Summer 2023

ENGINEERING THE ENERGY TRANSITION

An Initiative of the
NAE President's Business Advisory Committee

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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The
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NATIONAL ACADEMY OF ENGINEERING

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Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

A complete copy of *The Bridge* is available in PDF format at *www.nae.edu/TheBridge*. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

The
BRIDGE
LINKING ENGINEERING AND SOCIETY

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News and Notes

President's Perspective

Tribute to Great Engineering Leadership

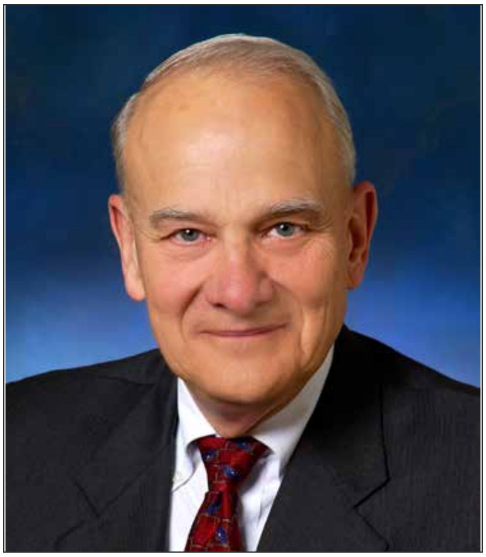
John Anderson is president of the National Academy of Engineering.

Credit: Intel Corporation

GORDON E. MOORE

NAE 1976

Contributions to semiconductor devices from transistors to microprocessors.



WM. A. WULF

NAE 1993

For professional leadership and for contributions to programming systems and computer architecture.

Great leadership rests on two important traits: optimism about the future, and commitment to do both great and good things. The engineering profession and our country lost two great leaders this year who demonstrated both: Gordon Moore (1929–2023; NAE 1976) and Bill Wulf (1939–2023; NAE 1993). They pointed us toward horizons not imagined before, and they led by example, keeping their eye on the value of engineering to advance society and improve the welfare of all its people.

Moore's law[1] is familiar even to those without a technical background. In 1965 Gordon noted that the density of transistors on a chip had doubled about every year of the previous decade; later he refined his observation to 18 months for the doubling. Today integrated circuit technologies can deliver more than a billion transistors on a chip, and the cost per transistor has fallen dramatically.

The impact on daily life of the miniaturization of electronic circuits cannot be overstated. As a cofounder of Intel, with the late Robert Noyce (NAE 1969) and Andy Grove (NAE 1979), Gordon led the advancement of the microelectronics industry with a vision based on technical knowledge, technological aspiration, and business foresight. Microelectronics are now foundational to everyday life in ways large and small—in smartphones, microwaves, cars, computers, MRI scanners, and hearing aids, to name just a few of their applications—all attributable to Gordon's foresight and actions.

[1] https://www.britannica.com/technology/Moores-law

In 2000 Gordon and his wife established the Gordon and Betty Moore Foundation to "create positive outcomes for future generations."[2] Financial support from the foundation has driven scientific discovery, improvements in health care, and environmental protection. In this and other ways Gordon Moore demonstrated that he was committed to doing good things.

Bill Wulf diverged from his undergraduate training in physics to earn one of the first PhDs in computer science in 1968—before the field had been established as an academic discipline. Early in his career, as a professor at Carnegie Mellon University, he and his wife Anita Jones (NAE 1994), also a faculty member, started a software company called Tartan Laboratories that was eventually sold to Texas Instruments. Bill and Anita joined the faculty of the University of Virginia in the late 1980s and worked there for the remainder of their careers except for their public service positions.[3]

While Bill was highly recognized for his technical achievements in computer programming and architecture, his legacy is perhaps more defined by his leadership in engineering. He served as assistant director (1988–90) of the newly established NSF Directorate for Computer and Information Science Engineering (CISE) and helped move computer science to the forefront of engineering and science disciplines. And when in 1995–96 the NAE suffered a leadership disruption and began losing its focus on its mission, Bill was appointed interim president by the Council. As a testament to his confident, creative, thoughtful, and highly principled leadership, he was elected by the NAE membership in 1997 to complete the 1995–2001 term, and in 2001 he was reelected, to a full 6-year second term.

I was elected to the NAE in 1992 but had no idea what went on "behind the curtain," although I was aware of the leadership crisis of 1995–96. I clearly recall how Bill (and Anita) stepped in to boost the sagging morale of the Academy and not only right the ship but also speed it along its intended course. Their vision, commitment, warmth, and enthusiasm were just what was needed.

Bill respected the staff and the members and was visibly engaged in NAE activities. He advanced diversity and inclusion as a priority of the NAE well before it was accepted by the public and the members. As he memorably wrote: "in any creative profession, what comes out is a function of the life experiences of the people who do it.... [Without] diversity, we limit the set of life experiences that are applied, and as a result, we pay an opportunity cost...."[4] EngineerGirl was established to encourage young women to study engineering and pursue a career in it. In addition, the Global Grand Challenges program was created, and he brought the Center for Engineering Ethics and Society to the NAE.

The goal of engineering is to create extraordinary things for the good of society. Progress—and the wellbeing of the profession—depend on visionary, thoughtful leaders such as Gordon Moore and Bill Wulf. They will long be remembered and treasured.

