NICE Future
Nuclear Innovation: Clean Energy Future
An Initiative of the Clean Energy Ministerial

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

BREAKTHROUGHS

NUCLEAR INNOVATION IN A CLEAN ENERGY SYSTEM

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Nuclear Innovation in a Clean Energy System

A product of the NICE Future Initiative under the Clean Energy Ministerial

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About the NICE Future Initiative

The NICE Future Initiative is an international collaboration that envisions a world in which nuclear energy innovation and uses advance clean energy goals. Its members are Argentina, Canada, Japan, Poland, Romania, Russia, United Arab Emirates, United Kingdom, and the United States.

This publication is available in other languages. Find out more at www.nice-future.org

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

About the Clean Energy Ministerial (CEM)

CEM is a high-level global forum to promote policies, programs, and learning to advance clean energy technology.

Find out more at www.cleanenergyministerial.org

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BREAKTHROUGHS

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MESSAGES FROM...

DR. FATIH BIROL

Executive Director, International Energy Agency

The International Energy Agency is committed to a secure, sustainable and economically efficient energy system. We firmly believe in the importance of an "all fuels, all technologies" approach in tackling sustainability and energy security challenges. While global CO_2 emissions reached a historical high in 2018, the large majority of the 38 key technologies covered by our *Tracking Clean Energy Progress* report remain off track. Unfortunately this includes nuclear power as well.

Electricity is the cornerstone of clean energy transitions. Electricity generation today is the largest source of greenhouse gas emissions and a major contributor to local air pollution. Cleaning up electricity supply is an essential step towards decarbonising the energy system. Despite impressive growth in deployment of wind and solar PV, growth in renewables generation still significantly lags global electricity demand growth.

IEA analysis, including *Nuclear Power in a Clean Energy System* which was showcased at the 2019 Clean Energy Ministerial in Vancouver, shows that nuclear power—as a dispatchable, energy dense, low carbon source of electricity—can play a key role in transitions to a cleaner energy future.

Today's nuclear power technology, though mature, faces major challenges. Decade long project lead times, serious project management risks, and limited operational flexibility, mean that nuclear power plants are not always an obvious fit in a transforming energy system. Innovation is needed to overcome these limitations. New reactor designs offer the prospect of modular construction that will be inherently safer, easier to finance and less risky to build, with flexible operations to complement renewables in a cleaner electricity system. There is a clear need to accelerate innovation and deployment of these new designs through appropriate government—industry cooperation. The NICE Future initiative's work on nuclear innovation is both timely and complementary to that done by the IEA.

WILLIAM D. MAGWOOD IV

Director-General, Nuclear Energy Agency

Energy has been both the source and the result of human progress since the day we first learned to make and control fire. With charcoal, we learned to smelt and shape iron. With coal and oil, we launched the industrial revolution and brought light to city nights. We learned to harness the wind, the flow of rivers, and the light of the sun to generate electricity.

But perhaps the single most impressive technological achievement of our species began when Albert Einstein published his equations showing mass–energy equivalence: the famous $E=mc^2$. His theories ignited an international wave of research and advancement, the like of which had never been seen before.

Otto Hahn, Lise Meitner, and Fritz Strassmann discovered atomic fission and in a few short years, theory became science; science became technology; and technology became electricity—electricity and progress. Under responsible stewardship, nuclear energy and the technological advancements that came with it helped rebuild Europe, Japan, and Korea after the Second World War and were an important part of the economic expansion of Canada and the United States in the post-war period.

The world is now poised for a new era of research, discovery, and progress. Rather than rebuilding after war, we today face a far greater challenge: powering modern societies and providing a path for people in all countries to enjoy better, healthier lives—and doing so while preserving the environment.

As before, nuclear technology is poised to be part of a future with plentiful, clean, reliable energy for all the world's people. The innovations to bring this vision to reality are before us. The work for the future begins here and it begins now.

DR. STEVEN PINKER

Johnstone Family Professor of Psychology

Humanity is standing at a crossroads. Over the past few decades, global development has brought about a massive reduction in extreme poverty worldwide, together with reductions in other scourges such as disease, illiteracy, crime, and war. One driver of this progress has been the abundant and affordable energy that has powered hospitals, schools, transportation, and the rest of the infrastructure of modern society. Yet our survival as a prosperous global civilization is at risk precisely because of the unintended consequences of this cheap energy, namely the waste from burning fossil fuels, which currently provide over 85% of global primary energy.

For poor countries to become richer, they must have access to affordable energy—yet the world must transition to carbon-free energy technologies. World energy consumption will and should rise. The question is how: how can we decarbonize our energy systems rapidly while expanding power for the people?

While everyone loves renewable energy with hypothetical storage technologies, all too often the most abundant and scalable carbon-free energy source is overlooked and often stigmatized: nuclear power. Nuclear's tremendous energy density and dispatchability make it an ideal complement to variable renewables such as wind and solar, and experts who do the math agree that we'll need to use all the tools available to transition to 100% clean energy. Though today's nuclear technologies must be on the world's decarbonization road map, we needn't be shackled to the technologies of the 20^{th} century indefinitely. Advances in the size, scale, safety, affordability, and sustainability of nuclear power are remarkable, and they promise nothing less than the means by which we can save the world.

KÁRA MCCULLOUGH

Founder, Science Exploration for Kids (SE4K)

Breakthroughs inspires us, leading us towards exciting and innovative nuclear energy solutions and options to meet the tremendous challenges of today and the future, around the globe.

Exciting advances in nuclear energy and its safety are causing the clean energy community to renew its interest in this technology, as nuclear energy is the workhorse of clean energy systems. Nuclear energy generates nearly a third of the world's non-emitting electricity (no carbon dioxide, sulfur dioxide, mercury, or particulates that cause smog.) Countries seeking clean energy solutions and moving aggressively towards renewable energy can now look to new approaches to achieving clean air goals by not seeing it is as a choice of "nuclear or renewables" but rather one of "nuclear and renewables."

My lifelong passion has been inspiring the budding scientists of our young generation. As our children grow, our world will need much more non-emitting, clean energy to sustain our planet, and the young generation will need to rise to this technology challenge through the power of invention. Visionary concepts and options for advanced nuclear systems, such as those in Breakthroughs, can help meet a variety of needs, both electric and non-electric. Integrated nuclear-renewables systems, desalination for clean drinking water to meet a leading global imperative, process heat, flexible electricity grids, hydrogen for transportation, energy storage and advanced designs, such as small modular reactors, are available and can provide options for areas of the world that may have never considered these technologies before.

Technological innovation and inspired education of the next generation of our youth are key parts of the solution to our technological and social challenges.

Kára McCullough, crowned Miss USA in 2017, started her career as a scientist at the Nuclear Regulatory Commission, working to ensure the safety of the U.S. nuclear fleet. Leveraging the Miss USA platform, Miss McCullough has been an inspiration to the young generation, founding a youth STEAM (science, engineering, arts ,and math) nonprofit called "Science Exploration for Kids," which inspires the next generation of scientists and engineers to embrace and celebrate scientific discovery in their lives through unique "fun with purpose" activities.

INTRODUCING *BREAKTHROUGHS*

This is the story of nuclear innovation as an enabler of global clean energy systems.

Nuclear energy is an important part of global energy supply. It is an emissions-free source of reliable, baseload electricity that currently produces one-third of the world's non-emitting electricity. More than 440 nuclear reactors are currently operating in 30 countries, with about 60 more reactors presently under construction.

To meet global clean energy objectives, modelling by the International Energy Agency estimates that global nuclear energy generation will need to nearly double by 2040.

This will require refurbishment of existing reactors around the world, some of which are already completed or underway. In the next two decades, the global market for new nuclear power is estimated at $2.6 trillion.

CLEAN ENERGY CROSSROADS

At the same time, the world is in the midst of a fundamental change in the way we power our societies.

The need for clean, reliable energy is growing globally. Alongside other renewable sources, society is increasingly powered by larger shares of variable renewable energy from wind and solar. The electrification of end-uses such as transportation that have traditionally relied on fossil fuels is bringing new sources of demand to increasingly decentralized and dynamic electricity grids. The very nature of the electricity grid is evolving too, as technologies become available that allow traditional consumers to produce or store electricity, and sell it back to the grid.

Beyond electricity, meeting global clean energy goals will require radical changes in other industrial sectors, including transportation, manufacturing, and agriculture. Many of these changes require new solutions—such as carbon capture, utilization, and storage—that go beyond options available today.

Energy systems of the future must also retain the confidence of the people and communities they serve. Energy systems need to remain affordable, safe, secure, sustainable, and reliable, and be implemented on a foundation of certainty and trust that protects the public and the environment.

NUCLEAR AS AN ENABLER OF CLEAN ENERGY

Countries will need multiple energy options to meet these challenges; nuclear energy systems can be part of the solution.

The model of nuclear energy as a large, central source of baseload electricity is changing. In some areas, markets are signalling for smaller, simpler, lower-cost nuclear energy systems. And in many countries, there is a greater emphasis on private sector development of technologies and projects.

There is an important story that has not been told in the broader clean energy dialogue: the story of nuclear innovation and the opportunities it can seize to complement and enhance tomorrow's clean energy systems.

This book tells that story.

ABOUT THIS BOOK

This isn't a typical policy report. *Breakthroughs* is a collection of stories of nuclear innovations and how they enable clean energy systems.

Each story is a short introduction to a new and exciting innovation that is here already, or is expected to be available in the near term.

The goal of *Breakthroughs* is to spark imagination and challenge ideas on what nuclear energy's role could be in energy systems of the future.

Three important points about this book

1. First, this is not just a technology story. In many cases, the key innovations lie in economic and social innovation—from disruptive business models to new models for engagement and gaining public confidence.
2. Second, the focus of this book is near-term innovation. The stories are not science fiction. The examples in this book intentionally focus on realistic, near-term applications of innovative technologies and systems. Many of these innovations already exist and are being implemented.
3. Third, *Breakthroughs* is a starting point for an examination of how nuclear energy can complement the broader clean energy sector. It is meant to capture your interest, spark your imagination, and challenge your conceptions of what nuclear energy can be.

Breakthroughs brings the story of nuclear energy as an enabler of clean energy systems to the broader discussion underway at the Clean Energy Ministerial. It highlights opportunities to build stronger, cross-sectoral partnerships through the "Nuclear Innovation: Clean Energy Future" (NICE Future) initiative. And it reveals the important role that nuclear energy can play in bringing about reliable, affordable, and clean energy systems of the future.


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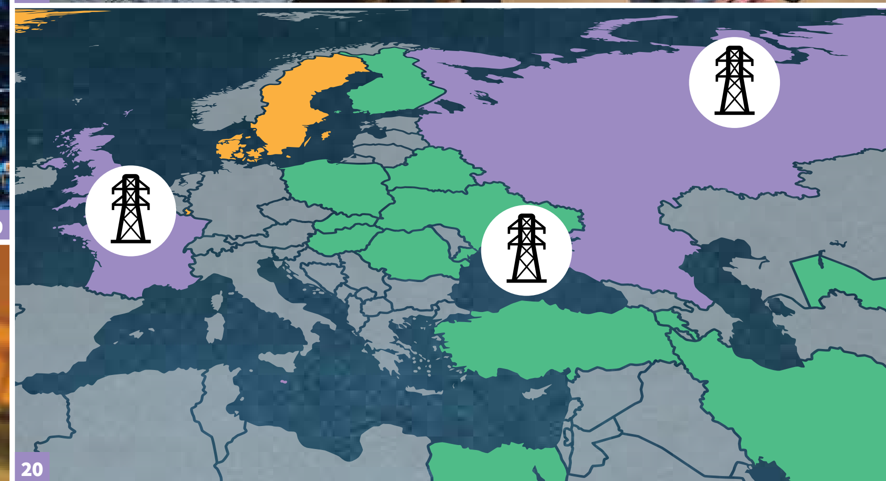
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CHAPTER 1
Non-Stop Innovation

Nuclear energy has always been an innovation story.

Existing and planned nuclear power plants are achieving breakthroughs in inherent safety, advanced manufacturing, and fuel design to cut costs, improve performance, and enhance flexibility.

Innovators are demonstrating solutions to long-term waste management built on trust and best-in-class approaches to community engagement.

