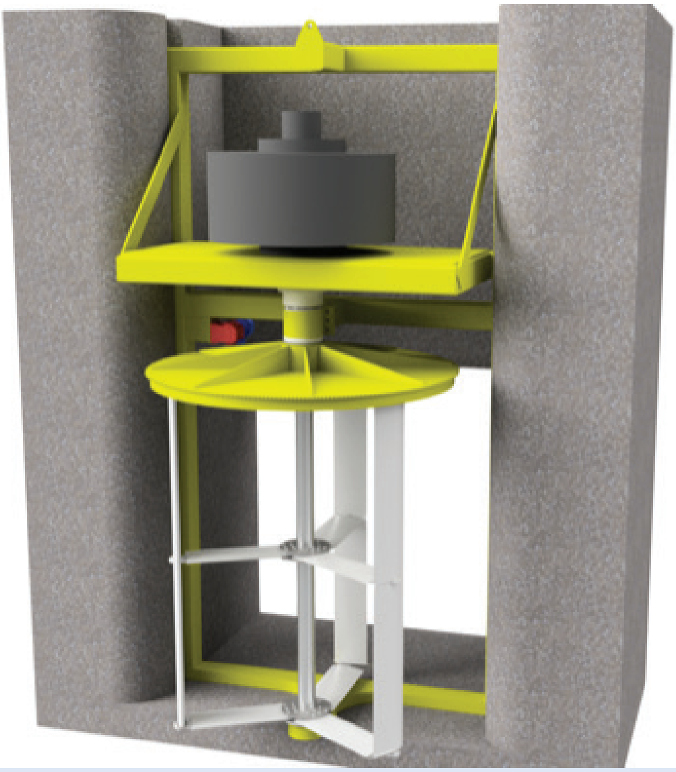


FIGURE 4 *Illustration of the Water2Energy water turbine design. Rotor mechanism, including vertical blades, illustrated in white.*

"Up to now, there has been no optimal design solution for this application. Water2Energy had some ideas for how to do it, and together with our simulation, we came to an even better solution," says Van Halewijn. "We were able to test several ideas in the software to demonstrate an optimal approach."

To do so, Van Halewijn modeled just one blade of the turbine in order to find the optimal angle of attack. To model the turbulent flow around the turbine blade, he tried out different computational methods for fluid flow in the COMSOL® software. The standard k-ε model was not well-suited for the problem and did not lead to an optimal power output. The so-called SST model combines the k-ε model in the free stream and the k-ω model close to the walls, which led to good results, but made the model take too long to converge. Therefore, the k-ω model suited both the needs of the project balanced with the computational resources.

After modeling the turbulent flow around the turbine blade, Van Halewijn was able to find an optimal blade profile for the project. "I always explain to customers that simulation software is a decision tool for research and development. I am not selling mathematics. With simulation, I am able to move a project in the right direction, without as much trial and error. Really, what I am providing is better decisions based on the sound principles of physics," says Van Halewijn.

"Once we had modeled a profile for the blade, we could run simulations of its motion past the walls of the channel (Figures 5, 6). This meant we had to adjust the mesh of the blade's surface to account for every step of its 360 degrees of rotation," Van Halewijn explains. "I was able to add a special note in the software to maximize energy generation in the design phase. And of course, we had to simulate the passage of fish through the turbine, to convince people that sea life would not be harmed, not even by our prototype testing."

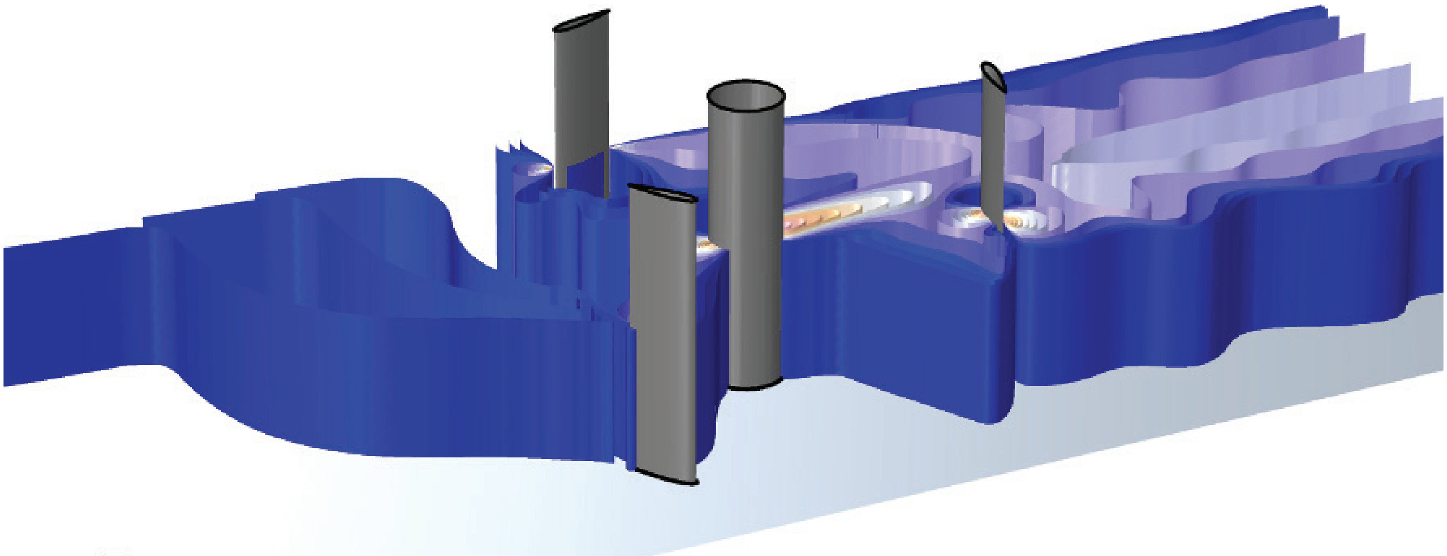


FIGURE 5 *Fluid flow through the Water2Energy water turbine.*

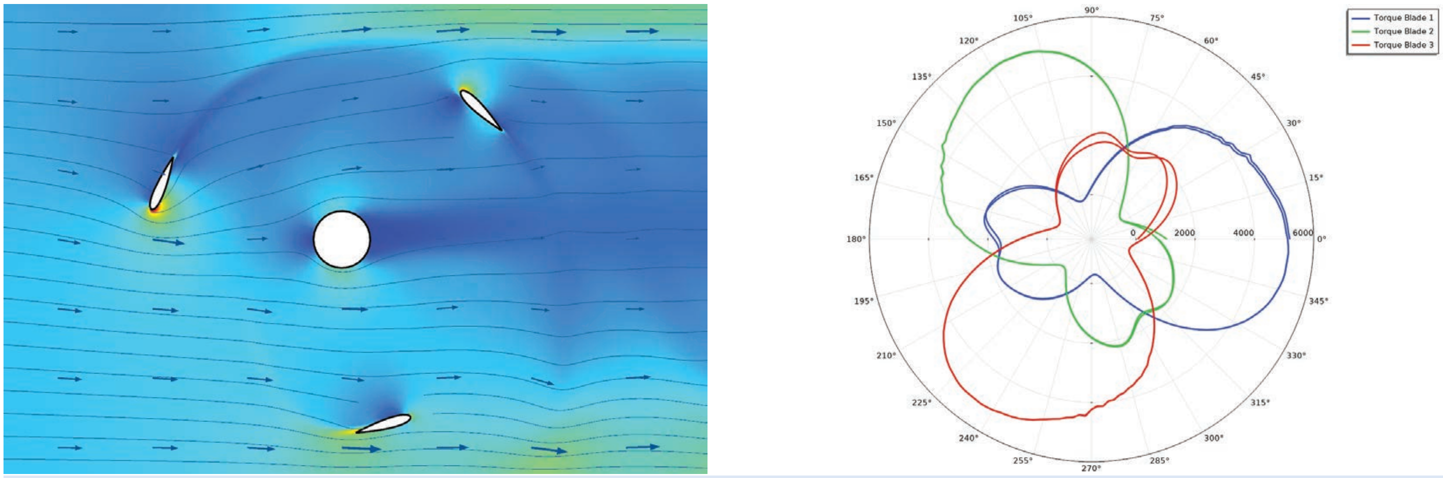


FIGURE 6 *Plots of the flow (left) and torque (right) around the turbine blades, modeled in COMSOL Multiphysics®.*

FIGURE 7 *The Water2Energy water turbine prototype, about to undergo live testing.*

EFFICIENT AND FISH FRIENDLY: LIVE TESTS CONFIRM NEW DESIGN'S POTENTIAL

Water2Energy performed live testing of its adjusting-blade VAWT mechanism inside a Delta Works sluice channel (Figure 7). The tests demonstrated that, in terms of power output, the redesigned turbine outperformed an existing fixed-blade design by more than 40%.

Just as importantly, the Darrieus rotor turbine proved that it could turn tidal currents into electricity while protecting sea life. In turbines using Kaplan rotors, up to 20% of the fish flowing past it are typically killed by the fast-spinning blades. The Water2Energy turbine, as optimized by Van Halewijn's modeling efforts, reduced the mortality rate to less than 1%. Cameras installed in the sluice channel vividly show the vertical adjusting blades working as intended, as trout swim safely past.

Having established the efficacy of their design, Water2Energy is now working to commercialize its potential. A consortium called Climate Power Plant Zeeland proposes to build a tidal power plant inside Zeeland's Grevelingendam. One of the solutions proposed could use up to 6 Water2Energy turbines, totaling 1.6 MW of output, to generate electricity for an estimated 1000 households.

A POETIC (BUT PRAGMATIC) ENGAGEMENT WITH THE RISING SEA

Although he is happy to share the particulars of his tidal power turbine project, Van Halewijn also reminds us to take a broader view: “This story is not just about simulation,” he says. “You have to put it in the context of the problems we face nowadays.”

From this perspective, we can see the larger significance of this work being done by small companies in a small country. The wellbeing of the world may now depend on our ability to negotiate with natural forces, whether those forces are as vast as a North Sea storm, or as small — but significant, and even inspiring — as a trout swimming safely out with the tide. Says Van Halewijn, “We are looking for a win–win situation.” ◎

ACKNOWLEDGEMENTS

Physixfactor would like to acknowledge Peter Scheijgrond from BLUESPRING for his review of this article, as well as the companies Water2Energy and BLUESPRING and the ENCORE project for their help in the work described in the article.

ABOUT THE ENCORE PROJECT

The aim of the ENCORE project is to advance four offshore renewable energy technologies — a wave energy convertor, a tidal and river current turbine, and offshore floating solar — in a structured and collaborative process, and to develop open-source tools and services to facilitate the accelerated uptake of offshore energy solutions for islands, harbors, estuaries, and offshore structures with a focus on the Interreg 2 Seas region and export opportunities.

The ENCORE project receives funding from the Interreg 2 Seas program 2014–2020, cofunded by the European Regional Development Fund under subsidy contract No 2S08-004. Also, the provinces of South and North Holland and Zeeland are offering financial support.

Lead partner and coordinator BLUESPRING brings together project partners from 4 European countries: Water2Energy (NL), EEL Energy (FR), Oceans of Energy (NL), Teamwork Technology (NL), Dutch Marine Energy Centre (NL), the European Marine Energy Centre (UK), Artelia (FR), Bureau Veritas (FR), Ghent University (BE), Inyanga (UK), and Deftiq (NL).

WATER2ENERGY

BLUE SPRING
BE GREEN GO BLUE

POLAR NIGHT ENERGY, FINLAND

HEATING BUILDINGS WITH SOLAR ENERGY STORED IN SAND

Polar Night Energy, a startup in Finland, has developed technology for warming up buildings with solar-generated heat stored in sand. The team uses thermal modeling to optimize the design of their heat storage and distribution systems, which are helping Finnish cities reduce their consumption of nonrenewable heating fuels.

by **ALAN PETRILLO**

As we try to objectively study nature, we are often reminded of how natural forces affect us personally. We can sit at a desk and consider heat in its various forms, but we might be distracted if our toes are cold! When we turn up the heat in our homes and workplaces, we must balance our personal need for warmth with the global impact of burning fossil fuels like oil, gas, coal, and biomass. Anthropogenic climate change confronts humanity with a challenge: How can we keep warm now as we try to prevent our world from overheating in the future?

It is a daunting question that a startup called Polar Night Energy, in the small and chilly nation of Finland (Figure 1), is attempting to answer. In a region known for long, dark winter nights, Polar Night Energy is building a system in the city of Tampere that can heat buildings with stored solar energy — all day, all night, and all winter long. The apparent contradictions do not end there. In an era of complex cleantech solutions, often made from rare and expensive materials, Polar Night Energy's heat storage and distribution system consists of simple ducts, pumps, valves, and sand. The novel system shows potential for tackling global problems in a patient, thoughtful, and human-scaled way.

A SMALL COUNTRY WITH LARGE HEATING NEEDS

Big problems demand big solutions, and there is perhaps no bigger 21st-century problem than climate change. To meet this challenge, many governments and organizations are investing in new technology to help lessen the use of fossil fuels. These initiatives have largely focused on renewable electric power generation, distribution, and storage.

FIGURE 1 *The nation of Finland, part of which is above the Arctic Circle. Polar Night Energy's heat storage systems are currently installed in the cities of Tampere and Kankaanpää.*

“When you ask people about cleaner energy, they think of electricity,” says Tommi Eronen, CEO of Polar Night Energy. “But we also have to cut emissions from heating.” Out of Finland’s energy-related emissions, 82% come from heating domestic buildings (Ref. 1). “We want to replace all of that if we are to have any hope of meeting our global climate goals,” Eronen says.