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[2] https://www.moore.org

[3] Anita was director of Defense Engineering and Research in the Department of Defense (1993–97).

[4] Wulf WA. 1998. Diversity in engineering. The Bridge 28(4):8–13.

Editor's Note

Transition at *The Bridge*

Ronald M. Latanision (NAE) is a senior fellow at Exponent.

aWith this issue I bid farewell to my *Bridge* partner, Managing Editor Cameron Fletcher. She is retiring after 11 years with the NAE and a total of 37(!) at the National Academies. She joined the NAE staff in June 2012 and so seamlessly and masterfully assumed her responsibilities that one NASEM colleague thought she'd actually created the NAE's flagship quarterly.

I couldn't have asked for a better counterpart. Cameron and I were so consistently on the same page (not a pun!) that I accepted all her suggested ideas for issue topics and guest editors for them. And together we hit on the idea of interviewing people with a background in engineering who made their mark in other ways, from our first interview with PE and poet Richard Blanco, who read at President Obama's inauguration, to engineer and writer Sam Florman (we consider him the godfather of the interviews), former Denver Broncos quarterback Charley Johnson, Boston rock band founder Tom Scholz, Girl Scouts CEO Sylvia Acevedo, and, most recently, bookstore founder and owner Lucy Yu. This is now one of the quarterly's most popular features.

Cameron oversaw *The Bridge*'s adoption of color printing for figures and photos, instituted an evaluation process for articles, added an alternating column dedicated to the perspectives of the NAE president and chair, and introduced a thoughtful column called Invisible Bridges on intersections between engineering and society. She also successfully produced the exceptional issue—with 50 essays instead of the usual 7–9 articles—that marked the 50th anniversary of *The Bridge*, identifying many of the authors as well as inspired topics for the next 50 years of engineering contributions.

Most importantly, Cameron rigorously ensured the quality and accessibility of the articles in every issue, knowing that our readership spans engineers of every stripe—both among the NAE members and in university departments across the country—as well as members of Congress, industry leaders, students, and many others. NAE members and other authors and editors so appreciated her attentive and helpful efforts that they not only thanked her in print but in some cases signed up for repeat duty, volunteering to edit another issue or contribute another article. Comments such as "You are a very thoughtful, probing editor" and "your editing added polish to my draft" and "improved text structure and clarity" were typical and regular. Cameron is a seriously good writer.

In all her work, Cameron made clear that her aims were to help the NAE and *Bridge* authors look their best by communicating effectively, to make my and the issue editors' work as easy as possible—and to have fun on company time! With her assiduous efforts and delightful humor, she achieved these goals, and more. With the ever-reliable assistance of Penny Gibbs, I believe we have been an exemplary team.

I want to include a cheerful and Cameronesque message delivered at her farewell party by a NASEM choral group known as the Refrains, with lyrics by songmistress Nancy Huddleston. It is in keeping with the Cameron we all know (and set to one of her favorite melodies).

Personent Hodie (for Cameron)

On this day that we sing
Cam'ron is re-tir-ing
We her choir, and her friends,
Bring our song before you,
Trying not to bore you

Refrain:

Say it's not so, so, Cameron don't go, go
We are sad, this is bad, in excelsis Deo!

2. Ours the doom, hers the mirth;
In her ab-sence a dearth
Of good cheer and sharp mind,
Editing our papers,
Joining in our capers

Refrain

3. New bright star o'er her head,
By her heart she'll be led—
No more deadlines to dread,
She can shed her work cares,
No more branding nightmares

Final Refrain:

If you must go, go, Cameron don't go slow
Get out fast, have a blast, in excelsis Deo!

Cameron, I will miss you. But I join all whose lives you touched during your time with *The Bridge* and at NAS-EM in wishing you much happiness, good health, and smooth sailing in this next chapter. Thank you.

President's Introduction

The Goal of a Net Zero Carbon Energy System: The Importance of How

John Anderson is president, National Academy of Engineering.

Engineering focuses not only on "what" but also on "how." The US goal of reaching net zero carbon emissions by 2050 is a monumental challenge—one of the greatest ever faced by our country.

To explore ways to reach this critical goal, the NAE President's Business Advisory Committee (PBAC), which was created in 2020 to help engage the business community, formed a focused working group. Among other ideas, the group decided to convene experts in the production, transportation, and use of energy to formulate potential paths toward net zero carbon. This issue of *The Bridge* is the result.

Tom Degnan[1] (PBAC chair and former manager, Breakthrough and New Leads Generation, ExxonMobil Research & Engineering Co.), and **Tim Lieuwen** (professor, Georgia Institute of Technology, with a strong record of contributions to the field of energy) agreed to serve as guest editors. They identified topics that effectively illustrate the broad scope of the energy transition, and enlisted deeply knowledgeable industrial practitioners as well as researchers at universities and national labs to offer their expertise and insight in each area.

The articles in these pages provide a clear-eyed assessment of engineering challenges to be addressed and opportunities to be pursued to achieve the critical global energy transition. They offer a blueprint—the "how"—for steps toward ensuring sustainable quality of life in the face of an existentially daunting threat.

I thank the editors and authors for this valuable resource.

[1] Bold denotes NAE members.