And on the horizon, Small Modular Reactors are an emerging area of innovation—supported by a diverse, passionate workforce of next generation leaders, that could be a game-changer for nuclear energy.

TOPICS

Engineers survey nuclear power plant operations using a modern digital control system interface. Power plants today use information systems and digital monitoring to increase productivity, ensure reliability, and enhance safety.
Source: Idaho National Laboratory

INHERENT SAFETY TODAY

Transforming the safety paradigm

Forget what you thought you knew about nuclear safety. Just like most everything else, nuclear power plants are being transformed by innovation—from digital technology, to robotics and artificial intelligence. Today's plants don't just protect against risks, in some cases, the risks are being eliminated altogether.

From how we run our cities, deliver healthcare, get information, and produce our food, transformative change has swiftly occurred, even if the changes are not always immediately visible.

Take the automobile, for example. From the outside, it appears similar to those of 40 or 50 years ago, minus the hood ornaments, wood paneling, and pop-up headlights. But today's car would feel more like a space station to a driver from the 1970s or even the 2000s. Modern automobiles are equipped with extensive safety systems—back up cameras, lane departure, blind spot sensors and other sophisticated technology that can rescue stranded motorists or help navigate you to the closest restaurant at the command of your voice.

Just as automobile manufacturers have used evolving technology to bolster safety and efficiency, so has the nuclear industry. The nuclear engineers of yesterday would find the changes at their nuclear facilities mind-blowing right from the moment they walked in. They would enter through sophisticated security systems with biometric hand geometry scanners into a plant where increasingly, jobs once done manually are completed with robotic equipment and digital sensors.

"The nuclear industry embraces research and innovation as a valuable investment," says Dr. Fiona Rayment, Executive Director, Nuclear Innovation and Research Office (UK).

Collaborative research and development is ongoing at national labs, universities, vendors and utilities.

Advanced information technology systems have played a significant role in transforming plant operations. Some plants now use digital monitoring to identify maintenance needs long before a problem ever occurs. Wireless sensors and pattern recognition software identify when calibration is required, allowing maintainers to work on equipment as needed rather than an arbitrary time period increasing productivity and reliability, two precursors to safety.

The use of robots to perform tasks in radiological areas has been another transformation in improving worker and plant safety. Operators who once suited up for work in highly-challenging and uncomfortable conditions are now operating robots from a command centre. The robots' built-in cameras and digital diagnostic systems give the operators far greater precision than the human eye, all at a safe distance from radiation.

Virtual reality platforms are allowing workers to practice and perfect tasks they'll perform before ever entering the plant. Tools and equipment can be tested in exact conditions and modified for greater performance in this same simulated environment.

"Innovation will drive the pace of change required through solutions that enhance economic performance, while continuing to underpin a strong and sustainable safety culture," says Dr. Rayment.

Retrofitting plants with new parts, systems and technologies is today's transformative change. And, the future holds further promise as innovative, advanced reactor designs change the paradigm yet again.

Community consultation and engagement by Canada's Nuclear Waste Management Organization (NWMO).
Source: NWMO

The Onkalo deep geological repository in Okiluoto, Finland.
Source: Posiva

WASTE MANAGEMENT

Trust and two billion year-old bedrock

To safely store waste from nuclear reactors, countries are turning to community-driven processes built on trust, collaboration, and rock-solid science.

At a time when the first signs of life on earth were making their debut, underground veins of uranium in what is now Oklo, Gabon began to fission. The same fission reaction occurs in a modern nuclear reactor, but in Oklo it occurred all by itself—a self-sustaining nuclear chain reaction that lasted for several hundred thousand years.

This completely natural reactor produced tonnes of what we would call nuclear waste if it were produced by a power plant. Due to the stability of the rock formation, that "waste" has remained immobile and isolated from the biosphere over billions of years.

Today, the construction of deep geological repositories to deposit the waste produced by nuclear reactors—as is being completed in Olkiluoto, Finland—in many ways is an analogue to the isolation experienced by Oklo's natural waste, but with a few extra barriers thanks to modern engineering.

"It's dusty and dark. It just looks like a mine," says Kai Hämäläinen of the Finnish Radiation and Nuclear Safety Authority, the country's nuclear regulator.

At Olkiluoto, spent nuclear fuel is to be deposited half a kilometre deep in the almost 2-billion-year-old bedrock. Studies have confirmed that this ancient bedrock has been stable all that time—despite earthquakes and ice ages—and claim that it will continue to be so.

In addition to the bedrock, bentonite clay will be used in the tunnels to protect the fuel even if any jolts were to happen. The fuel will be packed into a cast iron canister and placed in a copper sleeve. Copper is one of the most stable substances on earth, and does not corrode over time the same way other materials do. Metallurgists say that the copper sleeve will last at least a million years under the conditions at Olkiluoto.

And even if all other barriers fail, the fuel itself is in a ceramic form that would take millions of years to break down in water—long after the radioactive material inside ceases to present any health risks.

How can the local community trust these assessments? A combination of rigorous verification with external third parties and a long-standing relationship with the regulator built on trust. "We have been very open and active in the community," Kai says, stressing that the process started as far back as 1983.

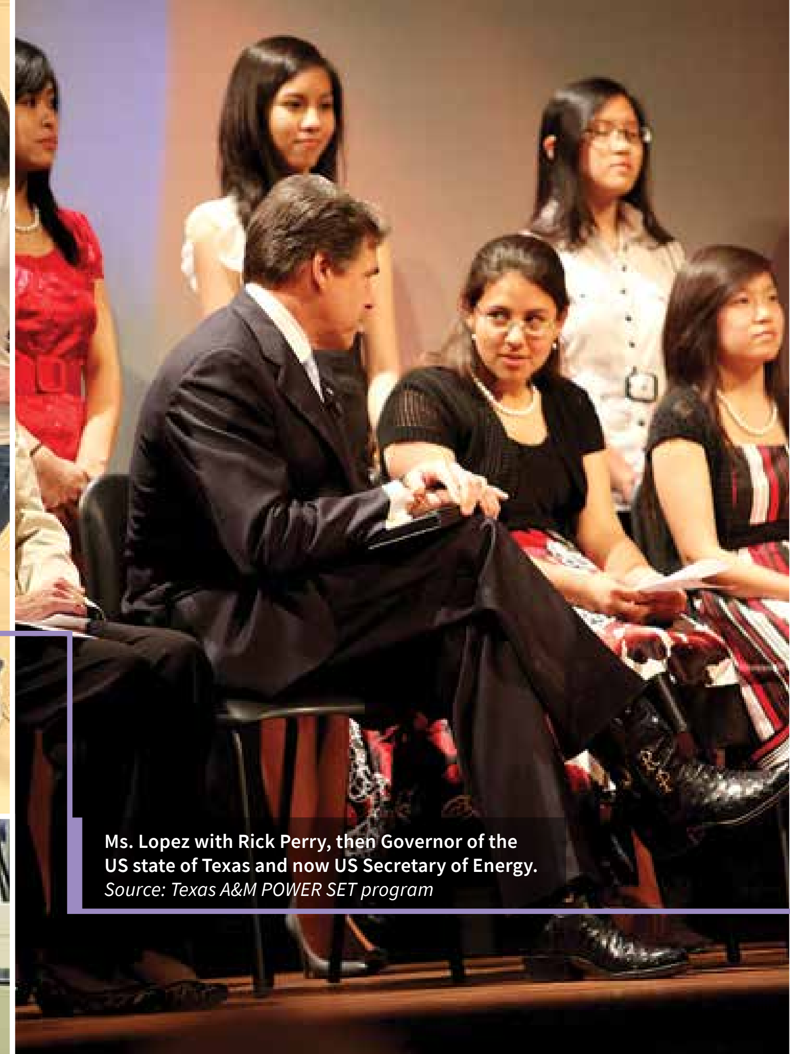
"People are used to a nuclear plant and feel kind of responsible for the waste created on this site, but it's also important to have independent verification". It's about trust in the regulator, he says. "It wouldn't work if we were on the same side as the licensee [the operator of the nuclear plant]."

You might wonder if Finland is an exception. After all, who would want to locate a nuclear waste repository in their backyard? But this community-driven, collaborative approach is being adopted in other parts of the world.

In Canada, for example, 22 communities voluntarily responded to a call to learn more about hosting a repository for the country's spent fuel. Today, after narrowing its focus through study and engagement, Canada's Nuclear Waste Management Organization is working with five communities to select a preferred site. The communities can opt out at any time, but they choose to remain involved because they see benefits and want to learn more.

This community-driven collaborative process has been a democratic policy innovation as crucial as any advance in engineering and technology to making a permanent solution for nuclear waste a reality.

Ms. Lopez participating with other students in the POWER SET program.
Source: Texas A&M POWER SET program



Ms. Lopez with Rick Perry, then Governor of the US state of Texas and now US Secretary of Energy.
Source: Texas A&M POWER SET program

GIRL POWER

Elizabeth Lopez

When Elizabeth Lopez was in high school she liked mathematics, but also English and writing. Then an exciting program came to her high school: Powerful Opportunities for Women Eager and Ready for Science, Engineering & Technology (POWER SET). Today she has a Master's degree in nuclear engineering.

"When they recruited me, I didn't know what I wanted to do," said Lopez, now 26, "They took us around to these plants." The tours included many of the industrial centers in the Gulf Coast of Texas, where Lopez lives: chemical and oil plants, the NASA headquarters, and the South Texas Project, a nuclear power plant.

Among the high points was a visit to the POWER SET program at her high school by Rick Perry, then Governor of the U.S. state of Texas and now Secretary of Energy for the United States. "They asked one of us in POWER SET to write a speech and to give it. I was the one who did that, and I got to meet him there. The principal took some pictures. They always joke around that we're like good pals.

"That was pretty impressive," she said.

The program, run by the Nuclear Power Institute at Texas A&M University, is offered at eighteen high schools in Texas, and is not limited to nuclear power. But it demonstrates the appeal of a nuclear energy program in stimulating young people's interest in technical fields. Often these are people who might not ordinarily gravitate in that direction; in the United States and in many other countries around the world, women are still under-represented in technical fields.

POWER SET offers technology and engineering mentorship opportunities to girls, including trips to universities. Perhaps most influential for Lopez were the talks with engineers working at all the places they visited. "They brought out people to talk to us, to answer questions. They set up all of us with someone from the South Texas Project to talk to. We could ask questions about the power plant or just work in general," she said.