THINK GLOBALLY, HEAT LOCALLY

The spirit of “Think Globally, Act Locally”, a mantra associated with the 1960s, lives on with Polar Night Energy’s team of innovators. Their journey began with a question posed by its founders, Tommi Eronen and Markku Ylönen, when they were university classmates: “Is it possible to build an energy-self-sufficient and cost-effective hippie commune for engineers using only solar power?” After graduation, the project they codenamed “Hippie Commune” became Polar Night Energy, with Eronen as CEO and Ylönen as CTO.

What began as a lighthearted (but serious) student project led to a 3 MWh/100 kW pilot plant in the Finnish city of Tampere, which began operation during the winter of 2020–2021. The system uses electricity to heat air, which is then circulated through an exchanger that heats water and distributes it to multiple buildings in the city’s Hiedanranta district (Figure 2).

Inside the system, electrically powered resistive heating elements heat air to more than 600°C. The hot air is circulated through a network of pipes inside a sand-filled heat storage vessel. The hot air then flows back out of the vessel into a heat exchanger, where it heats water that is then circulated through building heating systems. The sand’s heat storage capacity ensures that even when the resistive elements are cool, the circulating air is still hot enough to keep the water (and buildings) warm.

“We only have pipes, valves, a fan, and an electric heating element. There is nothing special here!” Eronen says, laughing.

BATTERY FOR HEAT MADE FROM SAND

Noted chemical engineer Donald Sadoway is quoted as saying: “If you want to make a dirt-cheap battery, you have to make it out of dirt.” Polar Night Energy’s system faces the same core challenges as any other energy infrastructure. It must deliver power to people when they need it, where they need it, and at a manageable price. This means that storing and distributing energy is as important as its generation. Existing infrastructure meets these challenges in familiar ways. For combustion-based heating, fuels like oil and gas are stored and moved to where they can be burned. The electrical grid also supports the efficient distribution of power and makes use of energy generated through renewable means like wind and solar. The intermittent nature of daylight and strong winds, however, is a stubborn problem. Energy storage is needed to maintain steady power output throughout the peaks and valleys of renewable inputs. But even with recent advances in battery technology, storing electric power remains relatively expensive, especially at the scale required for heating buildings. What if, rather than storing electricity, a “battery” could store heat instead?

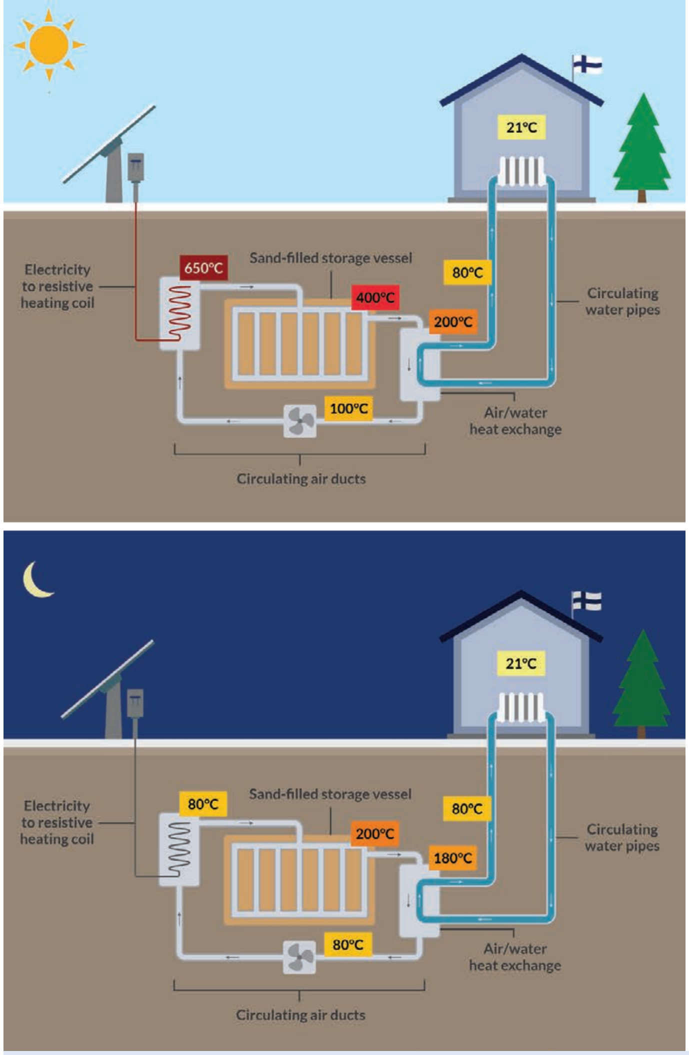


FIGURE 2 *A schematic of the components and operating cycle of the Polar Night Energy system.*

Many conventional heating systems already store and distribute heat by retaining and circulating warm water. Eronen and Ylönen recognized the benefits of water-based heat storage as well as its limitations. “There is only so much heat you can add to water before it becomes steam,” says Eronen.

"Steam can efficiently distribute heat, but it is not really cost-effective for large-scale storage." To avoid the drawbacks of storing heat in water, they instead turned to sand — 42 metric tons of it! (Figure 3) After the Sun goes down, the sand's stored heat is gradually released back into the circulating airflow. This keeps the air hot enough to maintain steady temperatures in the water that flows through customers' radiators. In this way, sand enables solar power to keep people warm, even during the darkest and coldest Finnish nights. "Sand provides four times the energy storage capacity of water," Eronen says. "Sand is efficient, nontoxic, portable, and cheap!"

FIGURE 3 *Markku Ylönen with a representative sample of Polar Night Energy's dirt-cheap heat storage medium.*

THE SOPHISTICATED ANALYSIS BEHIND A SIMPLE SOLUTION

Cost efficiency is the foundation of Polar Night Energy's value proposition. "As soon as we decided to pursue this idea, we were trying to figure out how the finances looked," says Eronen. In their quest to do more with less, Polar Night Energy has long depended on numerical simulation tools. Eronen and Ylönen began using the COMSOL Multiphysics® software as students and it remains integral to their design process. For example, Eronen mentions the specifications of an expanded heat storage system that would serve more buildings in Tampere. The team calculated that supplying heat to a district of 35,000 people would require a sand-filled storage cylinder that is 25 meters tall and 40 meters in diameter. How did they arrive at these dimensions? "The rough quantity of material needed is actually easy to calculate, because we know how much heat we can store in a cubic meter of sand," Eronen explains. "We also had to determine the space required for efficient heat transfer between the sand and our air circulating system (Figure 4). That is much more difficult to do! We used COMSOL® to model and evaluate different design options."

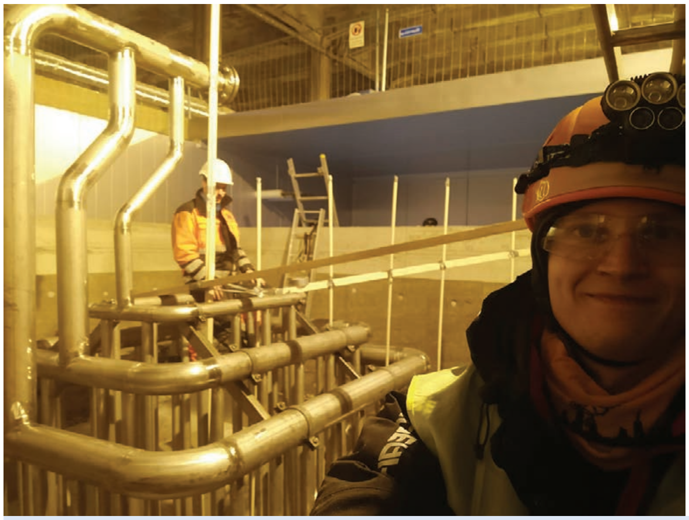


FIGURE 4 *Tommi Eronen (foreground) and Ylönen inspecting the ductwork of a Polar Night Energy heat storage vessel.*

Multiphysics simulation software helped shape Polar Night Energy's heat exchanger design (Figures 5–6). Eronen says, "We built a particular model to explore a design idea: What if we created a super hot core of sand surrounded by heating ducts around the perimeter?" By modeling fluid flow and heat transfer effects in the COMSOL Multiphysics® software, the Polar Night Energy team could quantify its design's comparative advantages and drawbacks. "The simulation confirmed that the 'hot core' design was good at storing heat for very long periods of time," says Eronen. "But for our intended operational cycle, it makes more sense to evenly distribute hot air ducts throughout the sand storage vessel," he explains.

The sheer scale of Polar Night Energy's sand-based heat storage system makes simulation software indispensable. "We cannot possibly build full-size prototypes to test all of our ideas. We need predictive modeling to answer as many questions as possible, before we commit to assembling all this equipment — and all this sand!" Eronen says. "It is essential for us to use these immensely powerful tools."

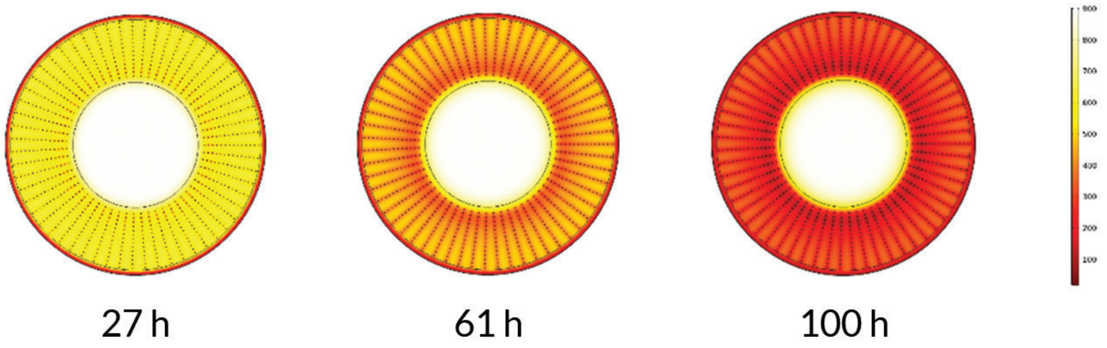


FIGURE 5 *Simulation images showing temperature changes inside a proposed sand–air heat storage vessel design over a 100-hour period.*

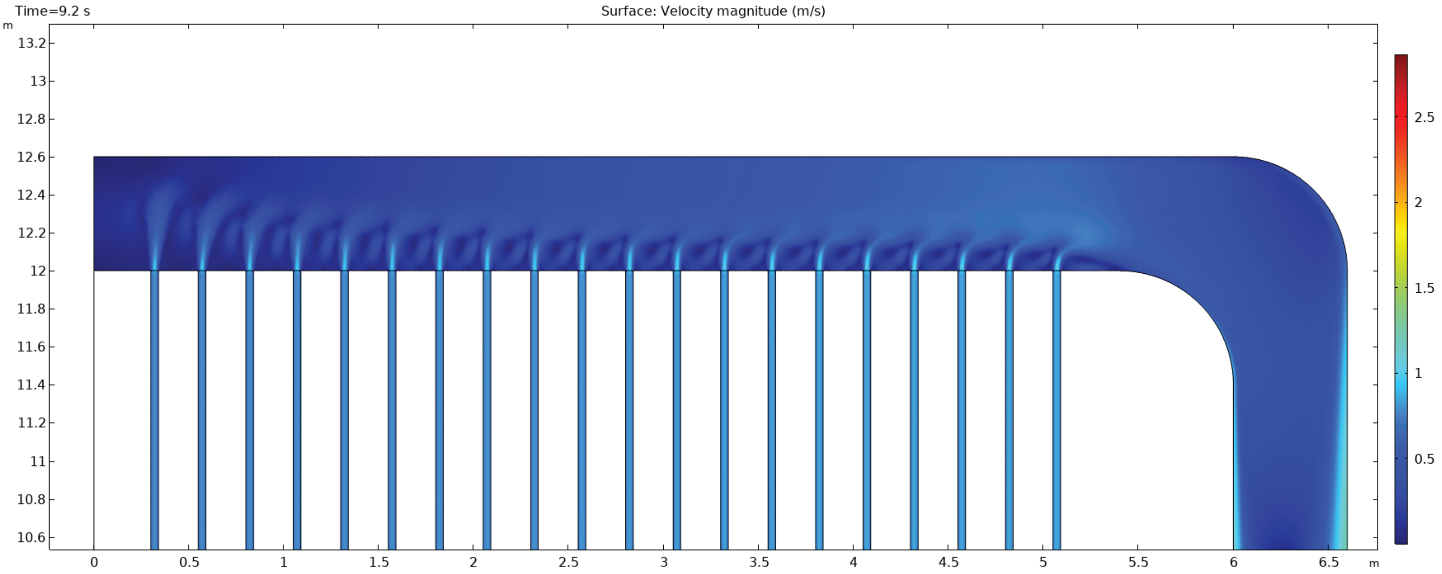


FIGURE 6 *Simulation image of natural convection effects through ductwork inside the sand storage vessel.*

ADAPTING NEW IDEAS TO EXISTING INFRASTRUCTURE

By separating the task of heat storage from heat generation and distribution, Polar Night Energy has made its system more efficient and adaptable. There is great potential for retrofitting their sand-filled heat storage and transfer systems into existing infrastructure (Figure 7). Tampere, an inland Finnish industrial city of nearly 250,000 people, is an ideal testing ground for this new technology. “Tampere, like many European cities, already has a district heating system that circulates water across entire neighborhoods,” says Eronen. “That enables us to switch many buildings to a renewable heat source quickly,” he says. Polar Night Energy’s pilot plant in Tampere can also tap into power from the existing electrical grid, along with electricity generated by new solar panels. Reliable thermal storage enables the city to generate or purchase power when it is most affordable and then distribute heat when it is needed most.