Guest Editors' Note

Analogies to Communicate the Engineering Challenges of the Energy Transition

Tom Degnan

Tim Lieuwen

Tom Degnan (NAE) is the Tony and Sarah Earley Professor in Energy and the Environment Emeritus, University of Notre Dame, and manager (ret.), Breakthrough and New Leads Generation, ExxonMobil Research and Engineering Co. Tim Lieuwen (NAE) is executive director of the Strategic Energy Institute, and Regents' Professor and David S. Lewis Jr. Chair, School of Aerospace Engineering, Georgia Institute of Technology.

"I especially love analogies, my most faithful masters, acquainted with all the secrets of nature…. One should make great use of them."

— Johannes Kepler

This century's greatest engineering challenge may be orchestration of the energy transition required to meet net zero carbon goals. But the magnitude of the energy transition is difficult for many individuals to grasp. So we turn to analogies.

Like Johannes Kepler, engineers and scientists love analogies. They can spark creativity. Leonardo da Vinci frequently resorted to analogies to guide his insights into the human body. They are a means to simplify communication and help people become more comfortable with concepts that are difficult to comprehend. For scientists and engineers, analogies can be useful to explain the essence of something that is technically complex.

Is there a good analogy to help convey the essence of the imminent energy transition?

Pundits and politicians attempting to describe the energy transition have drawn analogies to the Manhattan Project (1942–45) (Shanks 2022), the New Deal (Dolsak and Prakash 2019), and President John F. Kennedy's 1961 challenge to land a man on the moon (Clemens and Aliakbari 2022).

Like the Manhattan Project, the societal need for a transition in energy sources is almost existential. There is a strong sense that we cannot afford to fail. Also like the Manhattan Project, there is a need to assemble the nation's best technical talent, in this case to focus intensely on transitioning away from traditional hydrocarbon fuels.

Drawing an analogy to President Franklin D. Roosevelt's New Deal is a favorite tactic of politicians. Like the New Deal, the design, development, and deployment of a new US energy infrastructure require a "top-down" policy-driven program that captures the populace's attention and embraces a grand vision. The two are similar in their need to draw heavily on the public and private sectors.

President Kennedy's manned lunar landing challenge is often cited as an example of a visionary communicating a truly aspirational goal where technical uncertainty stands squarely in the way of success. It is easy to envision parallels between the engineering and logistical challenges related to landing a man on the moon in the late 1960s and those associated with successfully converting the energy system to a net zero carbon system by 2050.

But none of these analogies is particularly apt because the energy transition is intrinsically different. For one, it is a global challenge, not a domestic one. Coordination and consensus among countries with varying energy policies, different infrastructures, and vastly different economies will be essential. And although urgency is a common denominator, the time frame for achieving a successful outcome is different: about 25 years for the energy transition vs. 10 years in each of the three historic analogies.

The longer time frame for transforming the energy infrastructure accurately reflects the time required for designing, installing, and refining a new global energy system. Unfortunately, establishing more distant time targets detracts from the sense of urgency and allows seemingly more pressing, though arguably less important, priorities to intervene. The recent focus on energy security is a good example: European electricity suppliers reverted to using more coal when confronted with the threat of disruptions in the natural gas supply.

Are there better analogies? For inspiration, we might look to Greek history and Plutarch's ship of Theseus. The ship was made entirely of wood, which deteriorates over time and has to be replaced. In Plutarch's telling, the wood planks of Theseus's ship were replaced one at a time over a long period, until no more of the original wood remained.[1]

Like the ship of Theseus, societies must replace existing energy infrastructure with an entirely new energy infrastructure over an extended period *while* operating and maintaining, without interruption, the current hydrocarbon-based energy system. And this has to be done safely, economically, and equitably. To further extend the analogy, a "larger ship" will be needed to accommodate both the 775 million people who currently have no access to electricity as well as a global population that is projected to grow to 10 billion. And the reconstructed ship will have to be more durable to withstand the increases in climate variability and in the frequency of severe weather events. It amounts to a magnificent but daunting technical juggling act.

Much has been written on the topic of the energy transition, so why do we need this special issue of *The Bridge*? Much of what's been written has focused on basic science, technology advances, funding requirements, or government policy. Less has been written about the engineering challenges, rooted in rigorous lifecycle analysis and systems and resiliency thinking. These articles are intended to fill this gap.

The concept for a *Bridge* issue dedicated to the engineering challenges associated with the energy transition originated from a discussion between NAE president **John L. Anderson**[2] and his President's Business Advisory Committee (PBAC) in early 2022. Planning for the issue evolved concurrently with developing the groundwork for the 2022 NAE Annual Meeting. The two share the same theme: Engineering the Energy Transition.

The most critical role of engineers and scientists in the energy transition is to better communicate the realities surrounding climate change.

In his keynote address at the 2022 NAE Annual Meeting, **John Holdren** (NAS), science advisor to President Barack Obama,[3] listed what he saw as the 10 key engineering challenges of the energy transition:

1. More efficient buildings and industrial processes
2. A more intelligent, more efficient electricity grid
3. Improved batteries, longer-term storage technology
4. More efficient photovoltaic cells
5. Improved hydrogen production, transport, storage
6. More durable and affordable fuel cells
7. Drop-in fluid biofuels from sustainably grown feedstocks that don't compete with food and forests
8. CO_2 capture and storage/reuse for fossil and biofuel electricity generation and industry
9. Advanced nuclear reactors with lower costs, high safety, and proliferation-resistant fuel cycles
10. Practical fusion

Dr. Holdren concluded by emphasizing that the most critical role of engineers and scientists in the energy transition is to better communicate the realities surrounding climate change.