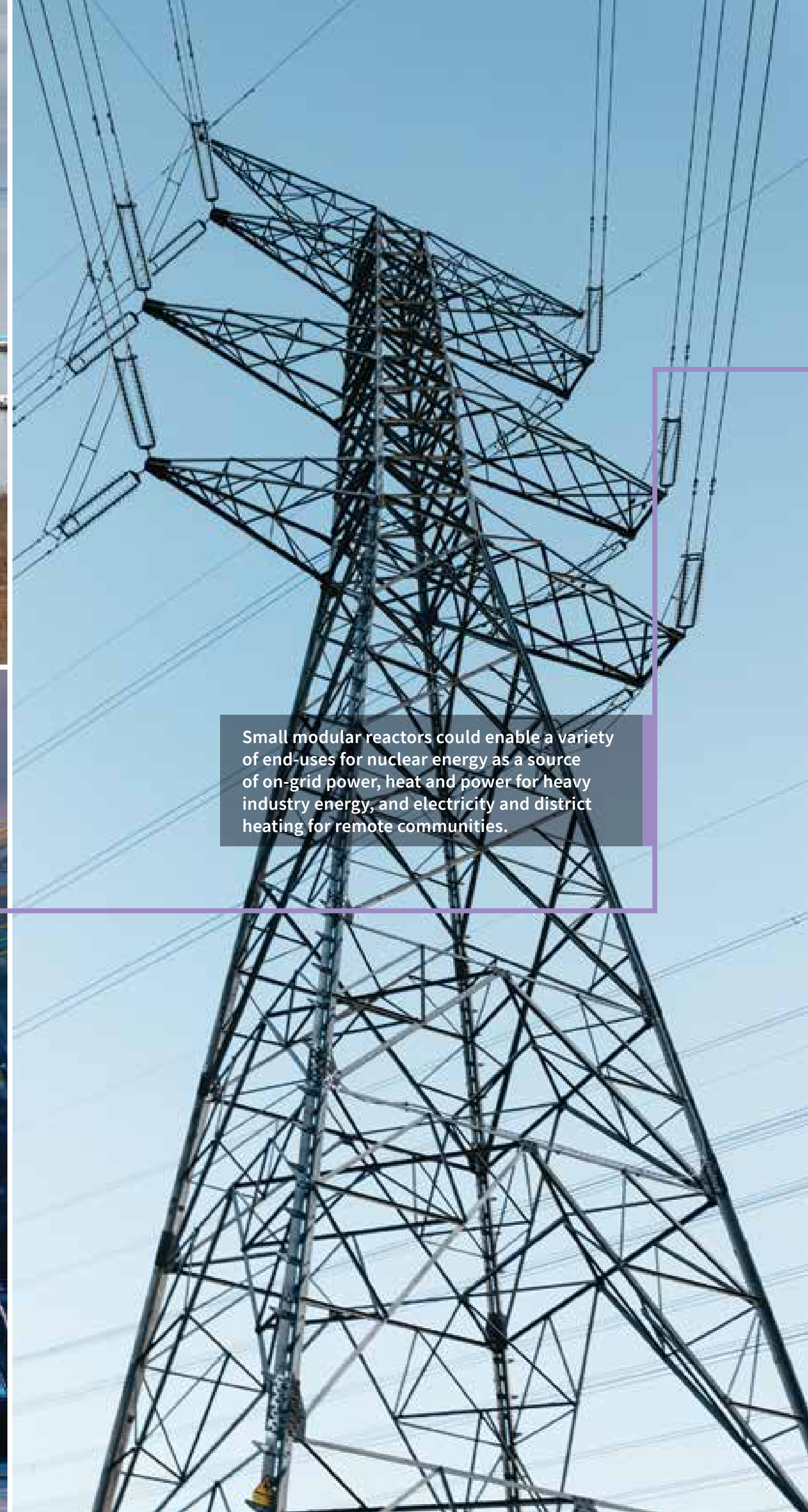
"That's when I decided I wanted to do engineering," she said.

Today, Lopez has a bachelor's degree in mechanical engineering and physics, in addition to her Master's degree. She was hired on at the South Texas Project power plant nearly four years ago as a mechanical engineer but today she designs reactor cores, one of the most technically skilled jobs at the plant. This spring she assisted in moving used fuel from a holding pool into casks that were being pumped full of inert gas and welded shut—the fuel will stay there for a few decades of storage before final burial.

"It's a great job and I recommend it," said Lopez.

She is the first in her family to work in the nuclear field. Her family is supportive, she says, although it sometimes takes people time to understand the benefits of the technology.

Lopez sees a bright future in the sector. She is certain that it will grow around the world because it is clean, safe and reliable. From where she sits, nuclear energy provides opportunities for good jobs for women and men of all backgrounds.



Small modular reactors could enable a variety of end-uses for nuclear energy as a source of on-grid power, heat and power for heavy industry energy, and electricity and district heating for remote communities.

SMALL MODULAR REACTORS

A building block of clean energy systems

Telephones used to be just for talking. Now they're for texting, shopping, keeping track of today's calorie burn, and settling arguments over who played R2D2 in the first Star Wars movie. Nuclear reactors are ready to take on new roles, too.

Ever since the first commercial nuclear plant opened in 1958—the Shippingport Atomic Power Station in the United States—reactors have fit one mold: big machines for producing baseload electricity.

But a new generation of reactors could make a familiar technology much more flexible and useful, just as the smartphone did to the telephone.

Small Modular Reactors (SMRs) have the potential to radically change not only how we make electricity, but how we make chemicals and plastics, how we integrate wind and solar into energy grids, and, indeed, how we live and interact with the infrastructure that produces our power.

These factory-built reactors provide less than 300 megawatts-electric, about one-quarter the output of big plants today, and sometimes far less—perhaps as little as a few megawatts.

Why get small? Because they are easier to build, easier to site, and easier to use.

They can be manufactured in a factory, one after the other, the way that airplanes or ships are—with all the economies of assembly-line production this offers—instead of being constructed on site, as is currently the case. And then they can be delivered to the intended site by rail, barge or heavy-haul truck. Because reactor manufacturing and construction of the surrounding infrastructure are conducted in parallel, these plants can be deployed promptly and at lower start-up costs.

For a large electricity grid, a power plant could incorporate multiple SMRs. Start with one or two and add more, like building blocks, as the need develops to respond quickly to changes in demand.

Big power plants need big grids to consume their supply, but SMRs can fit comfortably even on small grids, with no fears about electricity supply reliability when they shut down for refueling or maintenance since they are smaller units.

Because SMRs make use of the latest safety technologies, they could be located in the middle of a city to produce electricity where it is needed, or sited at a decommissioned coal plant to make use of existing infrastructure, such as transmission lines.

SMRs are designed for a modern grid, where demand can vary sharply over the course of a day, and where supply is mismatched because solar and wind electricity is abundant but variable. Some SMRs can switch between electricity production and other uses.

Because they are so adaptable, SMRs could enable "energy parks" that provide heat for industrial processes, steam for heating, or electricity for cooling homes, offices and shops—all without emissions of soot, smog precursors or carbon dioxide.

Their ease of transport and installation means that SMRs could be delivered to remote locations to provide pollution-free power for years or even decades before being returned for decommissioning—all without refueling, and without the need for hundreds of miles of transmission lines.

This isn't science fiction. SMRs are being deployed for delivery of electricity in some countries already and are near deployment for other, newer applications around the globe. SMRs are real. They are happening. And they offer a versatility and utility that doesn't just play by the rules—it promises to change the game altogether.

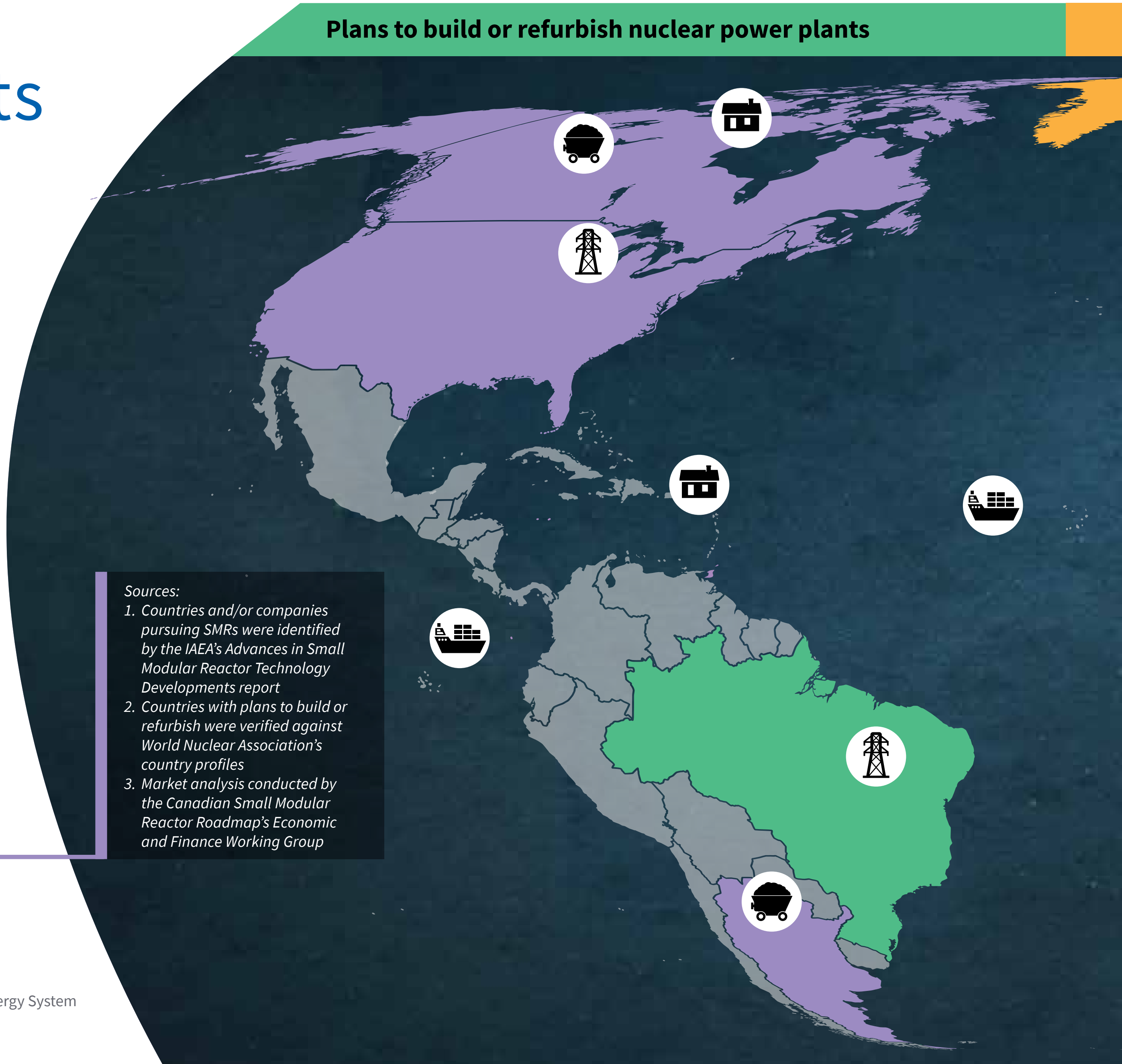
On-grid electricity

- The on-grid market is the largest potential market for SMRs, with new build potential of 30 GWe/yr by 2040.
- Market potential: $100B/yr in 2040.

HAPPENING NOW

Small Modular Reactor projects and markets

Countries around the world are developing and deploying Small Modular Reactors (SMRs) today—in addition to building new, large-scale power plants and refurbishing existing plants. In addition, there is a sizable global market for SMRs, estimated at a potential $150 billion per year in 2040. This map provides a tour of countries actively pursuing SMRs and nuclear energy projects, as well as representative end-use markets where SMRs may be an option in the future.



Sources:
1. *Countries and/or companies pursuing SMRs were identified by the IAEA's Advances in Small Modular Reactor Technology Developments report*
2. *Countries with plans to build or refurbish were verified against World Nuclear Association's country profiles*
3. *Market analysis conducted by the Canadian Small Modular Reactor Roadmap's Economic and Finance Working Group*

Merchant shipping

- As of 2018, there were over 90,000 merchant fleet ships around the globe.
- SMRs could provide hydrogen for fuels to power ships and other heavy-duty transport.