FIGURE 7 *Part of the heat transfer system installed by Polar Night Energy in Tampere, Finland. The vertical pipes at left are part of the heat exchanger, while the resistive heater elements are wrapped in white insulation at right. Between these components is the air-circulating radial blower.*

TODAY: FINLAND; TOMORROW: THE WORLD

Since the Tampere system began operation during the winter of 2020–2021, the Polar Night Energy team has been gathering data to compare to their models. “Our simulations have proven to be very accurate, which is encouraging,” Eronen says. And as the Polar Night Energy team continues to develop their ideas locally, they are aiming to act globally as well. The same technology that warms Finland’s long, chilly nights can also provide better energy management options to the rest of the world. Affordable thermal storage could help industries and cities capture heat that is currently wasted, as well as balance the inconsistencies in wind and solar power output. But while Polar Night Energy is eager to work directly with potential customers, they realize that the challenges ahead are too big for them to tackle alone.

“We want to license this technology. If you operate a power plant, please contact us,” Eronen says with a laugh. On a more serious note, he adds, “We have to get away from all kinds of combustion, even biomass. We need to protect and restore forests so they can keep removing carbon from the air. Because climate change is happening so fast, we want our ideas to spread as quickly as possible.” ◎

REFERENCE

1. *Statistics Finland*, “Over one-half of Finland’s electricity was produced with renewable energy sources in 2020”, November 2021.

TOYOTA RESEARCH INSTITUTE OF NORTH AMERICA, MICHIGAN, USA

GENERATIVE DESIGN PUTS HYDROGEN FUEL CELL DEVELOPMENT IN HIGH GEAR

As an alternative to battery-electric vehicle drivetrains, Toyota is pursuing development of hydrogen–oxygen fuel cells to power cars, trucks, and even entire cities. Toyota Research Institute of North America (TRINA) has developed a simulation-driven methodology for accelerating the R&D process for fuel cell flow field plates.

by **ALAN PETRILLO**

"Electrify everything." Among those seeking to reduce the world's reliance on fossil fuels, this phrase has become a rallying cry. We can see the electrification imperative in action all around us, as hybrid gas–electric vehicles (HEVs) and battery–electric vehicles (BEVs) are now familiar sights on the highway. But even as many automakers ramp up HEV and BEV production, one company is dedicated to developing electric cars that do not rely primarily on batteries for energy storage. Instead, these cars carry hydrogen, which provides electricity when combined with oxygen from the air inside a fuel cell.

The company pursuing this alternate route is Toyota. The commercialization of hydrogen-fueled vehicles faces many obstacles, but if anybody can put the world on fuel cell-powered wheels, it could be the world's largest automaker (Ref. 1). Toyota is directing great financial, physical, and human resources toward automotive fuel cell research, but it sees vehicle development as only the beginning of a long journey. The company's vision leads far beyond cars; it foresees the emergence of a global "hydrogen society". In this proposed society, fossil fuel-burning engines, heating systems, and generators would be replaced by fuel cells that extract electric current from hydrogen. Toyota's efforts to reach this destination are as far-sighted as its adoption of the Japanese city of Susono as a hydrogen-tech test bed, and as focused as its refinement of a generative design methodology for optimizing fuel cell performance.

GENERATIVE DESIGN ENABLED BY SIMULATION

Toyota Research Institute of North America (TRINA) has developed a simulation-driven generative design method and applied it to the design of flow field microchannel plates, which direct the movement of fluid reactants in microreactors like hydrogen–oxygen fuel cells. While much of Toyota's fuel cell R&D is necessarily confidential, the TRINA team has published an article in *Chemical Engineering Journal* (Ref. 2) about their simulation-enabled "inverse design" process. Applying this process to flow field plates resulted in four distinctive microchannel designs, as shown in Figure 1.

Each of the four designs has particular merits; all of them outperform existing benchmark designs in terms of key metrics. Just as important, they exemplify the power of process. TRINA has shown how generative design enabled by simulation can accelerate innovation — even when a project's ultimate destination may be far into the future.

"We think that the inverse approach can revolutionize current design practice," says Yuqing Zhou, a research scientist at TRINA. "We are enabling the next step in a long journey, even though we cannot know exactly where that journey will lead."

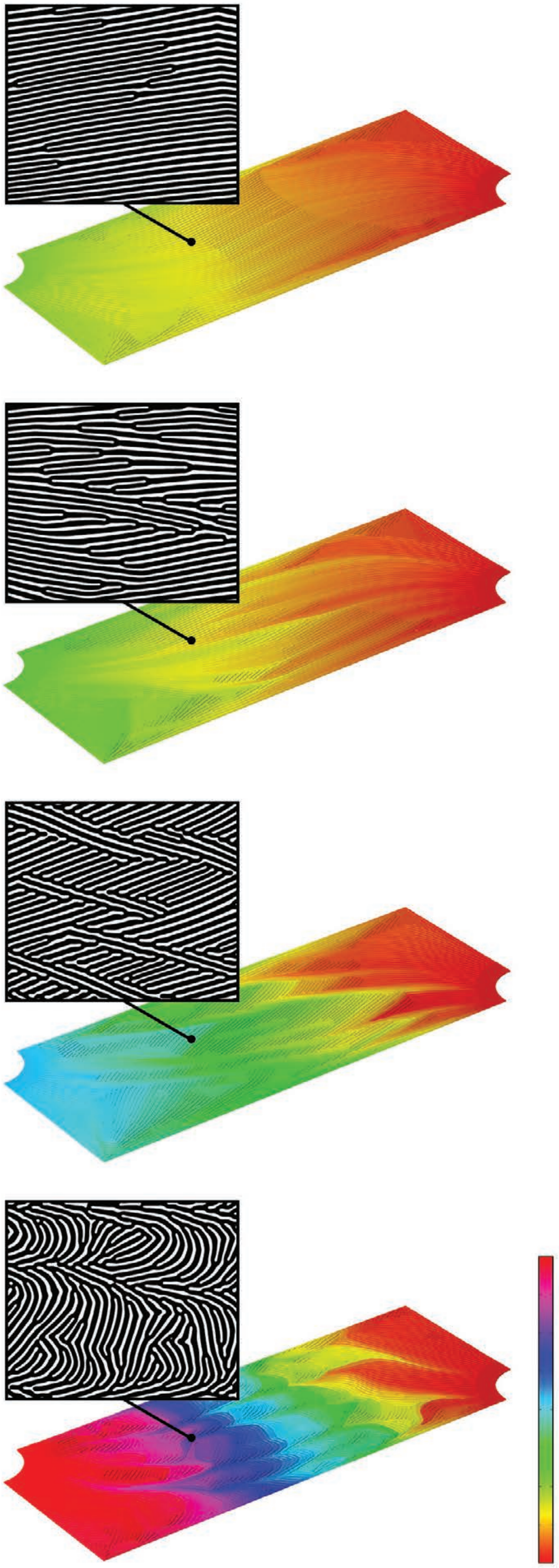


FIGURE 1 *Simulation results from the TRINA team's model, built using the COMSOL Multiphysics® software, showing the pressure distributions resulting from four different microchannel flow field designs.*

CLEANER POWERTRAIN OPTIONS

Considering this spirit of open-ended inquiry, perhaps it is understandable that Toyota is sustaining its decades-long pursuit of fuel cell research, even as most automakers have committed exclusively to battery power for electric vehicles. As Chairman Akio Toyoda put it in a November 2022 interview (Ref. 3): "Think of Toyota as a department store offering every available powertrain."

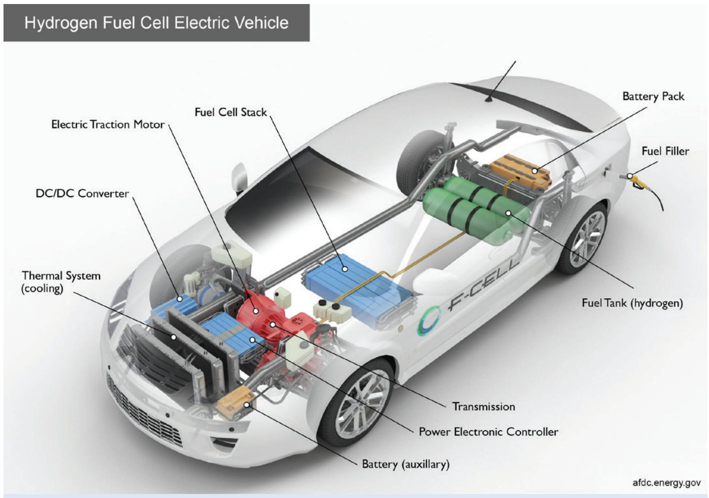


FIGURE 2 *A schematic of the important components of a hydrogen fuel cell-powered vehicle. Image in the public domain, via the U.S. Department of Energy.*

While a hydrogen–oxygen fuel cell may seem like an exotic way to supply power to a car (Figure 2), the technology itself is not new, and its operation is appealingly straightforward. Figure 3 presents the fundamentals of a generic fuel cell in action.

As hydrogen gas flows across the anode, it encounters a catalyst, which separates it into hydrogen ions and electrons. Whereas the hydrogen ions move through the electrolyte to reach the cathode, the electrons move through a conductor outside the fuel cell. It is this electric current that can be harnessed to perform useful work.

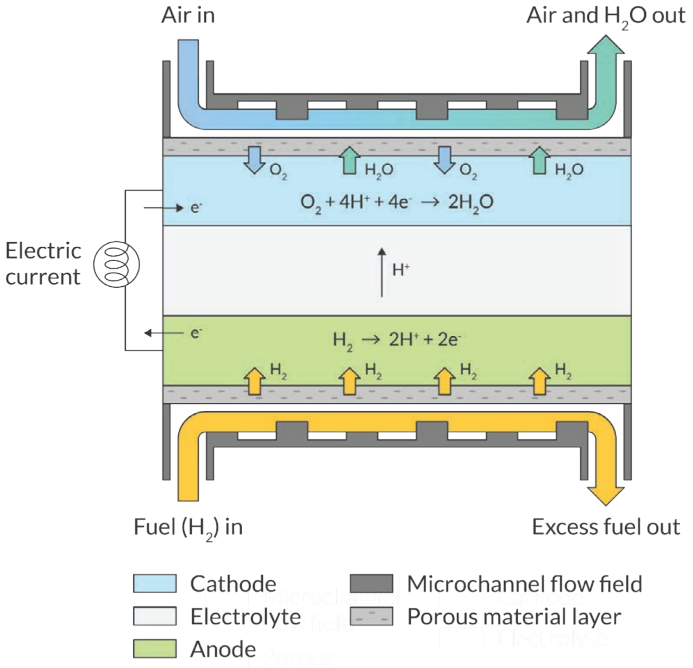


FIGURE 3 *A schematic of a generic fuel cell design. One flow field plate distributes hydrogen gas toward the anode–electrolyte–cathode stack while the other plate distributes oxygen to the stack and channels away water. Note: While this illustration shows the oxygen-side fuel plate on top of the stack assembly and the hydrogen-side plate below, the actual orientation of a fuel cell can vary.*

As oxygen gas from the air flows across the cathode, it encounters the hydrogen ions and returning electrons at the surface of the cathode. Here, the oxygen molecules split and combine with the hydrogen ions and electrons to form water.

A REACTANT'S PATH THROUGH A FLOW FIELD PLATE

For as long as hydrogen and oxygen keep flowing, a fuel cell will keep generating electric current. Managing the distribution of these essential gases is the job of the cell's flow field plates. Each plate includes both a microchannel structure and a porous sublayer. As hydrogen moves through the channels of the anode-side plate, it is also being forced through the sublayer toward the anode. Meanwhile, air is channeled through the flow field plate on the cathode side of the fuel cell. Air and water are exchanged through the cathode-side porous material layer, and the plate then channels excess air and water away from the cell stack. Figure 4 offers a simplified close-up of this essential process for the cathode side.

In their journal article on this project, the TRINA team explains that "uniformity of fluid residence time or fluid flow distribution, and the relationship to optimal heat transfer, is directly related to the design of the flow structure, which is of primary importance for proper control of chemical reactions."

Accordingly, the two main objectives for fuel cell flow field plate design are to maximize fluid flow across the plate's microchannel flow field and through the porous material layer, in order to supply sufficient reactant to the electrode. The first objective can be understood as a goal of reducing resistance to reactant flow, while the second seeks to enhance reactant conversion and reaction uniformity across the entire area of the electrode surface.