In this spirit, we planned this special issue of *The Bridge*. The articles examine various aspects of the 10 challenges listed above. To address them, we invited contributors

[1] The question of whether the ship of Theseus is the same ship after all the wood planks have been replaced is a central one in philosophy but need not concern us here.

[2] Bold denotes NAE membership.

[3] Holdren is also the Teresa and John Heinz Research Professor of Environmental Policy and cochair of the Energy Technology Innovation Project at Harvard University's Kennedy School of Government.

who have practical experience in the energy field and whose careers have involved making or advising on decisions requiring large amounts of capital and human resources in the energy industry.

The energy transition poses immense challenges and offers enormous opportunities for engineers. One of the best analogies describing engineering's role in the energy transition may be its role as a bridge—a well-designed, robust connection between what is and what has to be.

In addition to the authors, we thank the following for offering their objective assessment of the draft articles: Lindsay Anderson, Bhavik Bakshi, Julian Boggs, Nick Brown, **Mike Corradini**, Steve Csonka, Jeff Dagle, **Mike Doherty**, Wayne Eckerle, Rod Eggert, **Tom Graedel**, Steve Hartig, **Eric Kaler**, Brendan Kochunas, Tim Luce, Pierluigi Mancarella, **Arun Majumdar**, Mike McKellar, Hamed Mohsenian-Rad, David Peck, Stratos Pistikopoulos, **Joe Powell**, **José Santiesteban**, Ramteen Sioshansi, **George Stephanopoulos**, **Gavin Towler**, and **John Wall**. We also thank Cameron Fletcher for managing the project and John Anderson and **Al Romig** for their support and encouragement.

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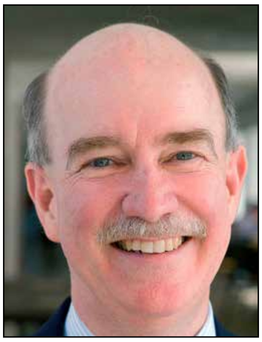
Engineers have the unique skills to develop models, technologies, and systems to guide policymakers and society through the energy transition.

The Role of Engineering in the Energy Transition

Vijay Swarup



Robert Armstrong

Vijay Swarup and
Robert C. Armstrong

Mitigating climate change while simultaneously increasing energy supply to meet growing energy needs equitably and securely is one of the world's grand challenges. Energy is fundamental to quality of life, underpinning essentially every aspect of modern living—from power to transportation to agriculture and more. Yet nearly 1 billion people globally do not have adequate (or any) access to energy. Moreover, because global population is growing, as is GDP/capita (driven particularly by emerging markets and developing economy countries), energy demand continues to grow. The energy gap needs to be closed.

Thanks to advances in solar and wind energy technologies that have dramatically driven down their costs, and technology innovations that have lowered the cost and increased availability of natural gas, the potential exists to close the energy gap. But emissions continue to rise. The challenge is to expand energy supply and equitable access and at the same time substantially reduce emissions.

To ensure that the energy transition is global—as it must be—engineers will play an important role in driving down costs and ensuring that technologies are deployable in emerging markets and developing economy countries.

Vijay Swarup is senior technology director, ExxonMobil Corporation. Robert Armstrong (NAE) is director, MIT Energy Initiative, and Chevron Professor, Department of Chemical Engineering, Massachusetts Institute of Technology.

TABLE 1 Global primary energy mix, 2000 vs. 2019. Reprinted with permission from NPC (2022).

Fuel mix primary energy				Fuel mix electricity		
coal/oil/gas ~80%				coal/oil/gas ~63-65%		
	2000	**2019**			**2000**	**2019**
Coal	23%	26%		Coal	39%	38%
Oil	36%	31%		Oil	8%	2%
Gas	21%	23%		Gas	18%	23%
Nuclear	7%	5%		Nuclear	17%	10%
Hydro	2%	3%		Hydro	17%	16%
Biomass	10%	10%		Biomass	1%	3%
Renewables	1%	2%		Renewables	0%	8% (including solar and wind)

Engineers are problem solvers, developing, deploying, and operating technology solutions to address societal challenges affordably and reliably.[1] They will be integral in the shifts in energy sources and the development and scaling of technologies and tools to support sustainability and lifecycle pathways. And engineers will be counted on to deliver

- research, development, demonstration, and deployment of existing and new technologies and infrastructure; and
- the educated and trained workforce with the skills needed for the energy transition.

For the energy transition, a variety of engineering—and other—disciplines will need to integrate chemical, physical, mathematical, and biological elements to conceive, design, build, and operate processes, produce materials, and deliver services for future energy systems. The fundamentals of the various disciplines will not change, but the ways engineers understand and apply these principles to develop and deploy energy solutions at scale have to evolve.

Beyond their technical expertise, engineers have a responsibility to engage with policymakers, educators, and local communities to ensure that improvements associated with the transition are equitably allocated and that opportunities are broadly shared and accessible.

Shifts in Energy Sources and Technologies

Engineers over the past several decades have continuously grown and optimized the energy system—chemical reactors have become bigger; offshore windmills are now at 15 MW capacity with 240-meter rotor diameter; and cars are lighter, safer, and more fuel efficient.