Small island states and remote communities

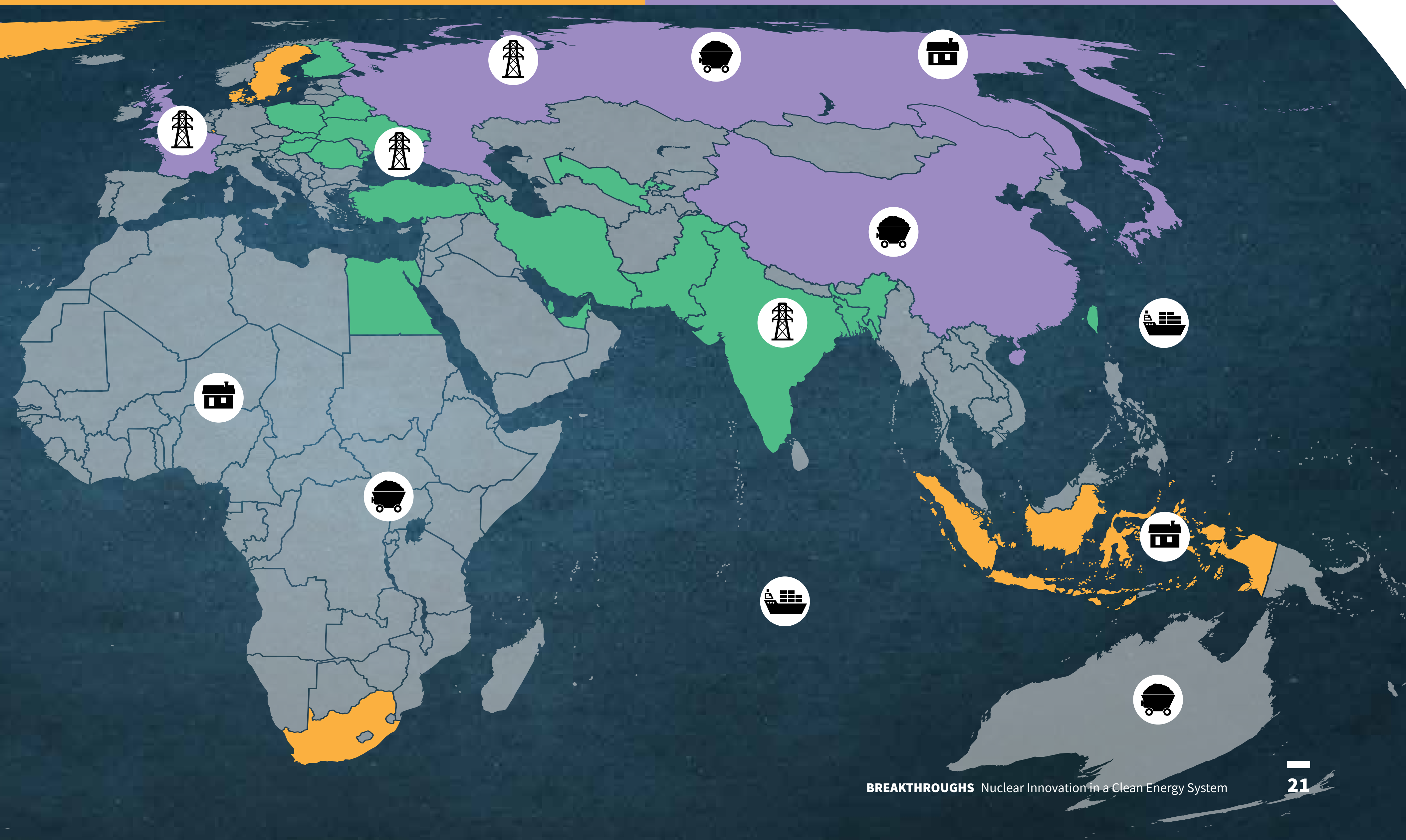
- There are a total of 58 small island developing states, many of which currently rely on diesel generators.
- This represents a 27 GWe potential market for SMRs.
- Market potential: $30B/yr in 2040

Mining and heavy industry

- SMRs could be a key supplier of energy to for industrial applications and global mining, especially in remote locations.
- Potential: $12B/yr market

Pursuing SMRs and/or countries with SMR vendors

Pursuing both large-scale nuclear and SMRs



Laser cutting technology used for advanced industrial manufacturing.
Source: UK Nuclear Advanced Manufacturing Research Centre

Cooks once spent hours cutting vegetables but are now prepping them in minutes with a food processor. Similarly, advanced manufacturing methods at nuclear power plants old and new are cutting through previously laborious tasks in a fraction of the time and cost.

ADVANCED MANUFACTURING

Costs on the chopping block

Technological advancements have radically changed the way today's nuclear plants operate, worldwide.

New technology also promises to reap massive savings in what has been the most challenging area of cost management for the nuclear industry: upfront construction costs.

Last year, the United Kingdom government brokered a landmark deal with the nuclear industry that aims to deliver billions of pounds in contracts to UK manufacturers and suppliers while industry must meet cost reduction targets, including a 30 per cent decrease on new build project costs.

Enter the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC) based at the University of Sheffield, formed to help industry deliver on that promise while helping UK manufacturers win work in the nuclear field.

The innovation chefs at the centre are slicing and dicing—applying advanced manufacturing and construction innovations to simplify nuclear component manufacturing and assembly.

The techniques can sound obscure, but they're nothing short of revolutionary in exacting cost reductions while improving quality.

For example, the UK's Nuclear AMRC and its industrial and research partners are developing an adaptive fixturing system to ease the movement of large parts around a factory, and ensure precision through a range of innovative forging, machining, welding, inspection and assembly processes. The new system could halve the production time of manufacturing large components.

Similarly, factory-built and shippable modular components for Small Modular Reactors (SMRs) create substantial construction savings.

The added value begins right with the trades work in the factories. A collaboration between Nuclear AMRC and the US Electric Power Research Institute (EPRI) uses a SMR pressure vessel prototype to demonstrate new methods that reduce welding time from about 10 days to just two hours. The work, part of a larger four-year collaboration, aims to reduce the total time needed to produce a SMR pressure vessel from around two and a half years to less than 12 months.

Nuclear plants internationally are also integrating artificial intelligence (AI) into many applications, automating techniques for machining and inspecting large components. In one instance, a six-axis industrial robot has been equipped to grind, deburr and polish fuel racks, removing a time-consuming manual process that comes with a vibration-related health risk for workers.

AI and virtual reality are the newest technologies being employed to improve nuclear effectiveness. And yet, sometimes innovation is as simple as applying an already-proven process in a new way.

Such is the case with a well-established process to manufacture components by pressing metal powder under very high pressures and temperatures to achieve uniform structures with superior material properties. This process, used for 25 years in the oil and gas sector and more recently in naval nuclear applications, could be a cost-effective way to produce complex piping joints and large valve bodies in nuclear plants.

Cumulatively, these and other innovations being developed in the UK and elsewhere by industry, government laboratories, and academia worldwide are transforming the cost profile of nuclear energy to a slimmer version of its former self with a far healthier bottom line.

Chemical engineer Aysha Al Ahbabi stands in front of a model of one of the Barakah nuclear reactors under development in the United Arab Emirates.
Source: Emirates Nuclear Energy Corporation

The United Arab Emirates is on the cusp of becoming the first Arab nation to generate power from nuclear energy. Over the past 10 years, it has established a highly-trained workforce to support a domestic nuclear energy sector—including chemical engineers, explains Aysha Al Ahbabi, who is working at the UAE's Barakah Nuclear Energy Plant, now nearing completion.

AN EMERGING LEADER
Aysha Al Ahbabi

Why employ chemical engineers?

Because reactors are assets that can last for 60 years or more, when properly operated and maintained by experts, including chemical engineers. That includes careful attention to the 'reactor chemistry' a delicate balance of chemicals in the millions of gallons of water used to transfer heat produced in the core to the rest of the plant where it is turned into electricity. Through reactor chemistry, impurities are filtered out of the water, and corrosion is suppressed.

There are other places in the UAE for a chemical engineer to work, including the country's five oil refineries. Al Ahbabi says she studied about them at United Arab Emirates University on the way to becoming a chemical engineer, but she prefers the Barakah Nuclear Energy Plant, currently under development by the Emirates Nuclear Energy Corporation (ENEC).

"Because nuclear is safe, clean and reliable, it is the future energy for the UAE," she explained.

Her training has taken her to South Korea, to see Shin Kori 3, the 'reference plant', or design model, for Barakah. She's also traveled to Florida, in the United States, to attend a seminar on water chemistry run by the Electric Power Research Institute.

Nuclear is "a new field for me, and a new area for the Emirates," she said. "As an Emirati growing up with an open mind, I wanted to take on new challenges, and I wanted to work in this new sector."

Electricity demand is high and growing rapidly in the UAE, she said, and it is "crucial for our country to meet this demand through clean and sustainable energy sources."

In all, four reactors at Barakah are under development, and construction of the first unit was completed in 2018. They will eventually provide up to a quarter of the country's electricity, with almost zero carbon dioxide emissions or other pollutants.

She is the first in her family to pursue an education in a technical field. Her family has been highly supportive. When she spent six weeks in South Korea in training, her father flew there for the day to visit, she said.

Her brother, six years old, misses her sometimes, because Barakah is four hours by car from her home, so she spends four nights a week there. "I told him that I am like one of the plant's doctors, and I am helping to take care of the health of the plant. Being in the chemistry department, I take a sample, and then I give 'medicine,' to prevent 'disease', which is corrosion," she said. "That's the easiest way to explain it."

Al Ahbabi's studies in nuclear energy were facilitated by the Energy Pioneers program. Launched in 2009 by ENEC, the program facilitates the training of young skilled UAE National professionals who will operate the Barakah plant and form the country's next generation of nuclear energy leaders. Al Ahbabi's training includes leadership skills, and she now helps train others to work at the plant.

The plant will likely provide lifetime employment, but her ambition does not end with water chemistry. "I am constantly working on my skills. I aspire to be a plant manager, and ultimately, a CEO."

The world's first complete, fueled and full-length test assemblies of Advanced Technology Fuels were installed in 2019 by Southern Nuclear at Plant Vogtle Unit 2 in Georgia.
Source: Southern Nuclear

As the world looks to do more with nuclear technology, researchers are finding ways to make it more resilient. A fuel that can adapt to the most challenging conditions and remain stable could be one of those breakthroughs.

ADVANCED TECHNOLOGY FUELS

At the core of reactor safety

Nuclear technology is largely invisible in our lives and yet, it plays an integral part in them every day from safe, clean electricity, potable water and safer food supply to a host of other benefits we don't even realize.

The importance of nuclear is only increasing with the urgent need for low-carbon electricity to meet growing demand.

Increasing nuclear energy's resilience to the impact of external forces has been an ongoing pursuit of both operators and the science community, with continual improvement of technologies being introduced as the result of research and operational experience. One area of innovative research is the redesign of the fuel.

Nuclear power is generated when uranium fuel that is made up of small, solid pellets securely contained in fuel rods made of steel. The fuel generates heat that boils water that in turn creates steam to power a conventional generator (the same equipment you would find in hydro-electric or fossil fuel power plants). Unlike fossil fuels, nuclear fuel does not create emissions. It does create heat and with it, radioactivity, both of which must be safely and securely contained.

With Advanced Technology Fuels (ATF) that are now being researched and developed, the fuel could withstand unforeseeable events that would otherwise cause it to overheat.

The U.S. Department of Energy (DOE) and materials research institutions around the world have turned their attention to ATF. The concept involves the development of fuels and fuel rods that can withstand higher temperatures for longer periods of time. In part, this research focuses on replacing traditional cladding materials with new alloys and changing some fuel design features.

In 2018, sample quantities of the first ATF designs were loaded into a U.S. commercial reactor. A wider range of research and development is also ongoing in the United States at Oak Ridge National Laboratory and Idaho National Laboratory test reactors.

Concurrent with the U.S. effort, the Paris-based OECD Nuclear Energy Agency is spearheading collaborative research and development on ATF, advancing the scientific knowledge essential for its development. NEA brought together 38 leading experts from 35 organizations, representing 15 countries, in a ground-breaking effort.

New regulations require nuclear plants to have countermeasures and actions to mitigate the consequences of any severe accidents, including even the most highly-improbable scenarios. All these innovations are significantly strengthening safety for current plant operations.

Researchers at Canadian Nuclear Laboratories are examining molten salts—a next generation technology that could operate at high temperatures safety.
Source: Canadian Nuclear Laboratories

In the same way space flight changed how we saw our limits in reaching new worlds, innovation in advanced reactors is completely reimagining how safety is built into design.

INHERENT SAFETY TOMORROW

One “giant leap” for a safe and secure energy future

When astronaut Neil Armstrong stepped onto the moon’s surface during his historic journey in July 1969, he said, “One small step for man, one giant leap for mankind.”

Today, the world continues to explore space as a new frontier. At the same time, researchers are solving the world’s most urgent challenges with solutions found right here on earth.

Humanity needs energy that is reliable, low-carbon, affordable and—above all else—safe. To meet these needs, we are constantly pursuing new solutions, anticipating the innovations that will move us forward.

Commercialization of inherently safe Small Modular Reactors (SMRs) and other advanced nuclear reactors is one such innovation. These energy sources of the near future will approach safety from a radically simpler design premise, incorporating passive safety systems and inherently safe materials to deliver reliable electricity that ensures the safety of people and the environment.

Passive safety systems

Passive safety systems reduce or eliminate factors that can fail, including electricity, pumps, complex machines, and human operators.

They use natural processes such as gravity and air cooling. Passive safety famously helped usher in the modern elevator—a technology distrusted by the public until the advent of a fail-safe brake mechanism.

An example of a passive safety system for one reactor design is a freeze plug holding back a tank of water. In the event the reactor gets too hot, the freeze plug melts, and gravity sends water to cool the reactor.