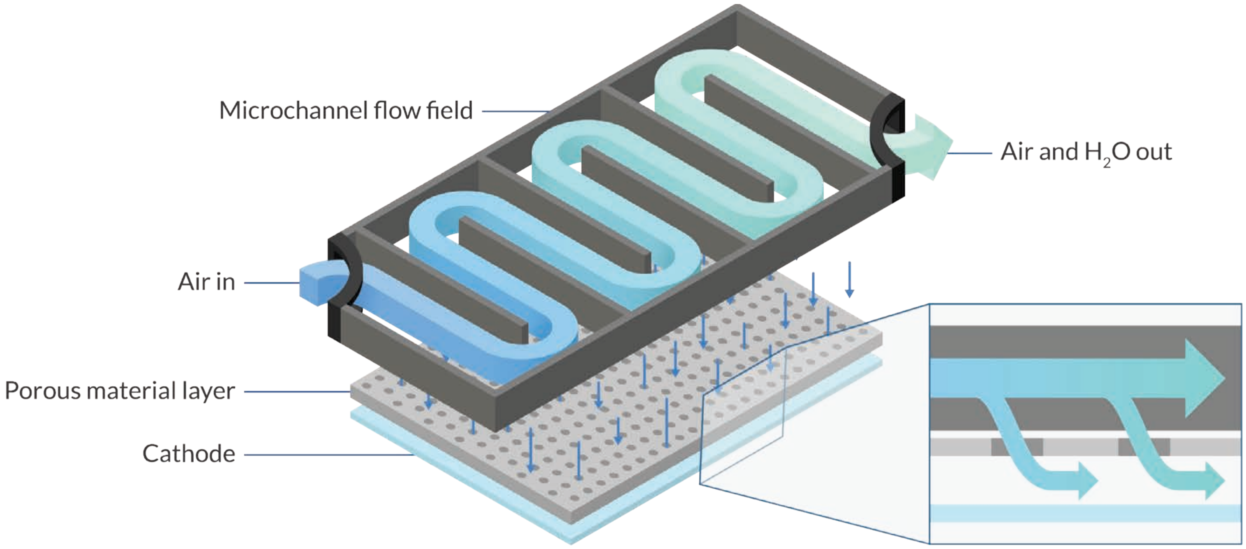


FIGURE 4 *A simplified schematic of how fluid moves through the cathode-side flow field plate assembly of a fuel cell. A microchannel structure (shown in dark gray) defines a path through which reactant fluid (in this case, air) moves from an inlet to an outlet. As the fluid flows, some of it is diverted away from the flow field, through a porous material layer toward the cathode surface.*

INVERSE DESIGN: A SIMPLER PROCESS FOR CREATING COMPLEX FORMAL SOLUTIONS

The physical arrangement of microchannels helps determine how well a flow field plate meets its performance objectives. Historically, microchannel designs have followed a few familiar patterns, such as the serpentine type shown at the top in Figure 5. More complex forms could improve performance, but increasing a design's complexity adds to the time needed to define, fabricate, test, and adjust that design.

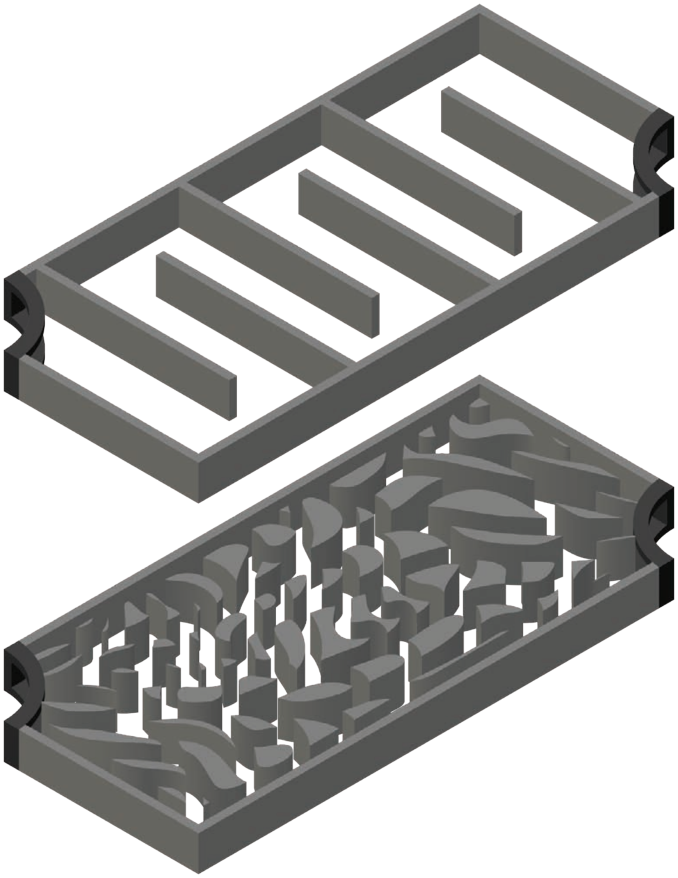


FIGURE 5 *Existing designs for flow field microchannels have followed simple patterns, such as the serpentine type shown at top. More intricate channel designs (bottom) could distribute fluid through the porous material layer more effectively, but adding physical complexity can also make design and manufacturing more complex.*

Zhou and his colleagues recognized that before trying to optimize their designs, they first had to optimize their design process. To generate a more complex (and higher-performing) formal solution to their problem, the TRINA team created their simulation-driven inverse design methodology. Their methodology does not define forms in advance of testing, but rather sets key parameters and then directs algorithms to generate forms that fulfill those parameters. Versions of this approach have been variously described as generative design, topology optimization, and inverse design.

"We were seeking an efficient way of approximating what a more complex simulation would show. We have sacrificed some modeling complexity, which actually enables us to explore more elaborate designs in less time," Zhou says.

To illustrate his point, Zhou points to complex microchannel designs like the one shown at the bottom in Figure 5. "Some people use topology optimization for problems like this, and they come up with designs that maybe have 10 channels. This is because they are asking their algorithm to determine the exact placement of every physical element of the channels in advance, which requires a lot of computing power and time to achieve a complex design like we see here," he explains.

FROM DESIRED RESULTS TO NOVEL FORMS, FASTER

So how could the TRINA team use its methodology to efficiently generate better microchannel designs? First, they simulated idealized flow trajectories through the effective anisotropic porous material, as shown at left in Figure 6; then they extracted values that described the idealized fluid behavior. Next, they input those values into another simulation, which generated the microchannel forms that would cause that behavior, as shown at right in Figure 6. Essentially, they defined the effect they wanted their designs to produce before designing anything. This sequence describes the inversion behind inverse design.

As described in the TRINA team's research paper: "By abandoning the explicit modeling of channels during the optimization stage, which requires a large number of function evaluations, the physics inside an anisotropic porous media is captured using relatively coarse mesh discretization of the design domain."

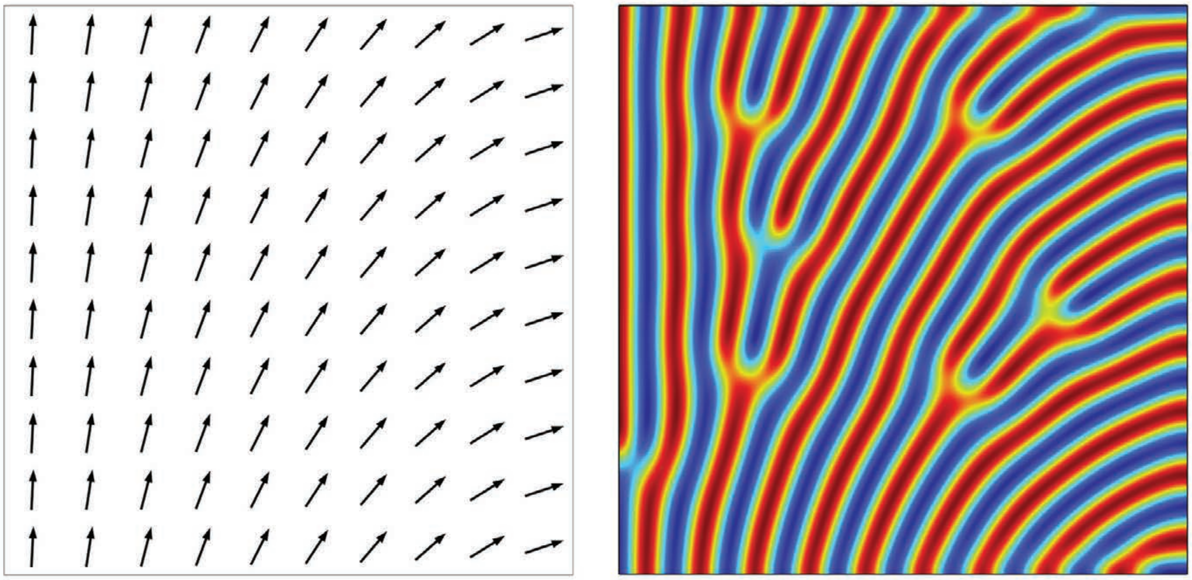


FIGURE 6 *An illustration of desired flow trajectories through the porous material (left), and at right, a simulation image of microchannel forms that will cause fluid to follow the desired trajectories.*

"Our COMSOL model of the porous material has only two material values and a very coarse mesh," Zhou explains. "We implement a sensitivity-based optimization process based on Navier–Stokes and advection–reaction–diffusion equations. We assume steady-state, incompressible, and laminar fluid flow through the porous media, and that the desired chemical reactions will occur proportionally to the reactant concentration. We run these simulations to arrive at an optimal distribution of fluid flow orientation through the pores. This process gives us valuable results with a huge reduction in computational complexity."

Zhou describes this part of the overall design process as *homogenization*. Having now established a pattern of ideal trajectories of fluid through the plate's pores, the next step is *dehomogenization*. This step involves the equation-driven definition of microchannel forms that will force fluid to follow these optimal paths.

GENERATED DESIGNS THAT MAXIMIZE FLOW, REACTION, OR BOTH

The dehomogenization step is needed, Zhou says, because "we cannot fabricate an ideal porous material with each pore individually designed. We need to install walls and channels to direct fluid through the pores in ways that approximate the ideal. To generate this design, we use COMSOL Multiphysics® to solve a customized partial differential equation (PDE) for pattern generation. The software also gives us plotting functions we can use to visualize the results."

Two of the formal options created by TRINA's dehomogenization equations are shown in Figure 7 and Figure 8. As noted earlier, the guiding performance objectives are: 1) to reduce resistance to reactant flow and 2) to enhance reactant supply and reaction uniformity across the entire plate. These objectives are represented by governing variables in the model's PDE. By assigning different weighting factors to these two objectives, Zhou and his team can induce the model to generate different design options. They can then evaluate the relative merits of each option and make adjustments to produce further iterations.

Of the design shown in Figure 7, Zhou says, "We call this the 'flow design' because it leads to the smallest pressure drop across the entire flow field surface. The model generated paths that are relatively parallel and straight, without much side branching."

While this design effectively moves fluid across the plate, it does less well at distributing reactant evenly through the porous material layer. Simulation shows lower reactant concentration (shown in green and blue in the bottommost image in Figure 7) on the outlet side of the design, which can limit reaction uniformity and the resulting power output from the fuel cell.

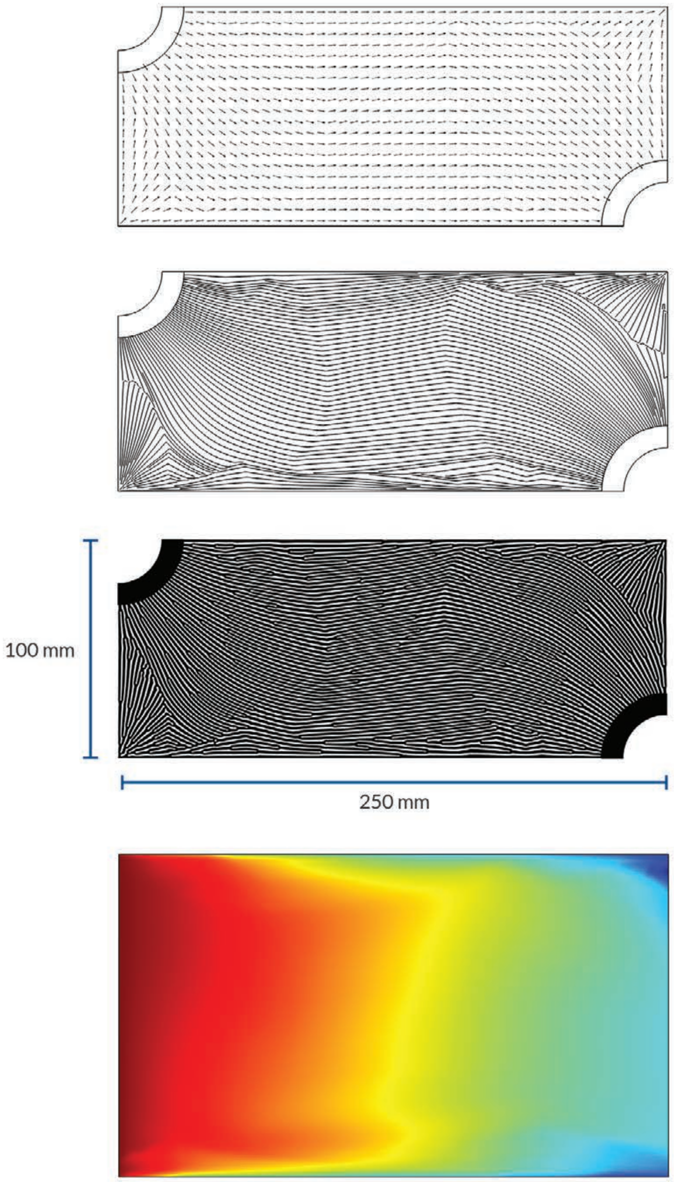


FIGURE 7 *Four visualizations that describe different aspects of a flow-optimized microchannel design. In all figures, fluid flows from the inlet at the upper left to the outlet at the lower right. First: the desired flow orientation vectors through the porous material. Second: orientation paths across the microchannel that can produce the desired vectors. Third: a dehomogenized microchannel design. Fourth: a simulation image of the sublayer showing the distribution of the reactant concentration.*