But oil, gas, and coal still make up most of the global primary energy (80 percent) and electricity generation (63 percent) (table 1; NPC 2022). It is important to note that although global coal use for electricity generation decreased only 1 percent between 2000 and 2019, in the United States it fell 52 percent between 2005 and 2019 (Davis 2022). During that time, US electricity generation by natural gas increased by 116 percent (Davis 2022), largely because of falling natural gas prices due to shale gas developments (Coglianese et al. 2020; Davis et al. 2021, 2022; Fell and Kaffine 2018). This transition to gas led to emissions reductions in the United States (EPA 2022).

The energy transition will require multiple energy sources to be deployed at scale. Figure 1 shows the range and scale of energy sources to limit global temperature rise to less than 2°C above preindustrial levels (IPCC 2022) or for net zero emissions by 2050 (temperature rise less than 1.5°C; ExxonMobil 2023; IEA 2021).

There will be much more emphasis on wind, solar, bioenergy, and other renewables relative to today's mix. Their development and deployment at the scale needed will entail multiple technologies, not only for harvesting solar and wind resources but also for storage (of many durations), transmission and distribution, advanced power electronics, and so on. Engineering demands of scale will involve both magnitude and geographic distribution, with the development of integrated energy systems tailored for specific geographies.

Continuous energy is a prerequisite—there can be no gap in energy supply while changing sources, carriers,

[1] For example, a recent report provides an overview of the criticality of chemical engineering including in energy (NASEM 2022).

infrastructure, or any other aspects of the energy ecosystem. Contributions from diverse disciplines must maintain and improve existing energy systems such as solar, wind, fission, oil, and gas, while new systems such as geothermal, hydrogen, carbon capture and sequestration, carbon removal, synthetic fuel production, and biofuels are developed, deployed, and scaled.

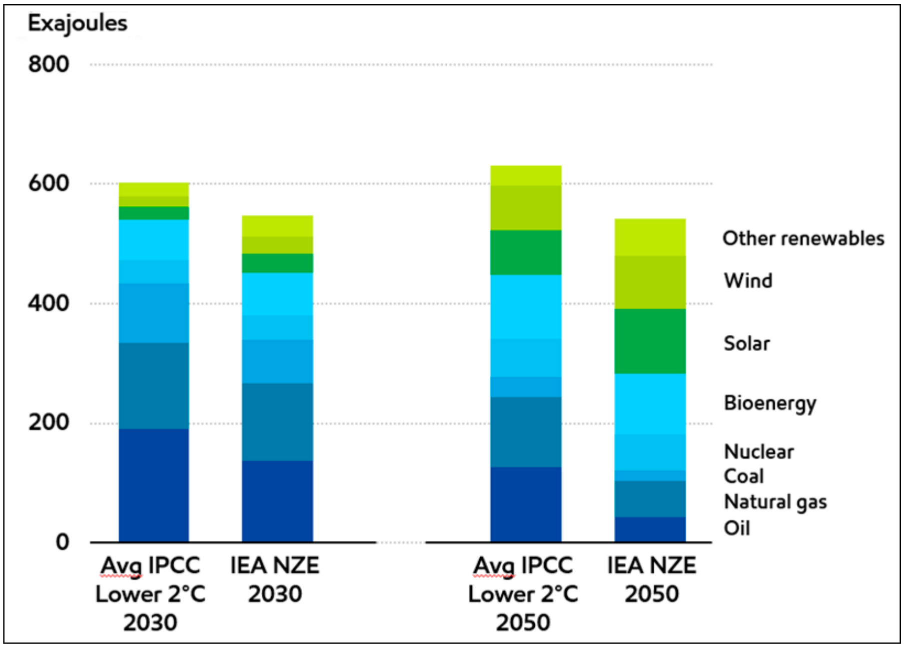


FIGURE 1 Global energy demand mix in 2030 and 2050 across the Intergovernmental Panel on Climate Change (IPCC) lower 2°C and International Energy Agency (IEA) net zero emissions (NZE) scenarios. Source: ExxonMobil (2023).

Tools for Sustainability

Improved tools for policymakers, investors, and strategic planners are equally important. Developing these tools demands engineering skills to (i) define potential pathways and their components and (ii) conduct assessments for both costs and lifecycle emissions.

In addition, mining, extraction, and processing of minerals must be greatly expanded—while drastically reducing their environmental impacts. Plastics recycling, lower-energy computing systems, and other emerging technologies must be deployed and scaled throughout the global economy. This will add multiple new pathways to the energy life cycle, from source to conversion to use.

MIT has developed the Sustainable Energy System Analysis Modeling Environment (SESAME) tool to compare energy pathways (including the life cycle) in terms of emissions and cost. Its modular design allows for new process steps to be modeled and incorporated as technologies emerge. Integrated models like SESAME will accelerate the assessment of energy pathways and help drive deployment (Gençer et al. 2020; Miller et al. 2020).

Recent assessments of gaps in the innovation and deployment necessary to meet climate goals drive home the significant and widespread opportunities for engineering progress. A White House (2022) paper highlights 37 game-changing innovations that could enable a net zero economy by 2050. But an IEA (2023) report shows that, out of more than 50 identified technologies in eight categories, only 2 (lighting, electric vehicles) are on track for contributing to a 2°C future (figure 3).