Other systems exploit the principle that, as liquids get hot, they rise, a natural convection process that drives cooling systems, eliminating the need for pumps and other equipment.

Modern light water reactors operating in China and those under construction in the United States and the United Kingdom have already incorporated some passive safety systems, such as relying on simple valves that operate automatically.

Looking forward, some advanced reactors could offer additional passive features—such as the ability to remove heat during abnormal conditions without the need for cooling water, thereby bringing the reactor back to a safe, normal state all on its own.

Inherently safe materials

Instead of trying to control hazards, another approach is to use the physical and chemical properties of the systems to build in safety.

Some fuels use advanced technologies such as materials that can tolerate a tremendous amount of heat, significantly reducing the chance of fuel overheating. Similarly, advanced reactors use fuels that expand as the temperature in the reactor rises, limiting how much energy the fuels can release.

Today’s great innovations may not require us to travel as far as the moon but, instead, rethink and simplify our solutions to the world’s most complex challenges.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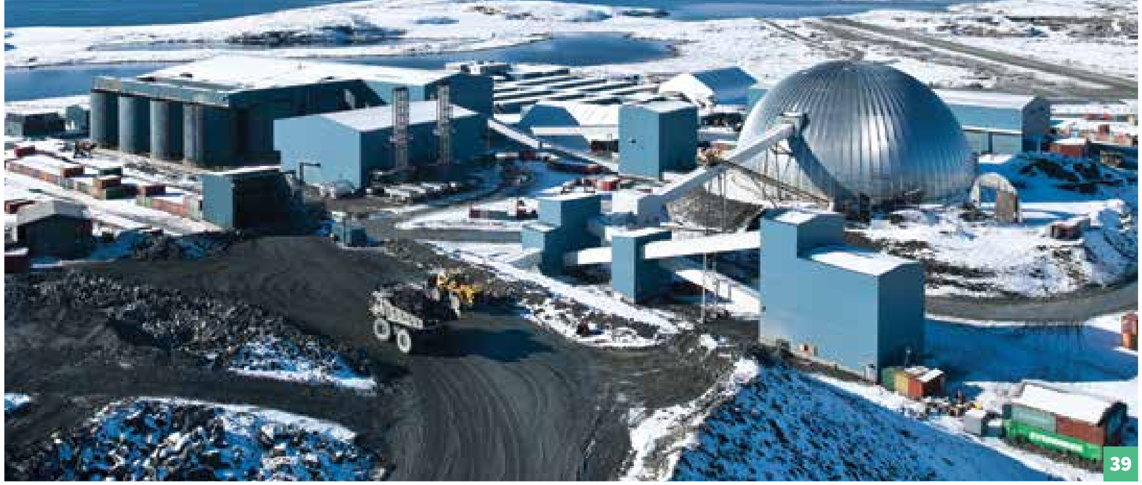
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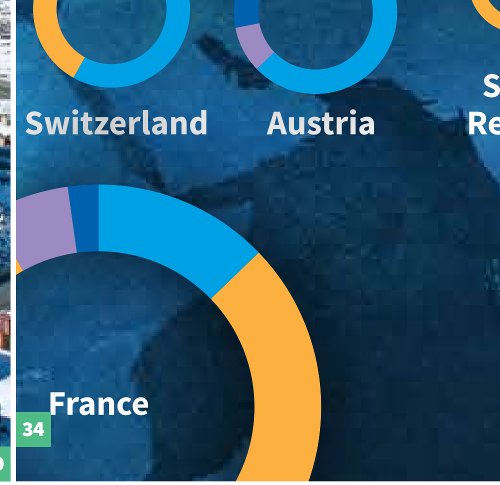
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CHAPTER 2
Changing the Game

Innovation is unlocking new roles for nuclear energy to enable clean energy systems of the future.

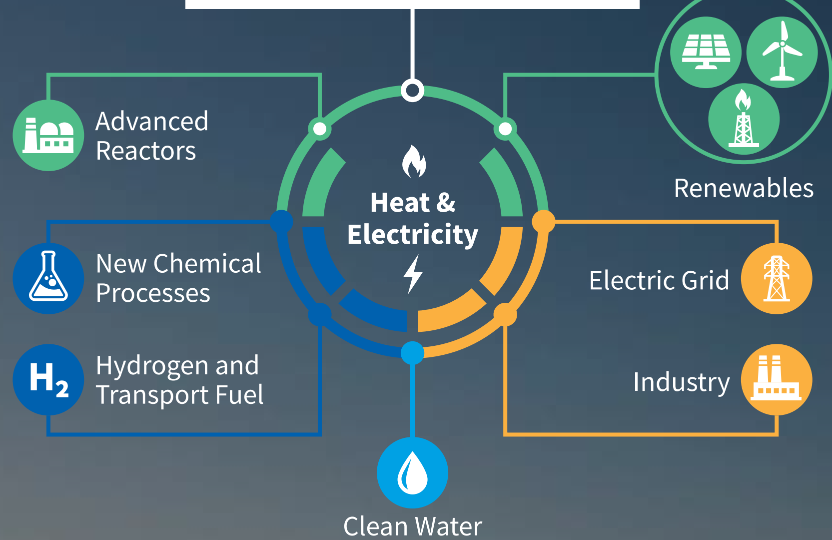
New technologies and business models could enable applications for nuclear-renewable energy systems, applications for mining, clean hydrogen production, and a source of heat and power for remote communities.

These roles could redefine nuclear energy's contribution in clean energy systems of the future—moving from baseload electricity to multi-functional and integrated energy services.

TOPICS

Innovative nuclear energy technologies are being developed to complement the deployment of wind and other renewables in integrated energy systems.

Integrated Nuclear Energy Systems will be dynamic and flexible



Source: Adapted from Idaho National Laboratories and Clear Path

Apart from not causing air pollution, nuclear energy and renewable energy have little in common. This may make them one of the best clean energy duos in the world.

NUCLEAR-RENEWABLE ENERGY SYSTEMS

Clean energy allies

In the summer of 2005, the Canadian province of Ontario set a dubious record, logging 53 days of smog advisories. At the time, Ontarians faced a terrible trade-off between air conditioning and air quality: keeping people cool required fossil-fueled electricity that led to greater air pollution, jeopardizing the health of elderly persons and people with respiratory problems.

Today, Ontario has eliminated the worst effects of smog from its cities (there were no smog advisories in 2018, and only one in 2017). This is thanks, in large part, to the restart of three nuclear reactors as well as growth in wind power, which together allowed the province to shutter a number of older, coal-fired power plants.

Cleaning up a large-scale grid doesn't need to be hard, expensive or far off in the future. Ontario's $600-billion economy has done it with nuclear and renewables, mainly hydroelectricity and wind.

You might think Ontario's approach is an outlier. After all, the traditional roles of nuclear energy and renewables have almost nothing in common. Nuclear energy is large, centralized, and (for the most part) always "on", whereas wind and solar are decentralized and dynamic.

But together, these features make nuclear and renewables a formidable pair. In fact, the handful of large economies in the world that have mostly or completely decarbonized their grid all enjoy a mix of nuclear and renewables (see next page), unless they have the fortune of a geography that allows for large-scale hydroelectricity or geothermal.

The secret is a balanced portfolio of "always available" energy sources (like nuclear and hydro) paired with variable, weather-dependent renewables like wind and solar.

This works well on big grids with a variety of energy sources. For example, Denmark—a pioneer in the development of wind power—generated 44 percent of its electricity from wind in 2018 thanks to an interconnected grid that lets it trade with its hydro- and nuclear-powered neighbors of Norway, Sweden and Finland. When the wind is up, Denmark exports its excess power; electricity is imported when it doesn't have enough.

And nuclear is also finding new ways of working with renewables. In France, nuclear power plants are tailor-made to follow fluctuations in electricity demand, a feature that makes them well-suited to a dynamic grid with larger shares of wind and solar.

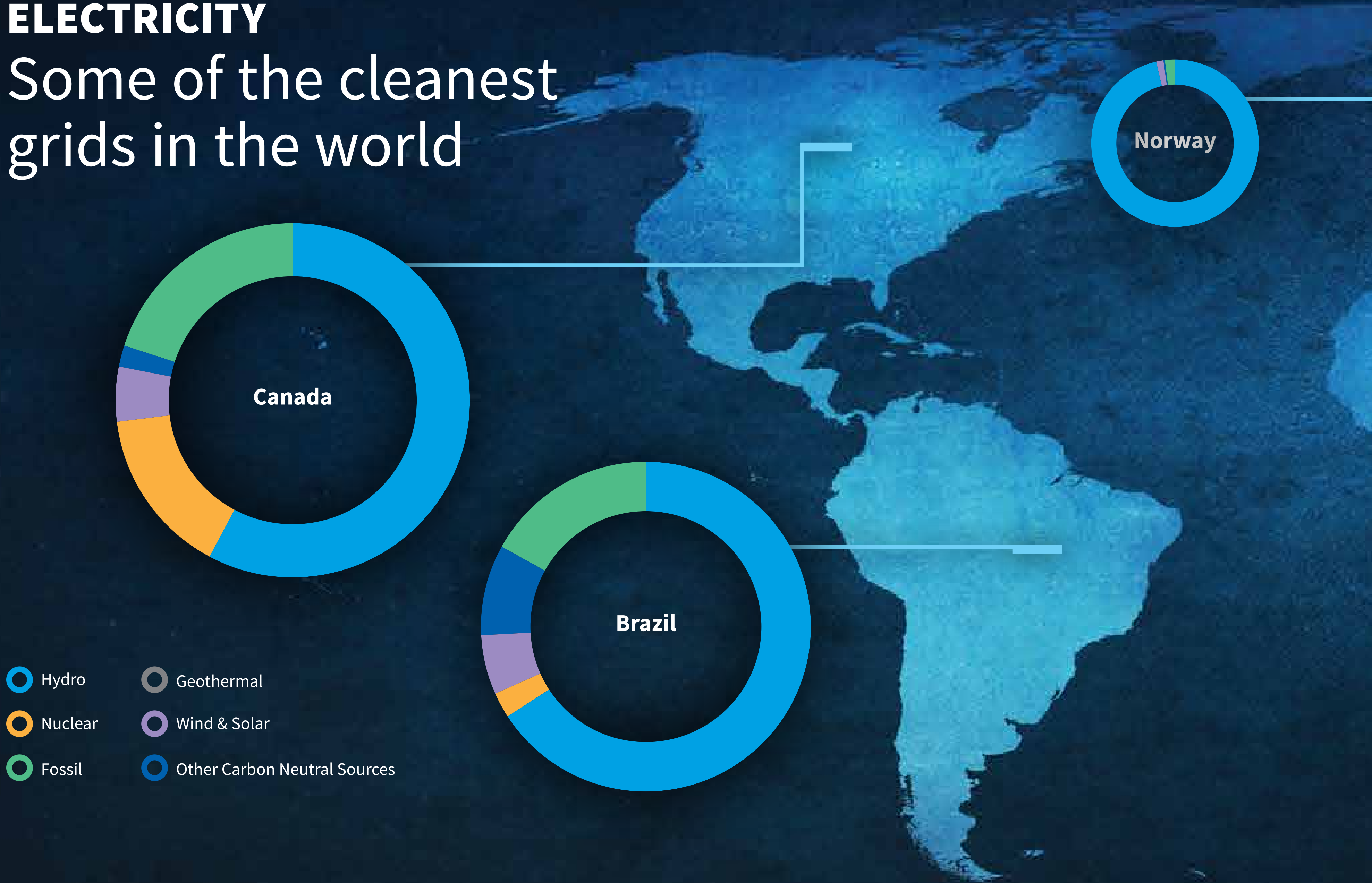
In the U.S., some nuclear operators are looking at options to make their plants more flexible by producing hydrogen, desalinating water, or heating industrial processes—in addition to producing electricity. This gives nuclear plants other places to send their energy when wind and solar are powering the grid.