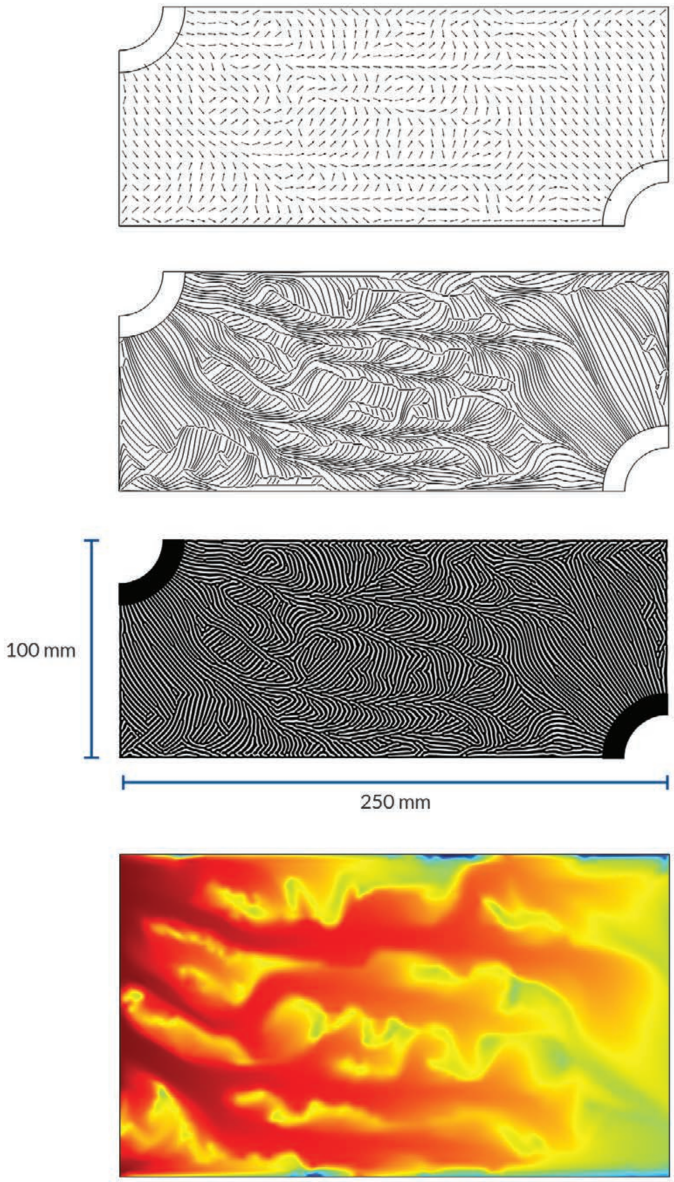


FIGURE 8 *Four visualizations that describe different aspects of a reaction-optimized microchannel design. This option features a mix of primary "arteries" and secondary "capillaries". The arteries sustain overall flow toward the outlet, while capillaries enable broader reactant distribution toward the electrode. In all figures, fluid flows from the inlet at the upper left to the outlet at the lower right.*

What if the weighting factors in the governing equation were adjusted to prioritize reaction uniformity, rather than flow? The model would then generate a design like the one shown in Figure 8, which Zhou calls the "reaction design". High reactant concentrations (shown in red and orange in the bottommost image) now predominate, indicating that a larger share of the available reactant is being put to work. The intricate forms of the "reaction design" microchannels may seem familiar to students of biology.

"Most commercial microreactors would use a design somewhat similar to the 'flow design'," says Zhou. But naturally occurring systems that distribute fluid reactants — such as leaves, lungs, and blood vessels — more closely resemble the forms of Figure 8.

"Engineers might prefer to use straight channels with no side branching, but nature chooses the 'reaction design'," Zhou says. The TRINA team's research paper notes that while some have previously experimented with natural-looking, fractal, or hierarchical forms selected *a priori* for flow field channels, "this is the first time that such large-scale branching flow fields have been discovered using an inverse design approach without assuming prescribed layouts."

RATHER THAN TRYING TO PREDICT THE FUTURE, CREATE IT

Along with the "flow versus reaction" comparison illustrated previously, TRINA produced two further designs (not shown) that combined attributes of those in Figures 7 and 8. Tellingly, every one of TRINA's four iterations outperformed baseline conventional designs across key reaction-fluid performance metrics. An additional design that was fabricated and experimentally tested (Ref. 4) by the TRINA team is shown in Figure 9.

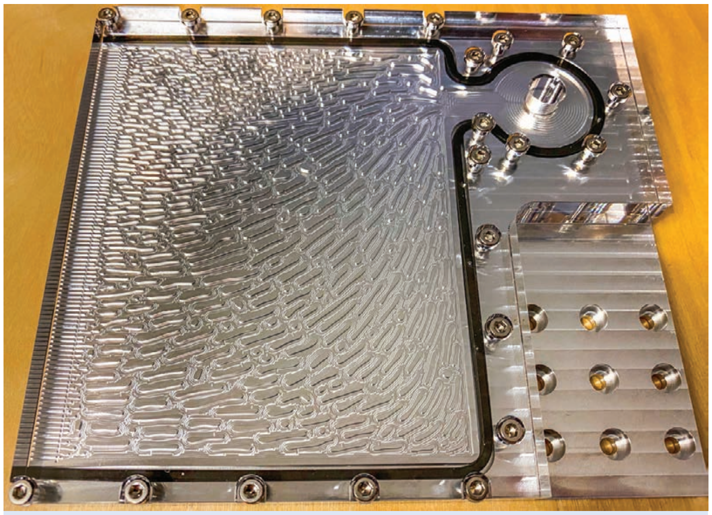
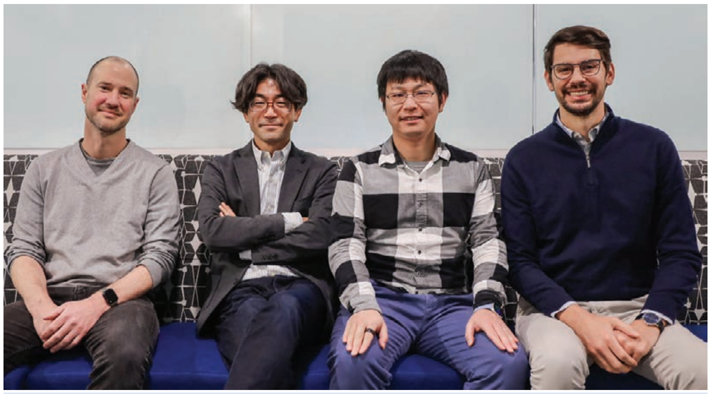


FIGURE 9 *A machined metal prototype flow field plate based on one of TRINA's generated designs.*

So, what is the ideal design for a flow field plate? There is no such thing, just as there is not a single ideal technology for replacing gasoline-powered automobiles. "From our point of view, we succeed by providing multiple good options for our engineers to consider," Zhou says.

TRINA is part of a large network of Toyota R&D teams that are striving to realize a potential hydrogen society. The company has continued to improve the range and performance of the hydrogen-fueled cars it calls Mirai, which is a Japanese word that means "the future", or literally, "not yet come". Perhaps, in a world not yet come, we will be living in smog-free cities equipped with hydrogen-distributing infrastructure and fuel cell-powered cars, trucks, trains, and buildings. Even though we cannot be sure of reaching this destination, we who live in today's petroleum society can still be inspired by Toyota's journey toward mirai.

Yuqing Zhou shares some advice that guides him and his colleagues: "Our chief scientist has said: 'We must stop trying to predict the future, and just work on trying to create it.'" ◎



Four core contributors to the flow field design project. From left to right: Ercan M. Dede, Tsuyoshi Nomura, Yuqing Zhou, and Danny J. Lohan. Nomura is affiliated with Toyota Central R&D Labs in Japan, while the others work at Toyota Research Institute of North America.

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NKT, SWEDEN

3D MODELING OF ARMOR LOSSES IN HIGH-VOLTAGE CABLES

NKT in Karlskrona, Sweden uses numerical models to investigate electromagnetic fields and calculate armor losses in 3D cable designs. To confidently perform design analyses with simulation, they then validated their modeling results with experimental measurements.

by **BRIANNE CHRISTOPHER**

Wires and cables make up a global industry worth hundreds of billions of dollars. In fact, Infinium Global Research reports that the cable market is poised to reach $220 billion by 2025 (Ref. 1). A major portion of the rapidly growing cable industry's revenue is from installation, maintenance, and development. For instance, the NorNed cable, a joint cable project connecting the power grids of Norway and the Netherlands, cost roughly €600 million (approx. $700 million USD) to install, and that was back in 2008 (Ref. 2). When cables of this magnitude need to be repaired or replaced, it can also be expensive. A 2010 report from the SubOptic submarine cable conference estimated that submarine cable repairs can cost more than $12,000 a day, and over $1 million per project. (Ref. 3) Since cable costs are so large, getting a return on investment also takes many years.

Apart from being major project investments, cables are demanding to test experimentally as well (Figure 1). In fact, cables researched by NKT, a global cable supplier, have been tested experimentally for many years, and it has been both time and resource consuming. "Cable losses are a complex thing to measure," says Ola Thyrvin, senior analysis engineer at NKT.

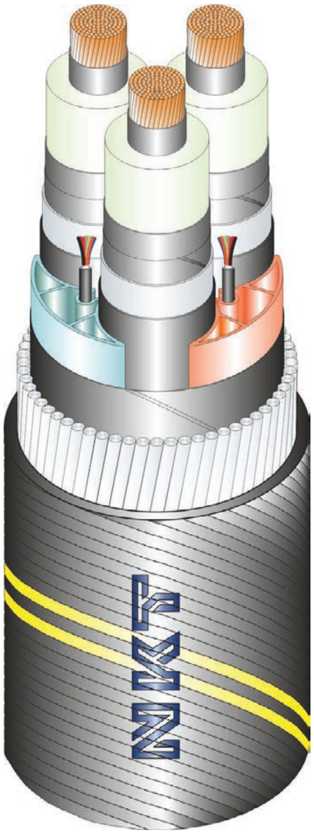

FIGURE 1 *High-voltage cables connect the world. They can also be expensive to maintain and difficult to analyze. Image courtesy NKT.*

One tool that can help in this regard? Electromagnetics modeling, which enables the NKT team in Karlskrona, Sweden to test cable designs virtually, visualize how different cable parameters affect armor losses, and predict cable performance in different installation conditions (Figure 2). With cable costs as steep as they are, designers can, with simulations, analyze the cable losses and reduce the amount of required conductor size and, thereby, cable cost. However, they need to be absolutely confident that their modeling tools can perform the analyses they need — and give them the correct results, since the cable cannot be measured until it is manufactured after the design is sold.

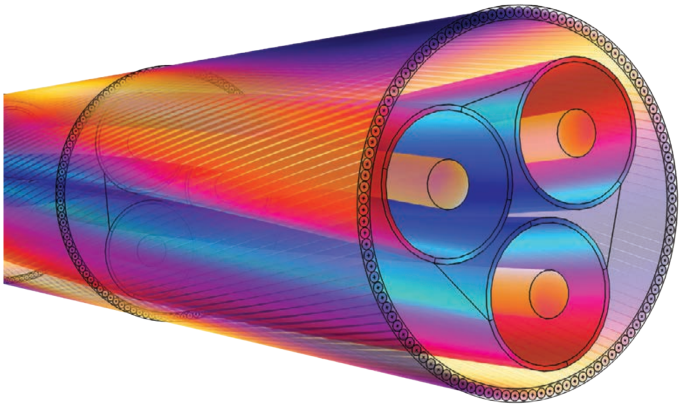

FIGURE 2 *A 3D cable modeled in the COMSOL Multiphysics® simulation software.*

BYPASSING LIMITATIONS IN CABLE MODELING

One issue when it comes to testing cable designs is that the standards are a bit outdated. In fact, some IEEE and IEC standards for cables are still based on analytical expressions that were derived about 80 to 100 years ago and simplified to enable hand calculations. Over the last decade, several publications have provided measurements that show that the formulas in the standard overestimates the armor losses. For some cases, the losses are around 50% of what the IEC standard gives. As the possible current a cable can carry is limited by a maximum allowed conductor temperature, a reduction of the losses enables a possibility to reduce the conductor size. A reduced conductor size means less copper or aluminum, which are expensive metals, and therefore cost savings for the cable project.

It is possible to measure the armor losses accurately with the methods developed ten years ago, but it requires that you have the cable. Almost all high-voltage offshore cables are custom made and therefore not available to test before a project is sold and manufacturing starts, and cables need to be designed already in the tender phase. With the adoption of numerical analysis, the study of cables and armor wires became easier, but still left a lot to be desired. In fact, the first 3D models of a cable were created less than a decade ago. Even more inhibiting: Models of this kind, up until recently, could take several days to a few weeks to run on a supercomputer. Advancements in both computer hardware and modeling techniques have made cable design and analysis quicker, easier, and more robust. A cable model that used to require a supercomputer, for example, can now be run on a standard laptop and take minutes instead of days. These enhancements have opened up new possibilities for NKT's research.