Research, Development, Demonstration, and Deployment

As engineers determine and advance solutions, mitigation and adaptation technologies will have to be developed and deployed at scale. Engineers will be central in defining the pathways to scale, to both meet the magnitude of energy required and bring down costs. Such efforts will draw on engineering systems–level approaches.

The current approach to research and development is primarily a series approach: programs pass sequentially through stages. To accelerate progress from research to deployment, we propose a parallel approach. Decision making must incorporate multiscale systems-level thinking, accounting for both scale-up and scale-out, to help prioritize technology options and design pathways to scale. Of course, the iterative process of design, build, test, and reiterate will also need to speed up.

Engineers must work across engineering and other disciplines to address the following in the energy value chain:

- *Improved efficiency:* Engineers will continue to provide options to improve the efficiency of current energy systems (e.g., through fuels, lightweight plastics, resilient grids).

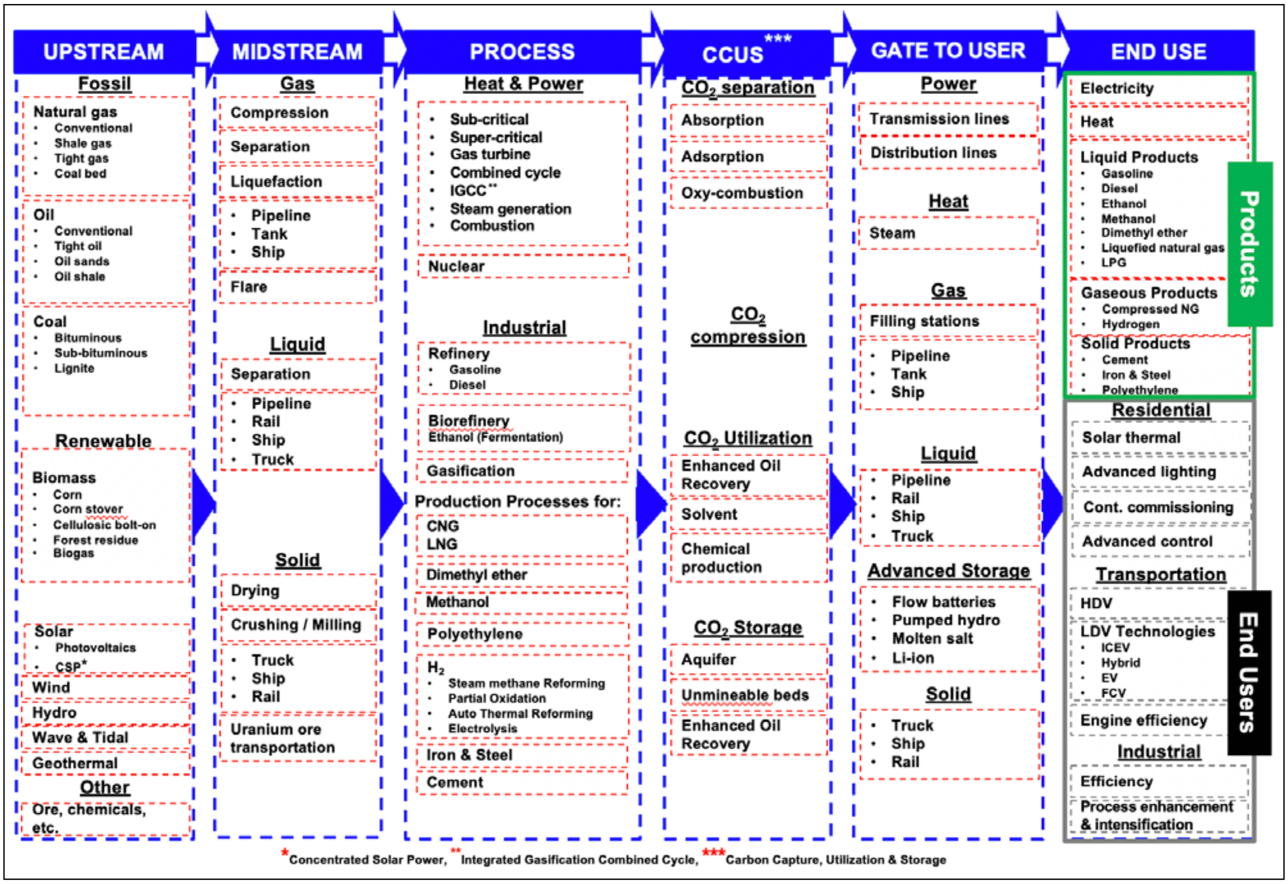


FIGURE 2 The MIT Sustainable Energy System Analysis Modeling Environment (SESAME) has a modular structure with six lifecycle stages. Existing and new energy pathways can be constructed and analyzed for lifecycle emissions and cost by combining modules in the six columns. Reprinted with permission from Gençer et al. (2020).