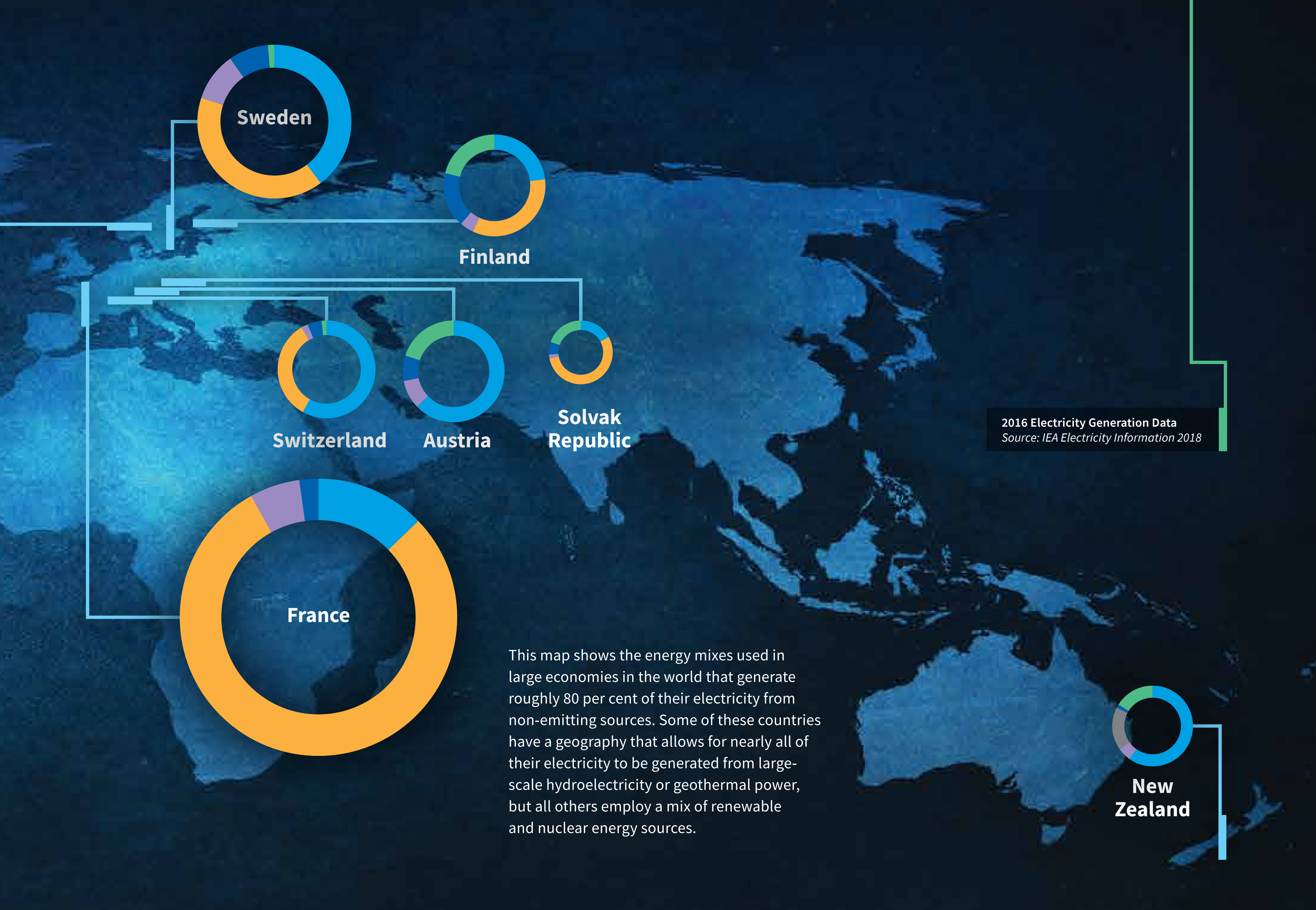
Innovations promise to make this kind of integration even easier. Small Modular Reactors could enable new applications for nuclear to contribute to smaller grids with decentralized energy sources. And many advanced reactor designs are better at dynamically following the demand for electricity, storing energy when it's not needed, or sending energy to other industrial processes.

For those looking to follow Ontario's lead, the good news is that new solutions are coming that could make this powerful clean energy duo widely available around the world.

ELECTRICITY

Some of the cleanest grids in the world





This map shows the energy mixes used in large economies in the world that generate roughly 80 per cent of their electricity from non-emitting sources. Some of these countries have a geography that allows for nearly all of their electricity to be generated from large-scale hydroelectricity or geothermal power, but all others employ a mix of renewable and nuclear energy sources.

The skyline of Nairobi, Kenya's capital city.
Photo Credit: Devasahayam Chandra Dhas of Bogota, Columbia

Pamella Kageliza is a teacher and PhD student in nuclear science whose aspiration is to one day manage a nuclear power station in Keyna.
Source: Pamella Kageliza

When she was younger, Pamella Kageliza studied math, physics, chemistry, and other subjects in school. Her marks were better in some other subjects, but she stuck with physics because it was more "practical". Now she would like to put physics to work in a nuclear power plant, if Kenya builds one.

THE TEACHER
Pamella Kageliza

In the small village in western Kenya where she grew up, only a few houses had electricity; everyone else relied on wood for cooking and kerosene for lighting. Now most houses do have power from the grid, but it is still too expensive for anything except lighting and perhaps a television. Adding nuclear power would solve several problems at once, she explains.

Today, women and girls spend long hours hauling water and fetching firewood for cooking. The girls have little or no time for school, and the women have no time for more productive work. "You are too busy collecting wood, and water, to do anything else," says Kageliza.

To find fuel to cook and keep warm, people are destroying the forests and leaving the land vulnerable to erosion, a problem common in Africa. The search for wood takes them further and further away from home every year.

The problem is borne from necessity, not greed, she says. "There is a policy that no one is allowed to cut the trees," explains Kageliza, "but they haven't provided another option, so people still go ahead and cut the trees."

The solution, she says, is a nuclear reactor. "It will provide clean energy, it's sustainable, and it's stable," she says. Kenya has tried other energy sources, including hydroelectric power. But after years of drought, supplies are limited, blackouts are frequent, and electricity rationing lies ahead, she says, for villages and cities alike. Already, industries are not running the way they should, because of a shortage of electricity.

Kageliza, 42 years old, taught mathematics and physics in high school before she went to Kenyatta University for a degree in education. In 2014 she completed a Master's degree in nuclear science from the University of Nairobi, and she is now working on her Ph.D. from the Technical University of Kenya. She is still teaching, but has bigger aspirations for a future career in nuclear energy. She would like to be a manager at a power station.

Kenya has completed a preliminary study of its options and is now characterizing potential sites across the country; it could break ground by the end of 2020. Kenya is one of nine African countries pursuing a future in nuclear energy.

Although it has yet to choose a technology, Kageliza says that Small Modular Reactors might be a good choice for Kenya, because they can be installed over time as demand grows, and work well on small grids. But she was also impressed with the larger Pressurized Water Reactors she's visited in Spain and Argentina. She has also visited China and Brazil for energy conferences or tours.

Nuclear power has helped her go places, meet people and develop a professional network. The first in her family to go to university, she's also a mentor for her nieces and nephews, she says.

The message is clear: women don't need to fetch wood and water: they can run nuclear reactors.

WHAT ARE MICRO REACTORS?

"Plug and play" reactors right-sized for providing heat and power to mining, heavy industry, and remote communities.

Benefits:

- **Transportable:** Fit on the back of a semi-truck and can be deployed to remote locations.
- **Simple-design:** Fail-safe and self-regulating designs that require fewer components, maintenance, and operators.
- **Fast on-site installation:** Can be connected and generating power within a week of arriving on-site. When the job is done, returned for redeployment or decommissioning.

Agnico Eagle's Meadowbank mining operation located North of Baker Lake, in the Kivallik region of Nunavut, Canada. The region is currently depending solely on diesel for energy. Clean energy alternative solutions are being explored for the near and long-term future.
Source: Agnico Eagle Mines Limited

Miners go to the ends of the earth for the minerals and metals we need to make clean energy. They may soon bring innovative nuclear reactors with them.

MINING

Unearthing a clean energy revolution

Under our feet lie the building blocks of the clean energy systems of the future. An installed solar panel, for example, requires many different materials found naturally, including copper, aluminum, steel, silver, and silicon, with some speciality modules using indium, selenium, gallium, germanium, cadmium and tellurium.

We rely on mining engineers to extract these materials from various locales, including some of the harshest and most remote areas of the world. And the scale of these operations can be mind-boggling: over 1,000 kilograms of copper ore is needed to produce the amount of refined copper used in an electric car—about as much as the car itself weighs.

The extreme conditions and remoteness of these operations can be hard to fathom. Take the Kupol mine in Russia, for example. This gold mine operates in a barren part of Siberia more than 160 kilometers from the nearest town. Temperatures can drop to 50 degrees Celsius below zero in the winter.

Remote operations like Kupol rely on diesel fuel to run their operations. But lugging diesel out to far-flung regions is expensive, and can leave the mines exposed to risks from supply-chain disruptions. It's also a key source of mining emissions.

Miners are looking for better options. And they may find it in nuclear energy—specifically, innovative designs referred to as a "micro-reactors".

Micro-reactors are even smaller variants of Small Modular Reactors, with an output of around 10 megawatts of electricity or less. A number of concepts are currently under development with the goal of providing energy options to even the most remote locations in the world.

These innovative reactors have found their champion in Vic Pakalnis, CEO of MIRARCO—a non-profit organization dedicated to mining innovation in Sudbury, Canada. According to Pakalnis, there are "a lot of great opportunities for Small Modular Reactors in mining".

"And did I mention, zero atmospheric emissions?" he adds with a canny smile.

Pakalnis's organization, MIRARCO, is working with researchers and nuclear operators to explore their feasibility for mining applications.

Micro-reactors promise a reliable energy source that is fuelled only once every 10 or 20 years and compact enough to fit on a flat-bed truck, in a rail car, or in a cargo plane. It's estimated they could reduce costs by 20 to 60 percent compared to diesel.

"A typical 20-year mining operation will spend over $500 million worth of diesel" says Pakalnis. "If you can reduce that by half—can you imagine?"

These reactors are small, simple, and right-sized to the needs and lifetime of mining operations. Once the mining is done, they are designed to be removed and either sent on to another site, or back to a central facility for decommissioning.

As a source of both heat and electricity, micro-reactors can power electric equipment, vehicles, and ventilation systems while also providing heat for mine operations.

Alongside the introduction of renewables at mine sites, micro-reactors could revolutionize remote mining. Pakalnis feels a sense of purpose and opportunity, "It's important for us to get engaged in this technology," he says, "this is our future."

Researchers use a range of advanced techniques, such as neutrons, x-rays and electrons, to conduct investigations into new materials for safer, lighter and more reliable energy conversion and storage technologies such as batteries or fuel cells.
Source: Canadian Nuclear Laboratories

The world needs better batteries. Curiously, nuclear science is helping to make this happen.

CLEAN ENERGY MATERIALS

Neutrons, a battery researcher's best friend

Electric vehicle company and battery superstar, Tesla, is rightly proud of how the island of Ta'u in American Samoa has been operating on nearly 100 percent solar energy for more than two years. This is thanks to a Tesla utility battery facility that stores the solar electricity for when it is needed.

But, there is a downside. The batteries can only store sufficient energy for this small population of 600 for three days.

This means that powering a larger population, such as a major city, on solar is going to need a lot more batteries. Even with rapid cost reductions in battery technology, this is still an impractical solution today.

We need better batteries

The solution is going to lie in the discovery of new materials. It all comes down to finding compounds that are inexpensive, that can safely take and dispense energy at a high rate, and that are able to store a lot of energy compactly (in other words, have a "high energy density").

"A 20 percent increase in energy density, for example, would produce about a 20 percent reduction in cost for an equal amount of energy storage," according to Jeff Dahn, a physicist and battery-research specialist at Dalhousie University, Canada.

It's still going to be a challenge however. "Increasing a battery's energy density is no easy feat because today's battery technologies are already pushing the limits of the materials' capabilities," says University of Waterloo chemist Linda Nazar, one of the world's most respected materials scientists.

In their quest for new materials that will improve our ability to store electricity, researchers employ one of the basic building blocks of matter: a subatomic particle called a "neutron".

Neutrons are found in the center of atoms. In a nuclear reaction, neutrons can be knocked out of an atom and fly off on their own. By firing a beam of these "free" neutrons at a material, researchers can measure how the neutrons scatter to learn more about the material's properties.