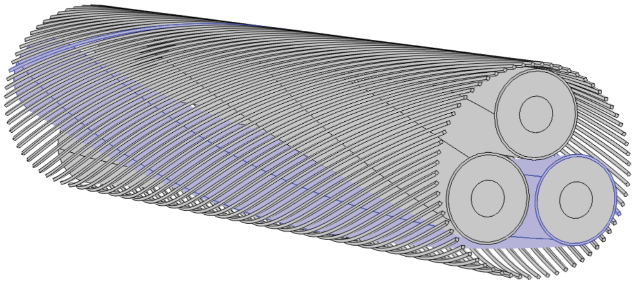

FIGURE 3 *The 3D cable model geometry, which includes the basic features of an armored submarine cable; the main conductors, the screens, and the armor.*

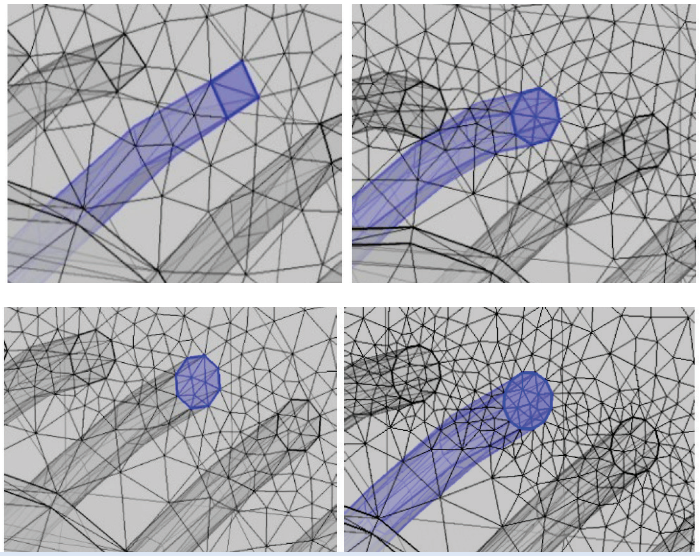

FIGURE 4 *Different degrees of meshing for the cable model, from one to four mesh elements per wire diameter.*

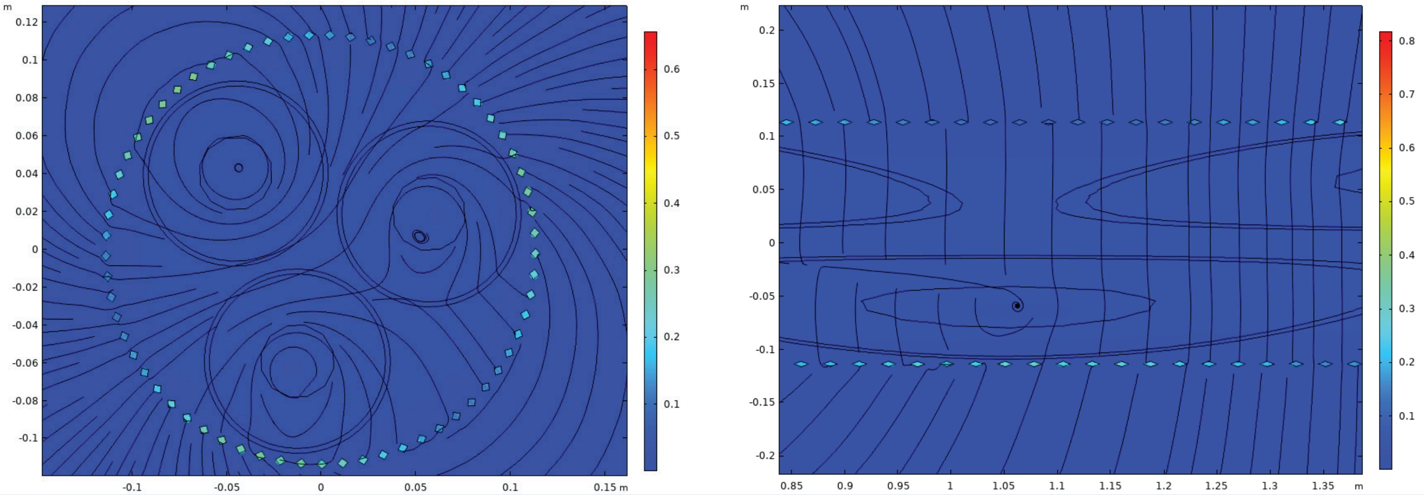

FIGURE 5 *The geometry of the 3D magnetic flux in the air gap between the conductors in the armored cable model.*

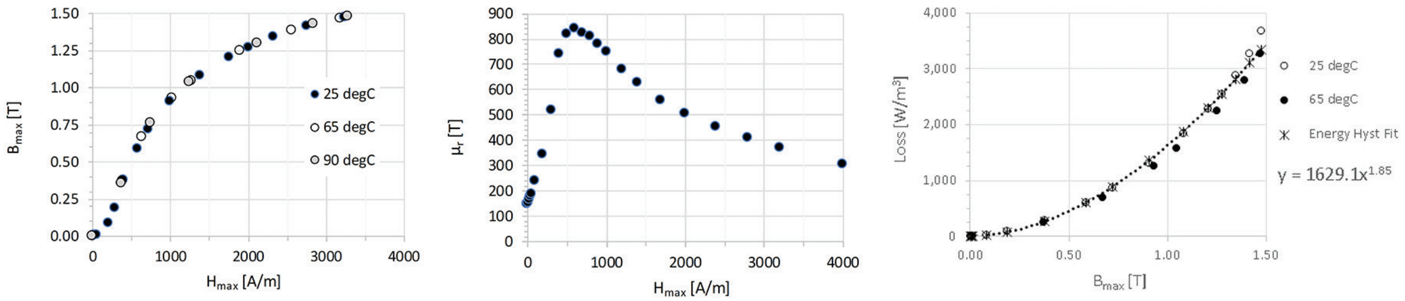

FIGURE 6 *Magnetic properties of the cable calculated from the hysteresis curves.*

MODELING AN ARMORED CABLE IN 3D

Part of the work at NKT in Karlskrona, Sweden involves the electrical simulation of cables, as well as calculating their temperature distribution and corresponding losses. In an armored cable, it is difficult to calculate the losses in the magnetic steel armor. This is because of a complex interaction between active and passive conductors, combined with nonlinear material properties (hysteresis) and temperature dependence. Further, the geometry of an armored cable model (Figure 3) includes small, detailed features, like the narrow gaps between the armor wires, leading to a large number of mesh elements, long computation times, and increased memory requirements. To address these challenges, NKT set to find out if they could use a coarse mesh for their cable model (Figure 4) while still accurately describing the nonlinear magnetic behavior of the steel material, a strongly magnetic soft steel with high permeability and large hysteresis losses.

The group turned to the COMSOL Multiphysics® simulation software, as well as the add-on AC/DC Module, which is especially suited for cable analysis. This software enables the 3D modeling of an armored cable in order to analyze the magnetic fields and compute the armor losses (Figure 5). Going back to the computational expense of cable modeling, Ola Thyrvin mentions a feature from the COMSOL® software that he found particularly helpful: the *Periodic* boundary condition, which enabled the team to model a small piece of the cable, keeping it as short as possible. The reduced size of the model saves on computational time and memory requirements that are specific to this application area, while also ensuring that all of the relevant physics are captured in the model. “The model needs to capture one conductor meeting one armor wire up until they meet again,” says Thyrvin. Another memory-saving modeling approach is the use of infinite elements, which lets the designers include a sufficient amount of air around the cable in the modeling domain, while still limiting the required mesh and memory.

INCREASED PERFORMANCE, ACCURATE COMPUTATIONS

The NKT team's modeling approach involved three main stages. First, they set up a current-driven model with predefined temperatures. The current is not affected by the cable impedance or variations in temperature and is instead controlled by the system load. Next, the team calculated the eddy current losses as losses that are induced by local currents flowing in the armor wires at the predefined temperature. They found that the losses are dominated by the screening currents around the armor wire perimeters, in the wire sections near the phase conductors. Third, they calculated the magnetic hysteresis losses by integrating a function of the magnetic B-fields over the armor wire volume (Figure 6).

In their 2019 paper "Fast Modelling of Armour Losses in 3D Validated by Measurements" at the 10th *International Conference on Insulated Power Cables* in 2019 (Ref. 4), NKT demonstrate additional ways to increase performance without significantly harming accuracy. First, even without resolving the skin depth in the armor, they have discovered that with the proper geometric correction factors and fitted material parameters, it is still possible to compute realistic loss values — typically more realistic than what the IEC standard provides, and in several cases, within the measurement accuracy.

Furthermore, while running the model with a coarse mesh, they used a uniform, real μ-value that has been fitted to experimentally obtained material data by considering only the average H-field in the armor wire, not the local one. Therefore, the permeability is not nonlinear or imaginary. Instead, it is set to the correct value for the average armor wire H-field, given the particular operating point of the cable. Once the solution has been obtained, the losses can be computed afterward as a postprocessing step. This is because from measurements, they know precisely what losses they get for a certain field intensity. So in their models, the hysteresis losses are not electrically linked to either the voltage or the current response of the cable.

To get the correct effective permeability, the team ran the 3D model for different μ-values for each modeled current. They calculated and averaged the H-values from each solution and took into account the reduction in armor wire cross section, when using coarse meshes. Then, the μ-values and average H-values were plotted on the measured μr(H) wire curve. The team found that higher μ-values meant lower average H-values in armor, and vice versa. Finally, the intersection of the curves with the measured one gave the correct effective value at the cable's operating point (Figure 7).

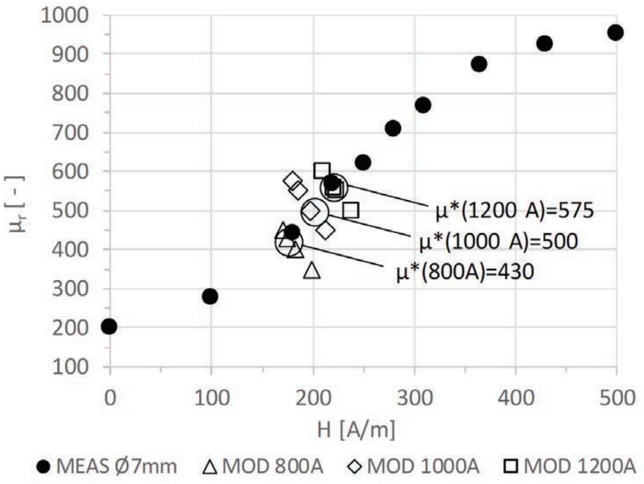

FIGURE 7 *Modeled* $\mu(H_{ave})$ *for three different currents in a cable design, as well as the measured μ-H curve for the armor wire.*

VALIDATING THE CABLE MODEL RESULTS

All of the modeling in the world will not matter, however, if the results of the model do not accurately represent the physics of the device in reality. To make sure that the simulation results for the cable analyses are accurate, Thyrvin and his team validated them with the existing cable data. When computing the armor losses of the cable, they found that the modeled results were within 3% of the losses measured from cables experimentally (Figure 8). While that sounds impressive in itself, these results are actually more accurate than the IEC standard for the type of cable being modeled, in which the total loss differs between 10 and 30% compared to measurements.

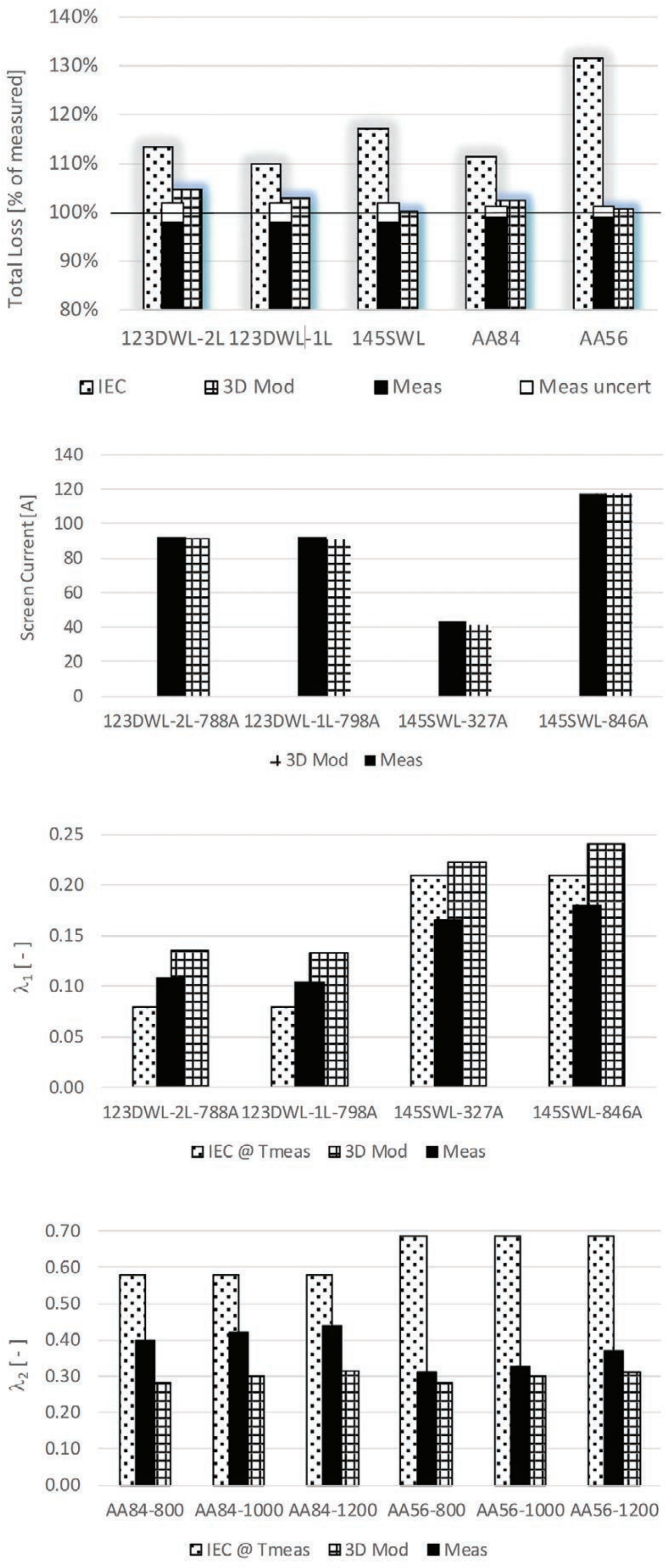

FIGURE 8 *Validated results, from top to bottom: IEC, measured, and modeled losses in five cable designs; measured and modeled screen currents; IEC, measured, and modeled values of λ_1; and IEC, measured, and modeled values of λ_2.*

PUTTING TRUST IN CABLE ANALYSES

The validated results of the 3D cable model proved to NKT that simulation is a reliable and trustworthy way to study cable designs. This knowledge has had far-reaching effects for the organization. For one, they feel confident studying cables without comparing to measurements each time, because they have already confirmed that the simulations are accurate based on the previously validated results. “We can now simulate instead of measure,” says Thyrvin. “You can simulate before making, but you can‘t measure before making.” Now, with simulation software, NKT knows how large the losses are in a cable before manufacturing, based on the simulation analyses. ◎

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SINTEX, DENMARK

MAGNETIC TRANSMISSIONS INCREASE LIFESPAN OF OFFSHORE WIND FARMS

At Sintex, multiphysics simulation is used to develop and analyze noncontact magnetic couplings. Such systems will offer significantly improved reliability, medium separation, and finding crucial roles in offshore wind turbines and chemical pumping applications.

by **ZACK CONRAD**

Whether it is an automotive engine, a wind turbine, or a wristwatch, the transmission of rotational power is important for various technological applications.