- *Systems-level integration:* As an example, increased deployment of intermittent energy resources such as solar and wind will depend on grid-scale storage and firm power. Their integration will also involve cross-sector opportunities.
- *Materials and processes:* Conversion and separations are foundational to energy. Both have seen advances, but energy delivery remains very energy intensive. New materials and processes that allow for lower-temperature and -pressure conversion and separations can help significantly reduce emissions.
- *Manufacturing:* Process intensification steps, together with new process components and configurations, must be developed and deployed to produce energy with lower carbon emissions. Entirely new manufacturing processes may be needed for new technologies (e.g., components of potential fusion devices).
- *Carbon dioxide (CO_2) removal:* Net zero targets can be achieved only with negative carbon emissions technologies, which necessitate advances in direct air capture (integration of materials and processes) and nature-based solutions (integration of biology and analytical chemistry to measure and verify CO_2 removal).
- *New routes to fuels:* A circular economy will involve production of fuels from carbon dioxide and water. Engineers can enable this through, for example, advances in electrolyzers, methods for CO_2 reduction, and new and cost-effective routes to making hydrocarbons from nonfossil fuel resources.
- *Nuclear fission and fusion:* Advances in small modular nuclear fission reactors suggest that nuclear energy can provide safe, reliable, emission-free power. Fusion continues to be of interest if economic and scalable pathways can be developed.

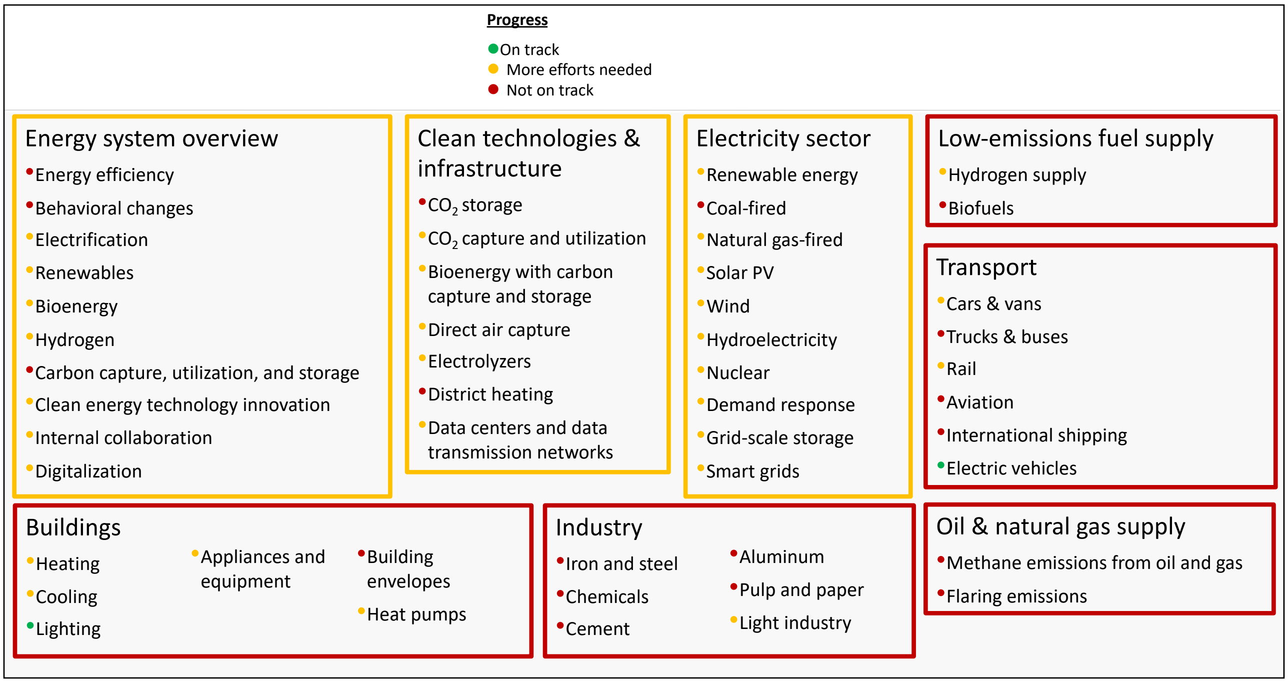


FIGURE 3 Technology progress needed to limit global warming to no more than 2°C above preindustrial levels. Based on data from IEA (2023).

Engineers will be essential in defining the steps to advance concepts to scale, but progress will demand collaboration between disciplines as well as between academia, national labs, and small and large companies. Progressing several ideas at multiple scales, in parallel, will be critical to accelerate technology advances.

The energy transition is a challenge designed for engineers to address: multiple time and physical scales, inter- and intraregional processes, and collaboration with policymakers and other stakeholders. Engineers can be the consummate integrators in the massive efforts to address this challenge.

New Skills and Directions

Understanding of the fundamentals of chemistry, physics, biology, and math on which engineering relies continues to improve, and capabilities and approaches for using them in the service of society will continue to evolve. Slide rules have evolved to exascale computers and biologists now have gene editing capabilities. Further changes are on the horizon, and engineers will be key to integrating new capacities such as the following:

- Computing speed will enter a new paradigm with quantum computing.
- Machine learning and AI will continue to accelerate.
- Magnets, batteries, and photovoltaic cells will utilize a broader range of metals.
- New materials will emerge, including biomaterials for conversion and separation.
- Process intensification and integration will use electric heat instead of burning fuel for heat.

Engineers will use systems-level thinking to consider carbon accounting and costs, for example. New or upgraded infrastructure that accommodates both inter- and intraregional requirements will underpin new value chains. Engineers will design energy systems fit for purpose, differentiating urban vs. rural and developed vs. emerging market economies.

The shift from high to low capacity factor energy systems will be effected by engineers. In addition to development and deployment at scale, the shift will involve energy storage, integration across sectors, firm power, and decarbonization steps like carbon capture and carbon removal (e.g., direct air capture and nature-based solutions). Again, each of these areas will entail integration across engineering disciplines to advance technologies.