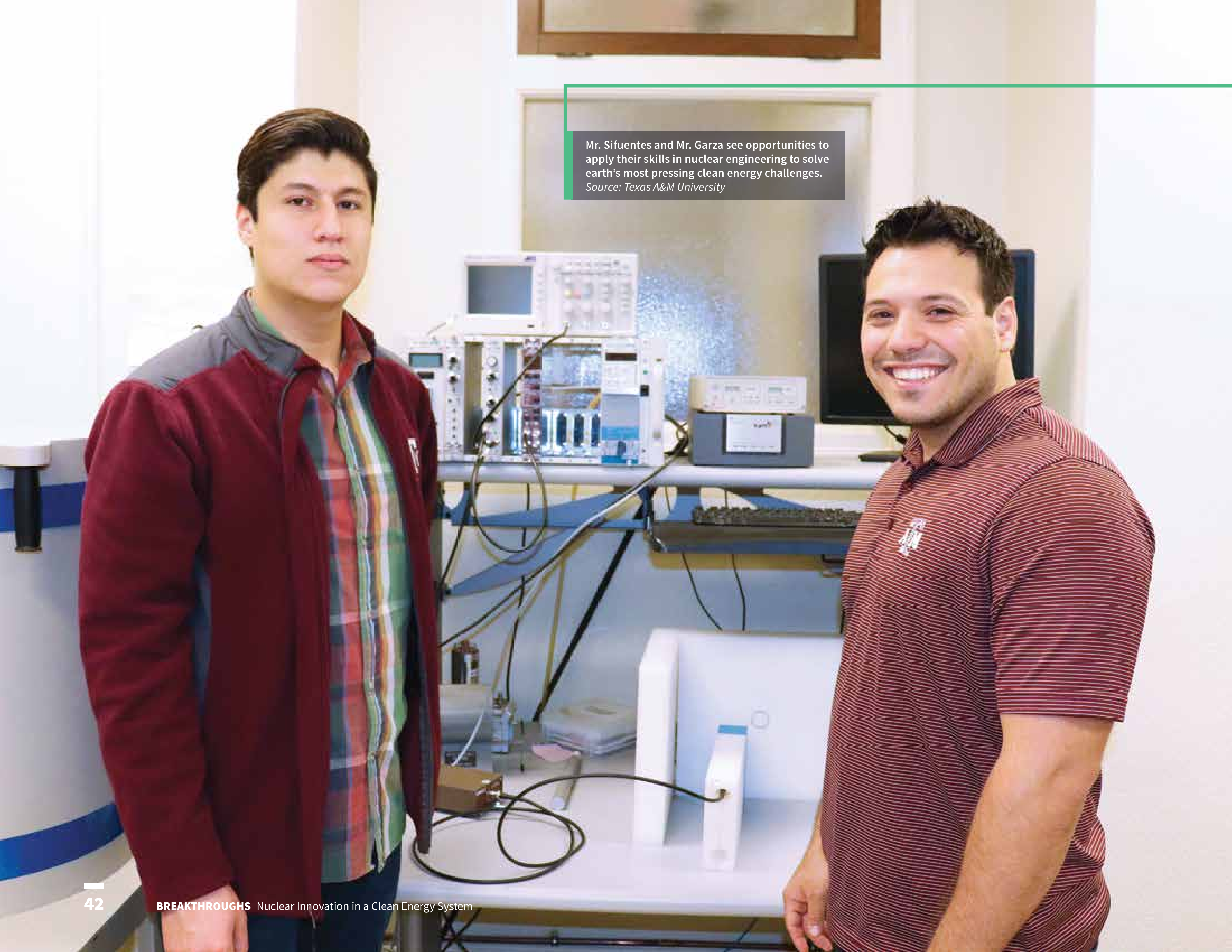
There are other ways of doing analyses like this, but just like your doctor might use an X-ray or MRI or CT, different tools provide different information. For some applications neutrons offer much greater sensitivity—they can penetrate deeper into materials and are better at identifying different atomic and isotopic properties. This gives researchers more information on materials that might bring them closer to a better battery.

"Neutrons are indispensable for the structural analysis of battery electrode materials that contain lithium, and are also very important for ones containing sodium," stresses Nazar.

Neutron beams aren't easy to come by. They can only be produced from nuclear installations such as reactors or particle accelerators. And battery research isn't their only clean energy application. Specialists around the world have used neutron scattering to:

- Improve the performance of hydrogen fuel cells;
- Increase the lifetime of wind turbine blades;
- Enhance hydrogen capture from industrial waste gas;
- Advance superconductor research for more efficient power lines and high-speed trains; and,
- Slash the energy requirements of aluminum production.

Nuclear reactions may be best known for the energy they produce, but neutrons are the unsung heroes of nuclear science and are making important clean energy contributions of their own.



Mr. Sifuentes and Mr. Garza see opportunities to apply their skills in nuclear engineering to solve earth's most pressing clean energy challenges.
Source: Texas A&M University

THE ENVIRONMENTALISTS

Cristian Garza and Christian Sifuentes

The path to a career in clean energy isn't always straight. Growing up in Texas in the United States, Christian O. Garza managed an auto repair shop after he graduated from high school. Now he's part of a team that is designing a nuclear reactor that will one day power a colony on Mars.

As a boy, Garza was fascinated by science fiction. "Every show you'd watch, the spaceships and what-not were always powered by nuclear,'' he said. Now 27 years old, he will graduate soon with a degree in nuclear engineering. The Mars reactor design is his senior project.

He is the first in his family to pursue a career in technology or science. His mother is an accountant and his father is a building contractor who installs floors. As a nerdy kid who used to dream about space, Garza says his education is "a dream come true."

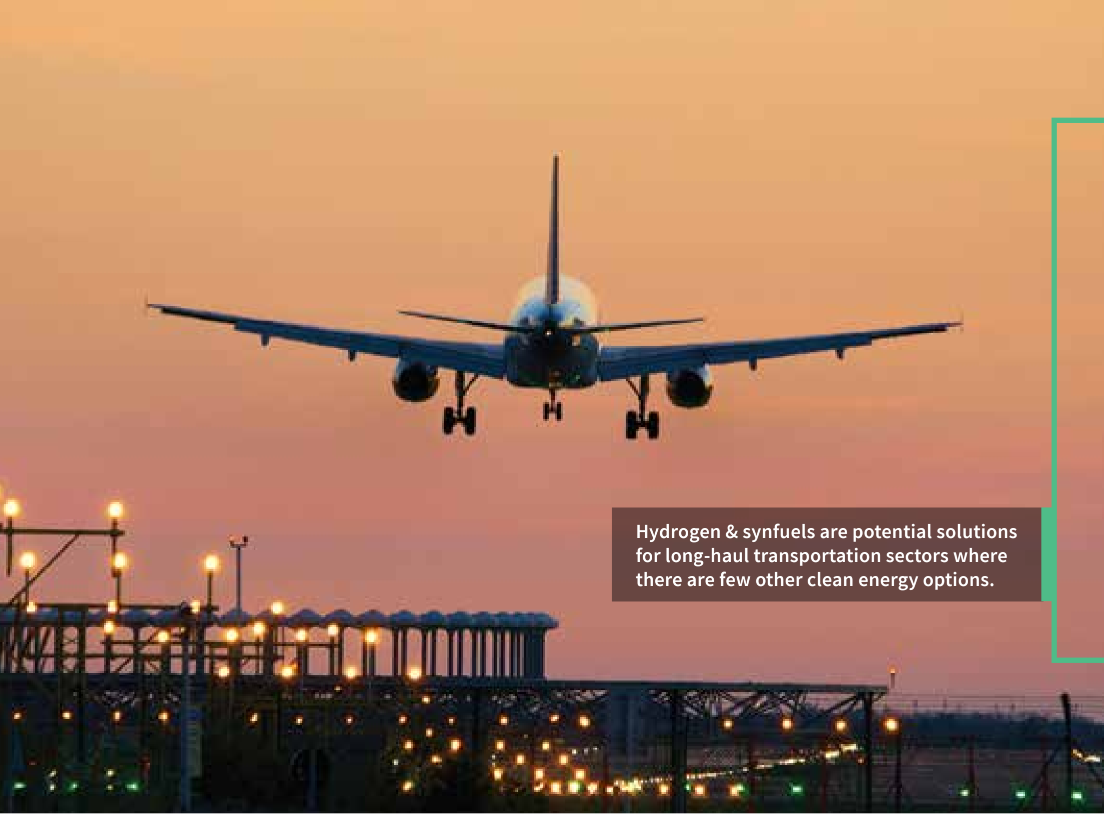
But what he would like to do is apply the engineering background he is acquiring to problems here on earth. "I started seeing how nuclear could benefit the world and provide clean, sustainable energy," he said.

His classmate Christian Sifuentes, who will graduate this fall, shares Garza's passion for the environment. Sifuentes joined engineering with an early interest in wind and solar power. Those carbon-free sources come to mind because they are visible, and "look really cool," he says.

Nuclear plants, on the other hand, are mostly tucked away in places off the beaten path, but Sifuentes now sees them as an important part of the equation because nuclear energy "is energy-dense and it is carbon free," he says. Sifuentes believes nuclear energy has a key role to play in meeting a lot of the world's growing energy demand.

Sifuentes, like Garza, is the first in his family to go to college. He is now studying criticality safety and used fuel management and will spend this summer at an experimental fusion energy laboratory in Kazakhstan, where scientists are testing materials for a power plant.

Meanwhile, Garza is hoping to work in a field that is on the cutting edge of advanced reactors. Most reactors today put the uranium fuel in water, but the Mars reactor design uses a molten metal that allows for a reactor that is smaller and generates higher-temperature steam. This will require developing better codes for computers, and probably some new materials. But as Garza, the environmentalist/science fiction buff points out, that's good for Mars and good for Earth too.



Hydrogen & synfuels are potential solutions for long-haul transportation sectors where there are few other clean energy options.

In transportation, the electric future is upon us, but there remain some transport sectors that are just really hard to electrify. Nuclear energy offers a potential path forward in a completely different role than it has played before.

HYDROGEN

Cleaning up "hard to clean" transport

In 2018, Norway became the first country in the world where a majority of all new car sales were electric vehicles. That year also saw deployment of the first electric mid-range heavy-duty trucks from companies like Tesla and Daimler.

Canada's Corvus Energy is, right now, delivering electric energy storage systems to operators of ferries, tugboats, and even cruise ships. This is, in turn, permitting these vessels to run on electricity during nearshore marine operations, which lowers maintenance costs, reduces fuel consumption, limits emissions, and prevents potential spills from polluting waterways.

As many as 20 different electric airplane start-ups such as Ampaire, Wright Electric, Zunum Aero and even Uber are racing to see whose regional services and flying taxis take off first. They aim to deliver as soon as the early 2020s, quieter, cleaner and cheaper short-haul flights than fossil-powered planes can offer.

But what all these transport sectors have in common is that they operate over short to medium ranges for light-duty activities. Long-haul trucking, shipping and aviation fall into the category of "hard-to-clean" sectors because they are difficult to electrify. For such distances, batteries need to be much larger and heavier. Flight, in particular, presents a problem if batteries are too heavy for the planes to achieve liftoff.

As a result, the hard-to-clean transport sectors are likely going to have to depend on some sort of clean fuel instead of electrification.

Production of carbon-neutral, or even carbon-negative, synthetic hydrocarbons is one elegant solution, as this transition can be achieved by simply changing the fuel without the need to swap out the internal combustion engines of the existing fleet of long-haul planes, ships, and trucks for battery packs and electric motors.

But there's a catch: synthetic hydrocarbons, or synfuels, need a supply of hydrogen as feedstock, and the cheapest way to produce hydrogen today is not very clean—by splitting natural gas with steam. In fact, for every kilogram of hydrogen pumped out, ten times as much carbon dioxide is also produced.

We need a better way

Electrolysis—using an electric current to split water molecules into hydrogen and oxygen instead—is clean, but incredibly energy intensive, which in turn makes it very expensive. And this is what makes nuclear an ideal candidate for clean hydrogen production.

Electrolysis is much more efficient and cheaper if water is first heated to form steam before the electric current is passed through. And production of steam is what nuclear plants do.