Traditionally, transmission is achieved through a series of collinear mechanical gears or shafts that transfer torque and thus power. But mechanical transmission has inherent limitations, namely a susceptibility to friction, wear and tear, and overload because of the continual contact. As the scope of technology continues to expand into more hostile and unforgiving environments, these limitations can be of extreme detriment. In places of limited accessibility and harsh conditions, replacing failed transmissions is a challenging and tremendously costly task.

POWER TRANSFER WITHOUT THE FRICTION

Engineers at Sintex have developed an innovative alternative that provides robustness and reliability: magnetic couplings. The essence of these couplings is that the power transfer is achieved via magnetic forces, rather than mechanical forces, therefore removing contact and wear and tear and drastically improving the lifetime of the transmission system. Power is transmitted through a torque coupling between concentric arrays of permanent magnets (Figure 1). A power source causes one drive to rotate, while the coupling of the magnetic fields between the drives causes the other to rotate with the same speed. This system allows rotational power to be transferred just as in mechanical transmissions but without the friction and risk of overload. If the torque transferred from the motor is too high, the coupling will limit excessive amounts from being applied to the shaft. This limit prevents the shaft from undergoing torque values greater than what it was designed for, thus assuring operation in its intended conditions.

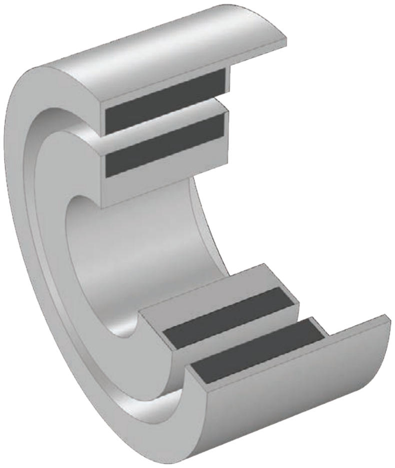


FIGURE 1 *Schematic of a magnetic coupling.*

Sintex's noncontact magnetic couplings are ideal for their customers in offshore wind turbines and industries that employ complex pumping systems. Offshore wind farms are becoming increasingly integral with their generation of electricity, but require high levels of reliability in their components because of how difficult these parts are to repair. In individual turbines, magnetic couplings transfer energy from the motor to water pumps that cool the electrical components 24 hours a day. As these offshore systems involve such remote installations, preventative maintenance or repairs are burdensome and expensive, making the reliability of magnetic couplings invaluable. In addition, the air gap between drives easily accommodates the insertion of a separator can (Figure 2), allowing for media separation and closed systems for use in chemical and food industries. Pumping systems that are completely devoid of leakage are critical for the transport, mixing, stirring, and grinding of chemicals and toxic materials.

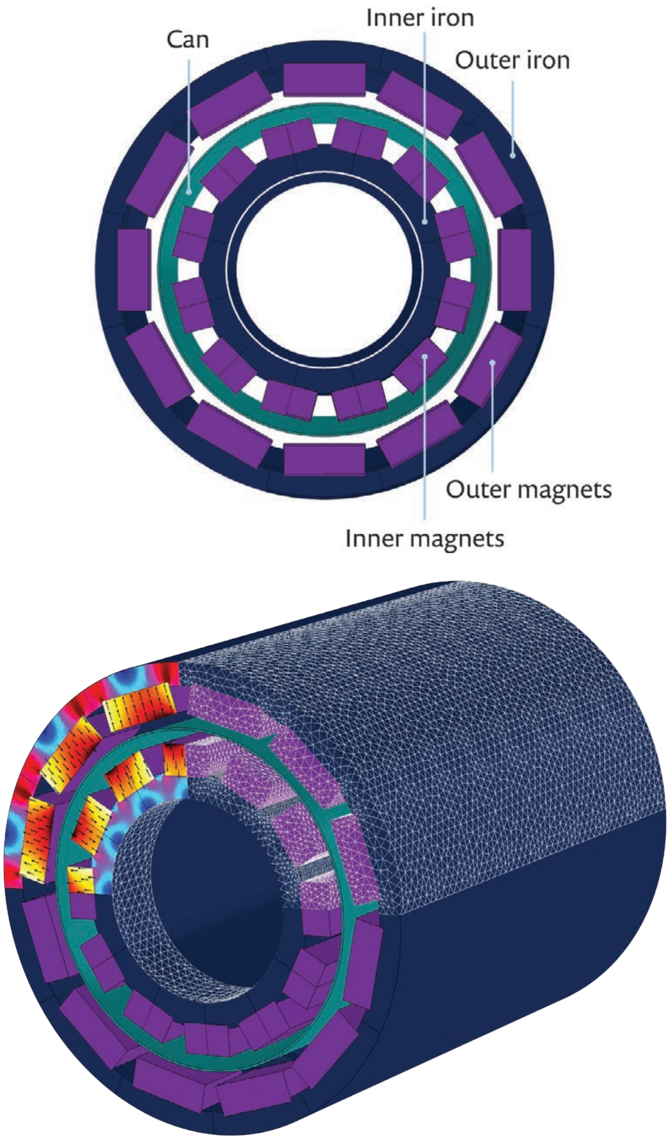


FIGURE 2 *Top: Front cross-sectional view of a magnetic coupling. Bottom: 3D model of a magnetic coupling (the temperature distributions of the magnets, magnetic flux densities through the iron, and mesh are shown).*

MAGNETIC COUPLINGS ACROSS INDUSTRIES

Sintex's magnetic couplings are employed in a diverse range of applications and must be individually tailored based on given constraints, which can include weight or material requirements and geometric restrictions. During the design process, engineers need to be able to interchange shapes and materials of magnets to meet their customers' requirements without having to build physical prototypes, as magnetic prototyping is costly and time consuming. In order to save time, Sintex uses multiphysics simulation to characterize configurations and provide virtual prototypes of designs. Flemming Buus Bendixen, a senior magnet specialist at Sintex, has used finite element analysis for twenty years, with COMSOL Multiphysics® as his primary tool of the last decade.

"One of the big advantages of COMSOL from my point of view is that you can do many kinds of simulations; you can include many kinds of physics and these physics can interact with each other," said Bendixen. His team has a plethora of incredibly thorough and complex models and because of the intense verification and validation that the models undergo, the team now places full trust in them. This not only saves time but also reduces the price for customers and allows a greater emphasis to be placed on the finer details.

ELIMINATING RISK WITH NEW DESIGNS

Using multiphysics simulation Bendixen studies the interactions between the drives of a magnetic coupling and calculates the torque transmission from the outer drive to the inner drive. As the primary purpose of magnetic couplings is to transmit maximum torque and power along an axis, the torque transfer is the most defining characteristic; therefore, it is calculated in multiple ways, including Maxwell's stress tensor, postprocessing integral methods, and the Arkkio method. The analysis is verified through experimentation and has yielded errors as small as 1%, speaking volumes to the accuracy of the model. During the development process of a new design, the model can be used to maximize the torque transferred in a specific configuration.

Since permanent magnets and their fields give rise to numerous secondary effects, Bendixen makes a substantial effort to model them. In metals, such as the steel can in this coupling, eddy currents are generated by the external magnetic fields, resulting in electrical losses. "The shifting north and south poles create voltages across the steel; it conducts electricity and this dissipates energy from the system," explains Bendixen. These are referred to as can losses, which are simulated with postprocessing tools in the software, and need to be reduced as much as possible. The team also recently developed a machine that experimentally tests the can losses of designs and confirms the accuracy of their model to a few percent.

"We are dedicated to capturing the truly nonlinear nature of magnetism, and COMSOL allows us to do just that, assuring optimal magnetization of the array," says Bendixen. By employing highly nonlinear hysteresis curves and utilizing their own material temperature dependences for magnetic loading, the simulations (shown previously) help prevent the permanent magnets from reaching their critical temperature and becoming irreversibly demagnetized, which is paramount to assuring the reliability of their products. "It is very important to know the temperature that the magnets can withstand, and I can calculate this quite precisely," Bendixen adds. "If the magnets get too hot, they can become partially demagnetized."

Bendixen takes further advantage of the flexibility of multiphysics simulation having imported Sintex's library of magnetic materials, allowing for a vast array of custom magnetic configurations.

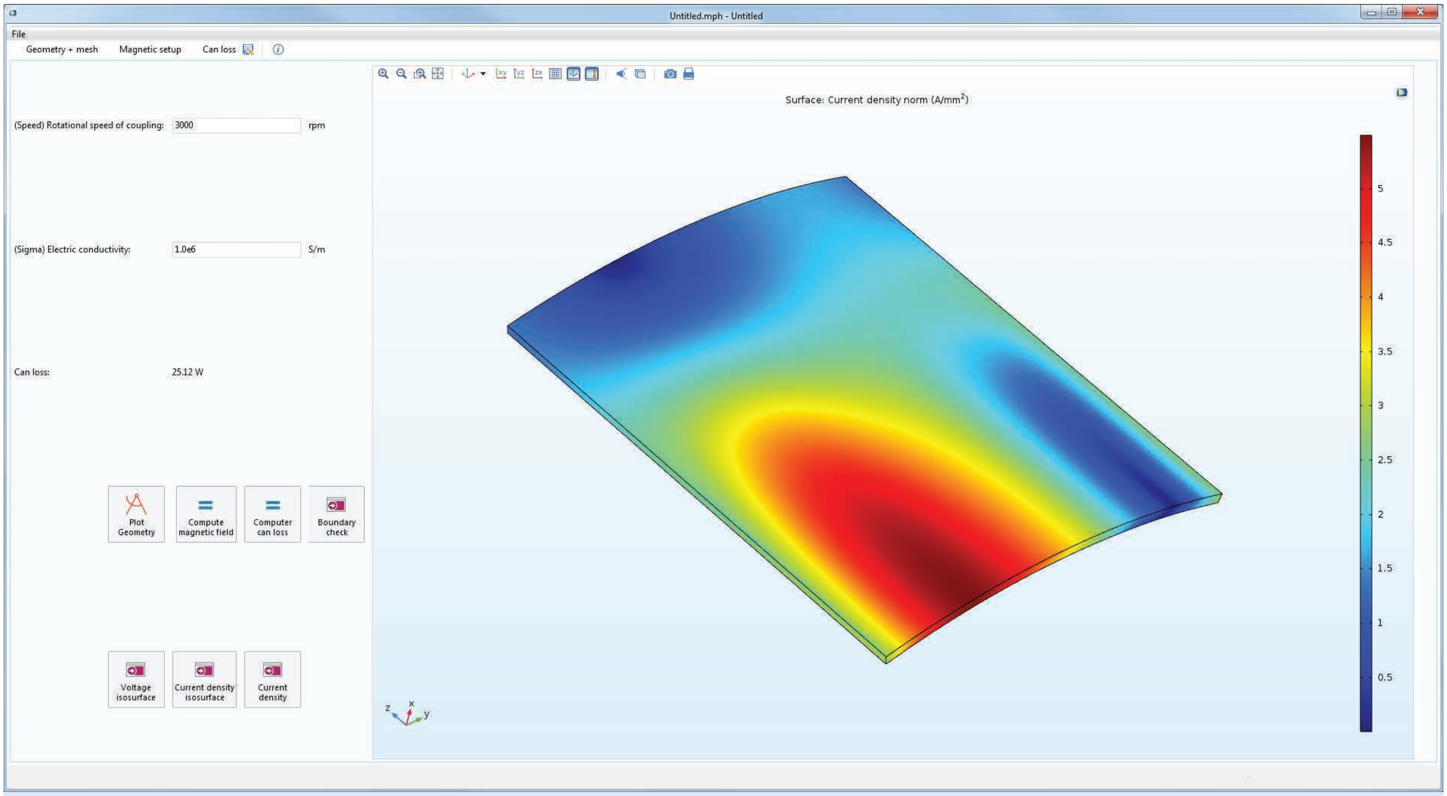
FIGURE 3 *Standard magnetic couplings.*

THE EASY BUTTON FOR SIMULATION EXPERTISE

Once Sintex was comfortable with the level of complexity in their models, the next step was to broaden their usage and make them more accessible to nonsimulation experts. Previously, when sales representatives and other colleagues that were not versed in simulation techniques needed to run tests on designs, they went to Bendixen to have all of the calculations done.

Bendixen created simulation apps based on his multiphysics models and found productivity and convenience of simulation at an all-time high. Sintex currently employs ten different simulation apps with up to twenty different users. The apps are created directly in COMSOL Multiphysics® through the Application Builder tool and can then be accessed via a web browser by connecting to COMSOL Server™. The simplified user interface and straightforward deployment provide ease of use to all of their employees. Select customers are even given access to these apps and their computational power. "I built the apps because some of my colleagues are not so skilled in simulation software and would like to do some system testing and simulations by themselves, and the apps enable them to easily do this," Bendixen says.