Researchers from all over the world are working on new processes that use heat from nuclear reactors to unlock clean and efficient hydrogen production. Initially the idea is to use both waste heat and off-peak low-cost electricity from existing plants and renewable energy sources. But ultimately, dedicated nuclear hydrogen production facilities would run 24/7, reducing costs still further by avoiding the maintenance expense of ramping production up and down.

Cleaning up the grid and electrifying everything is a common refrain heard in climate circles. This is mostly correct. But there are a handful of sectors that do not have many electrification options. The good news is that hydrogen production from nuclear power could be a driver of new solutions to put clean, long-haul transportation in motion.

Steel coils in a hot rolling process at the SSAB hot strip mill in Raahe, Finland

INDUSTRY

The next frontier for clean energy

Many industrial processes are closely intertwined with fossil-fuels, making them difficult to decarbonize. Clean hydrogen, produced by a nuclear reactor, may be the key.

Imagine a young couple living in Tokyo, Haruto and Yui, whose lifestyle gives them one of the lowest carbon footprints that can be imagined in Japan at the moment.

They take the Metro to work at the University of Tokyo, and when the weather's good they cycle to complete their errands. Haruto and Yui take the Tokaido *Shinkansen* ("bullet train") when they visit family in Kyoto, which runs on electricity generated by increasing shares of renewables and nuclear plants returning to operation. They have an electric heat pump at home instead of kerosene or natural gas for heating.

From electricity and transport to buildings and agriculture, Yui and Haruto are doing what they can for the climate. They regularly buy eco-friendly products and sometimes even write letters to public officials, pushing companies and government to do more in all these areas.

But they would be surprised to learn that there is an often overlooked contributor to their carbon footprint. An unseen source of emissions from something so commonplace that they take it for granted.

Steel

The bikes they ride are made of it. The wind turbines that have started to dot the hillsides make heavy use of it. As do many parts of the buses and trains they travel on and dozens of components of their heat pumps. In fact, almost every sector involved in the clean transition makes use of steel in some way.

But steel production accounts for 7 to 9 percent of global greenhouse gas emissions. Steel is an intricate combination of iron and carbon that requires baking molten metal at extremely high temperatures—over 900°C. These temperatures are very hard to achieve electrically, and for most of the world's steel, there are few practical options for reducing emissions from the process.

And steel isn't alone. Many other crucial industrial processes, like the production of cement, fertilizer and plastics, likewise need high-temperatures achieved via fossil fuel.

Industry is in many ways the next frontier for clean energy solutions. Carbon capture, storage, and utilization techniques are being perfected as an option for reducing emissions. And nuclear energy systems are also emerging as a way to provide the high temperature heat needed to drive industrial processes without causing emissions in the first place.

In Yui and Haruto's own backyard, in Ibaraki prefecture, next to Tokyo, the Japan Atomic Energy Agency has been developing very high temperature test reactors since the mid-2000s for this purpose. The Agency is currently at work on creating nuclear cogeneration systems capable of operating at 850-950°C. In the near future, this system could deliver enough heat to produce up to 650,000 metric tons of steel a year or 120 metric tons of hydrogen production a day. It is also able to provide heat for homes and fresh water production.

Other countries are also developing high-temperature test reactors. In fact, China is likely to be first out of the gate, with the world's first high-temperature reactor based on next-generation nuclear technology expected to come online later this year. An industrial group in Sweden is also looking to demonstrate an entirely new way to make steel using hydrogen with virtually no emissions. The process doesn't have to run on nuclear energy, but nuclear reactors could be an ideal way to deliver a clean source of hydrogen, via nuclear waste heat, that it needs to work.

These industrial innovations are integral to further decrease emissions. Solutions like these are going to be an essential part of a clean energy lifestyle for us all.

A vision of a clean energy park with centralized advanced nuclear reactor.
Source: Third Way "Nuclear Reimagined"

Imagine a carbon-free community unlike any other today. At its heart lies an advanced nuclear reactor that does more than provide electricity; it provides a foundation for a fully sustainable community.

ENERGY PARKS

Catalyst for clean growth

This reactor is the linchpin of a nuclear-renewable hybrid electricity grid powering the city—in cooperation with a nearby wind farm and rooftop solar installations.

Excess capacity from the reactor is used to power an onsite desalination plant that provides the city with water from a brackish underground aquifer. It also powers a hydrogen production facility that gives local factories a carbon-free source of hydrogen to make the steel and fertilizer that are driving economic development in the region.

The city's transportation is electric, powered by the fully carbon-free power.

Co-locating them in an "energy park" provides a triple benefit of electricity, heat, and steam to provide flexibility, gain significant efficiencies, and reduce costs, as well as delivering district heating and cooling to the local community. Other related sectors have also been plugged into this nuclear-renewable energy park: medical isotope production, food processing, and municipal waste-water treatment.

The complex supports hundreds of well-paying jobs, offers nearby residential living, and provides community and recreation spaces for the public. It ranks high in annual quality of life surveys, and it has one of the highest approval ratings for nuclear energy in the country. In fact, the community is participating in a voluntary process for siting a deep geological repository that will safely dispose of spent fuel from the reactor.

The concept of an energy park is one realistic vision along with the many other near-term clean-tech innovations that are poised to fundamentally change our relationship with energy.

Could this be the future?

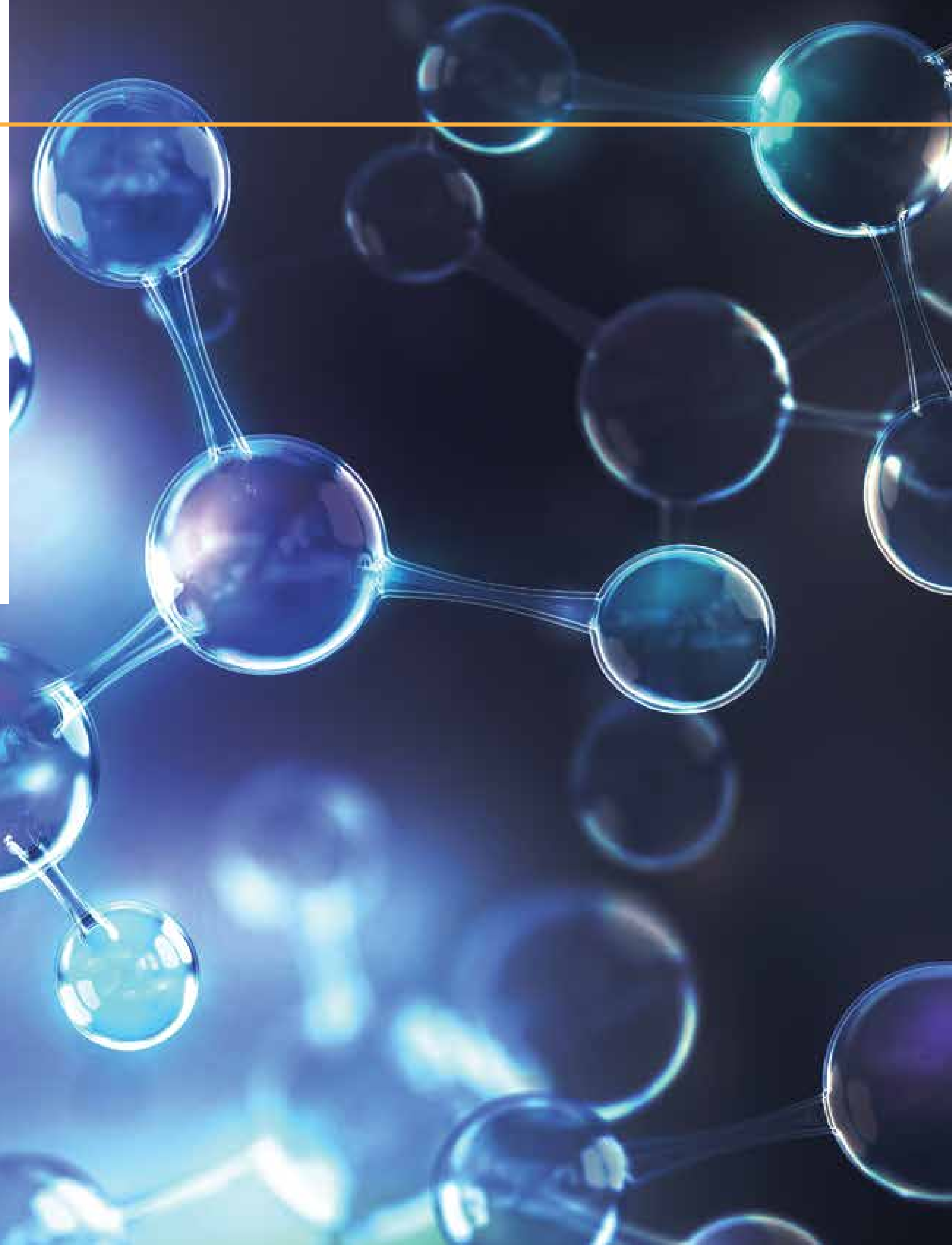
Not for those who are already pursuing these technologies, business models, and models of public, local, and Indigenous engagement.

This is the here and now.

Author's Note: This vignette draws, with permission, from a visual story for an energy park developed by Third Way in partnership with Gensler, an architectural, engineering, and design firm. Find more at: www.thirdway.org/blog/nuclear-reimagined

CONCLUSION
The power of partnerships

The world's ability to meet global clean energy goals will in part depend on the strength of partnerships.



Breakthroughs is the seldom-told story of nuclear innovation as an enabler of clean energy systems.

The stories in this book reveal what may be surprising or unexpected contributions—contributions that re-imagine the role of nuclear energy in clean energy systems of the future:

- A flexible source of energy, **ready to work with renewables**, energy storage and diverse end uses;
- A source of **non-emitting heat and power** for hard-to-clean sectors such as transportation and industry; and,
- A **driver of economic growth and opportunity**, and an option for communities and countries looking to alleviate energy access issues.

But if one looks further there is even more to the story.

The people, approaches, and solutions in this book provide answers to some of the tough questions facing nuclear energy development. Their stories address essential conditions needed for nuclear energy to play a role in meeting global clean energy goals:

- A culture of **continuous learning and innovation** to ensure safe and reliable operation, while realizing new levels of efficiency and performance.
- The development of **new technologies and disruptive business models** to cut costs, compete with alternatives, and unlock the significant investments needed to build tomorrow's energy systems.
- Models for building **trust and a positive dialogue** with communities, including Indigenous groups, on complex energy issues and the pros and cons among a holistic set of clean energy options.
- The **importance of stewardship** and an environmentally-responsible approach to the long-term management of both resources and waste that protects the health and safety of the public and the environment.
- And a **strong, diverse and passionate workforce**, attracting talented next-generation thinkers and leaders with opportunities for growth and innovation.

At the core of these conditions are foundational requirements that apply across the full spectrum of clean energy options, creating opportunities to share lessons and best practices.

In other words, *Breakthroughs* demonstrates that in developing innovative and practical solutions to clean energy challenges, nuclear energy has a lot to offer.

THE POWER OF PARTNERSHIPS

So where do we go from here to explore the roles that clean, innovative, and advanced nuclear technologies can play in furthering economic growth and effective environmental stewardship?

What's clear is that this exploration and sharing cannot happen solely in traditional nuclear fora.

To be successful, it will require new partnerships across traditional sectoral boundaries to develop integrated perspectives on the complementary roles that nuclear energy could play alongside all other forms of clean energy.

Governments will have an important role to play as well. They can explore how to include nuclear energy in dialogue, policies, programs, and planning. They can support enabling frameworks and appropriate licensing approaches to stimulate innovation and enable market-driven solutions. And they can advance strong bilateral and multilateral clean energy collaboration.

The Clean Energy Ministerial and the NICE Future initiative offer a unique opportunity to start building these partnerships:

- To **engage in dialogue and action** across energy sub-sectors.
- To **raise the profile** of discussions on nuclear energy's contributions to clean energy goals.
- To **collaborate and share knowledge** among interested countries on the role of nuclear in integrated systems of the future.
- And to **encourage a diverse and inclusive audience** to engage in multilateral discussions and activities to drive nuclear innovation in clean energy systems

To bring nuclear innovation to a global clean energy discussion, we told a story of stories.

And together we can write the next chapter.

FURTHER READING

A selection of references and articles for more information on the innovations described in this book.

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