Simulation apps allow the user to vary parameters without having to alter the underlying computational model. "Sales people can change dimensions and perform simulations while they are on the phone with clients to verify agreement with their specifications within minutes," says Bendixen. But despite the simplicity of the interface, there is still extensive flexibility to be innovative with design iterations. Sintex's apps let the user adjust both geometric and magnetic parameters. The model then calculates the critical temperatures of the magnets, remanence distributions, magnetic field flux densities, torque, and can losses. Figure 4 is an example of an app that simulates the eddy currents generated in the separator can. These currents can then be used to calculate the resulting power loss. Now, people at all stages of development can contribute to the design process and help maximize reliability in their products.



(Speed) Rotational speed of coupling: 3000 rpm

(Sigma) Electric conductivity: 1.0e6 S/m

Can loss: 25.12 W

FIGURE 4 *This portion of the simulation app models the induced eddy current density in the can and calculates the resulting energy loss.*

LOOKING AHEAD

Sintex is also developing a novel magnetic reluctance gear, which will expand the application range of gears in general. In addition to offering reliable, noncontact magnetic transmission of torque, these gears can alter the speed or torque between drives, allowing for mechanical advantages to be created with fixed gearing ratios. In a unique design feature, these gears will incorporate a single permanent magnet with a magnetization parallel to the shafts, greatly simplifying assembly and enabling a high degree of customization. And with simulation apps involving more people in the analysis process, Bendixen can spend more time making consistent improvements to all of Sintex's magnetic technologies. ◎

NTS, PITTSFIELD, USA

MULTIPHYSICS PROTECTS WIND TURBINES WHEN LIGHTNING STRIKES

Multiphysics simulations help NTS engineers understand what happens when lightning strikes a wind turbine.

by **GARY DAGASTINE**

As the world moves to reduce its dependence on fossil fuels, the global market for wind turbines is growing, projected to reach around $70 billion dollars annually in the next few years. While wind power on such a scale is a great achievement, another powerful force of nature is preventing the industry from reaching its full potential: lightning.

Lightning strikes are the single largest cause of unplanned downtime in wind turbines, responsible not only for the loss of untold megawatts of power but also for huge operation and maintenance costs.

Wind turbines are particularly susceptible to lightning strikes because of their great heights, exposed locations, and large rotating blades. Lightning can wreak havoc, both directly and indirectly, on virtually all wind turbine components, including blades, control systems, and other electrical components. Repair is not only expensive but also physically challenging given the logistical constraints.

Lightning Technologies, an NTS company, is a world leader in the design and validation of sophisticated lightning protection systems for the aerospace industry, including aircraft, space vehicles, and launch facilities. They also developed systems for wind turbine farms, industrial complexes, golf courses, theme parks, and other high-risk locations.

Engineers at NTS are actively involved in the committees that form the International Electrotechnical Commission (IEC) , which define the lightning levels and situations that blades must endure. Industry regulations such as IEC 62305 require wind turbine manufacturers to incorporate lightning protection designs into their blades. For maximum protection, it's essential to know how much lightning current is likely to flow through a blade following a lightning strike and precisely where it will flow. The problem is that simple assumptions about the behavior of lightning current often lead to inaccurate conclusions.

FIGURE 1 *High-voltage generator (2.4 MV Marx generator) operated by NTS.*

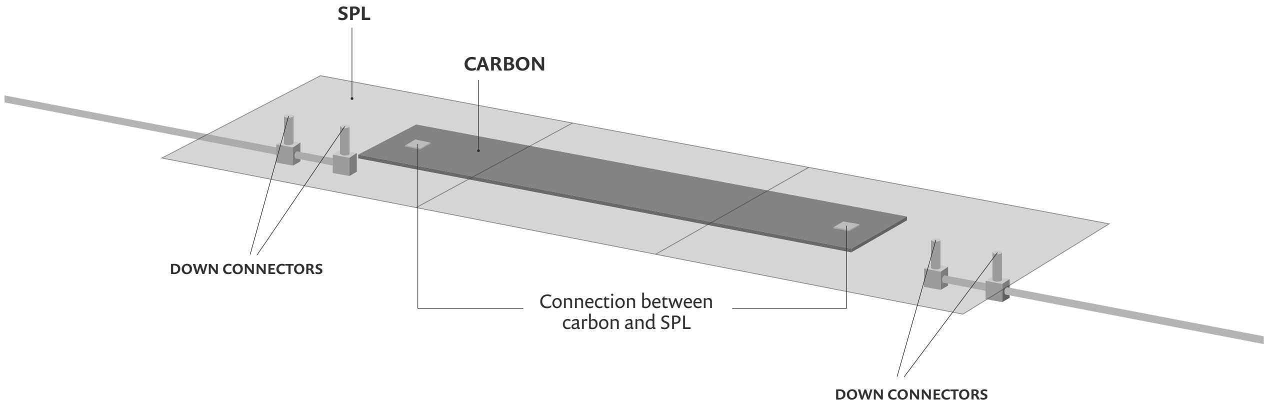


FIGURE 2 *Geometry of the thin aluminum surface layer protection (SPL) placed on top of a carbon stack.*

DEEP INSIGHTS INTO LIGHTNING CURRENT

NTS operates one of the most complete lightning simulation laboratories in the world from an 18,000 ft^2 facility in Pittsfield, MA, USA, featuring 14- and 25-foot tall lightning generators capable of generating as much as 2.4 MV (Figure 1).

NTS has been involved in the research and development of protection designs for wind turbine blades for decades. Because wind turbine blades are airfoils, the company's deep knowledge base of aerospace applications is directly transferrable.

Justin McKennon, who leads the Modeling and Analytical Team at NTS Pittsfield, said that traditional wind turbine protection schemes consist of a surface protection layer (SPL) covering the lightweight, high-strength carbon fiber composite blades. Often, the SPL consists of a conductive mesh meant to safely carry lightning current from the point where it "attached to" (e.g., hit) the blade and then from the root to the ground.

"Many blade architectures feature stacked carbon fiber structural layers running parallel to the SPL, with periodic electrical connections between the stack and the SPL all along the blade's length," McKennon explains. "This is done to prevent a high voltage potential from developing between the two, because if that should happen, arcing could occur and damage the blade. However, while these electrical connections can reduce voltage, they also allow current to flow in the carbon, which creates additional design considerations."

Understanding a carbon stack's ability to carry various amounts of current, along with other factors such as likely attachment points and puncture possibilities, isn't trivial. McKennon said that given the cost to physically test these blades, some of which are 70 or more meters long, the numerical modeling of lightning effects has become a crucial part of the design process.

"Because of the complexity of the physics involved, though, it's easy to make improper assumptions that can have a large effect on the accuracy of the models," McKennon says.

SIMULATION REDUCES OVERENGINEERING

One common but improper assumption is to assume that the carbon stack's conductivity is the same in all directions, even though in reality there could be significant differences in carbon's conductivity along different directions. Figure 2 shows the geometry of a carbon stack placed 5 mm below a 500-µm-thick SPL mesh made from an aluminum sheet, whose conductivity is set according to experimental measurements. The carbon's conductivity is also set according to experimental values, both its idealized isotropic and realistic anisotropic behavior have been considered in the COMSOL model.

An analytical representation of an IEC-standard current waveform is used to inject current into one end of the SPL. The current exits at the opposite end through a down conductor, which is made of copper, as are all of the connections to the carbon.

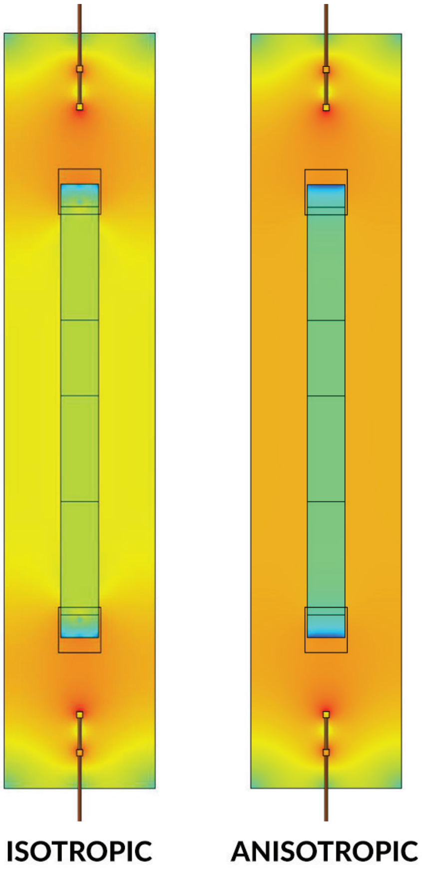


FIGURE 3 *Simulation results showing that the amount of current in the SPL in the idealized isotropic case is significantly less than the realistic anisotropic case.*

To investigate his designs and model the propagation of electromagnetic pulses, McKennon solved a time-domain wave equation for the magnetic vector potential in the COMSOL Multiphysics® software. The results enabled him to determine the associated currents, electric fields, and other values at those points, providing insight into the current's overall behavior throughout the entire structure.

The isotropic case underestimates the amount of current traveling through the SPL, implying that more current is traveling in the carbon and not in the SPL (Figure 3). Carbon is made up of many layers of individual fibers. It is very conductive in the fiber direction, but getting current into and out of the carbon is very challenging. If too much current has to pass through an interface between the carbon and something else, many of the individual fibers in the carbon can be burned away through heating and/or arcing (Figure 4). Carbon bears the primary structural loads, and damage here greatly reduces the lifetime of the blade and, in some cases, can lead to catastrophic loss of the blade. More current in the carbon is something engineers want to seriously avoid.

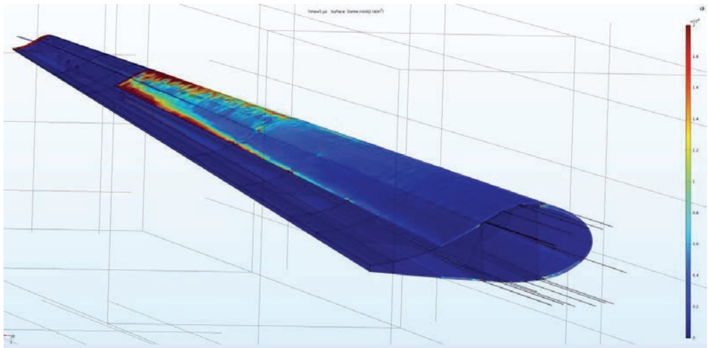


FIGURE 4 *A visualization of a satellite in orbit, showing the position and orientation relative to the Sun and Earth as well as the irradiation onto the satellite's exposed faces. Earth image credit: Visible Earth and NASA.*

The isotropic case grossly overestimates the amount of current in the carbon because it ignores the very real orientation-dependent resistances in the carbon (Figure 5). Thus, given its large volume and comparable length, the carbon seems to be a more preferred current path than the SPL, even though it isn't in reality. Such an overestimate would introduce additional challenges that are not present, thus slowing down the development process and leading to an overengineered product.

McKennon says, "In modeling such complex physics, you really have to know what's important and what's just noise, and you must build your model carefully in a step-by-step fashion so that no errors or false assumptions are introduced that can significantly affect your results."

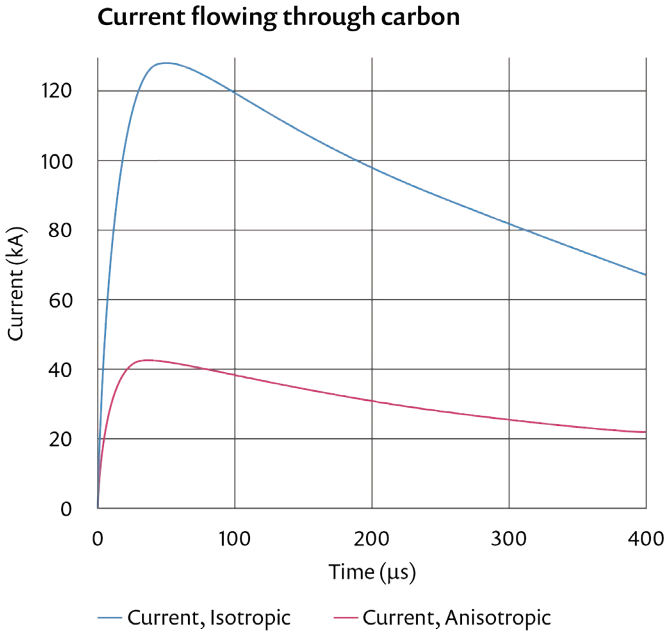


FIGURE 5 *A plot demonstrating the current levels in the isotropic and anisotropic carbon cases.*

RELIABLE RESULTS FOR BUSINESS DECISIONS

"Our ability to rapidly simulate and turn around models greatly reduces program risk and allows for engineering level data to be obtained almost in an on-demand fashion," says McKennon. "Rather than spending considerable amounts of time and money fabricating complex test articles, we can use COMSOL to simulate the physical phenomena and drastically reduce the problem scope for these projects. In many cases, critical data simply cannot be measured on real test articles, which requires simulation and analysis to fill in these holes."

"Time is money in our industry, and our customers are very pleased with the service we are able to provide thanks to these capabilities. In fact, some customers are so confident in the validity of our simulations that they have begun to make wholesale business decisions based solely on our results, with little experimental verification. With that much at stake we simply cannot afford to make mistakes, and COMSOL is a valuable tool that we trust to deliver real-world accuracy." ◎