Novel materials will be needed, as will new skills for discovery and assessment of new compositions, faster ways to screen for scalability, new production processes, and new methods to use the materials.

And, of course, digital solutions will be integrally involved, in, for example, demand-side management, vehicle-to-grid integration, materials discovery, and supply chain management. Engineers will be called on to leverage digital capabilities, including AI, to accelerate progress from idea to large-scale commercialization.

Engagement with Policymakers, Local Communities, and Others

Engineers have the skills to play a central role in developing roadmaps and models to guide policymakers and society through the energy transition. Understanding the theoretical limits of technologies will be particularly important, given the urgency of the transition. Engineers will need to work with economists and policymakers to translate theoretical limits to practical cost targets and deployment rates. Such knowledge will help define the potential for a technology or pathway and inform policies to accelerate deployment.

Engineers must work with community groups and urban planners, among others, to obtain buy-in and ensure equitable treatment.

In addition to technology, infrastructure must be assessed, planned, and built, in collaboration with economists, regulators, and policymakers. Again, engineers will play a vital role in defining and anticipating the scale (magnitude and location) of critical infrastructure such as pipelines, transmission lines, and energy storage locations.

Engineers must also work with community groups and urban planners, among others, to obtain buy-in and ensure equitable treatment essential for both political action and the permitting of energy developments.

Ensuring a Just Transition

Navigation of the energy transition will depend on a strong and appropriately skilled workforce, with a variety of STEM talent as well as diverse backgrounds and viewpoints. Inclusion of diverse perspectives, together with robust and respectful exchange of ideas, will be key to developing the range of solutions to ensure an effective, just, and sustainable energy transition.

As engineers consider a project's metrics and specifications (e.g., cost, time, and performance), it is commonplace to consider not only "averages" but also "distributions" and, particularly, to develop "robust" solutions that minimize downside risks. In the energy transition, there will be a distribution of costs and benefits in terms of geography, industry sectors, and populations. Engineers can use probabilistic robust design approaches to rigorously analyze the distributions of costs and benefits in engineering systems–level decisions and calculations about least cost and highest performance, while considering ways to minimize downside costs and risks of these systems. They should seek ways to optimize the robustness of solutions and quantify trade-offs among cost, performance, and distribution.

Careful engineering analysis will help to determine not only the fastest and most economical pathways from today's energy system to net zero systems but also those that are just and equitable. Environmental burdens on minoritized and economically challenged communities, as well as the dislocation of workers whose jobs depend on current energy systems, should be explicitly considered in proposed plans.

Conclusion

The energy transition will take decades, during which engineers must look for ways to expedite progress. Engineers understand constancy of purpose, which will be required to navigate the extended process. There will be shifts in relative emphasis on fundamental research, applied science, and scaling, as well as scale-out and scale-up concepts.

Engineers will be counted on to discover, develop, deploy, and integrate solutions at both regional and global scales. Efforts to address the effects of climate change demand new systems-level thinking to develop reliable and affordable energy systems while reducing emissions regionally and globally, with both mitigation and adaptation solutions.

Education and development of next-generation leaders is essential. Collaboration will be critical to accelerate the development and deployment of new technology. Academia, government, and industry will be called on to explore new ways to work together. Industrial collaboration can bring together the requisite skills to advance ideas to the project stage and share the risk/benefit of new technologies as they enter the deployment phase. Engineers will work with scientists (as is common today) as well as social scientists, economists, business/management experts, and policymakers.

All this must be done without any disruption to the energy that undergirds modern life, and must support a transition that is socially just and equitable.

The fundamental role of an engineer is to create and innovate to provide solutions to society's challenges. The energy transition presents an exceptional challenge—and opportunities—for engineers in virtually every discipline and all over the world.

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Wind energy and EVs have demonstrated the value of wise materials choices and point the way forward for other clean energy technologies.

Critical Materials for Low-Carbon Technologies in US Markets

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Alexander H. King

The deployment of any new technology at large scale burdens the supply of the materials from which it is made, and the availability (or lack thereof) of those materials can, in turn, impact the deployment of the technology. Here, I describe the impact of materials availability on the progress of recently emerging technologies, and identify materials that may be needed in a growing clean energy economy. Based on anticipated needs and recent case studies, I offer approaches to the problem that may be effective in reducing the threat of material unavailability as a barrier to clean energy deployment.

Introduction

Technologies that grow to large scales cause changes in demand for the materials from which they are made. Thus in the 19th century the advent of railroads in the United States spurred the development of a robust steel industry, and in the 20th century the growth of aviation relied on efficient production of aluminum alloys. Today, new and evolving technologies require an ever greater variety of elements (King 2019), and even small-scale emerging technologies can stress the supplies of materials that are produced in small quantities.

Rapid growth in the demand for materials may outstrip the capacity for developing new sources, which can take two decades or more (Ali et al. 2017). Emerging clean energy technologies have already impacted the supplies of several materials and can be expected to affect more of them as the world's energy portfolio becomes cleaner and more diverse.

Constrained supplies of materials also affect the adoption of new technologies, as illustrated in the following examination of the complex interactions between materials supplies and clean energy technology adoption. I describe the widely used definition of critical materials, explain factors that influence their criticality, and consider some of the materials that may become critical for specific energy-related technologies.

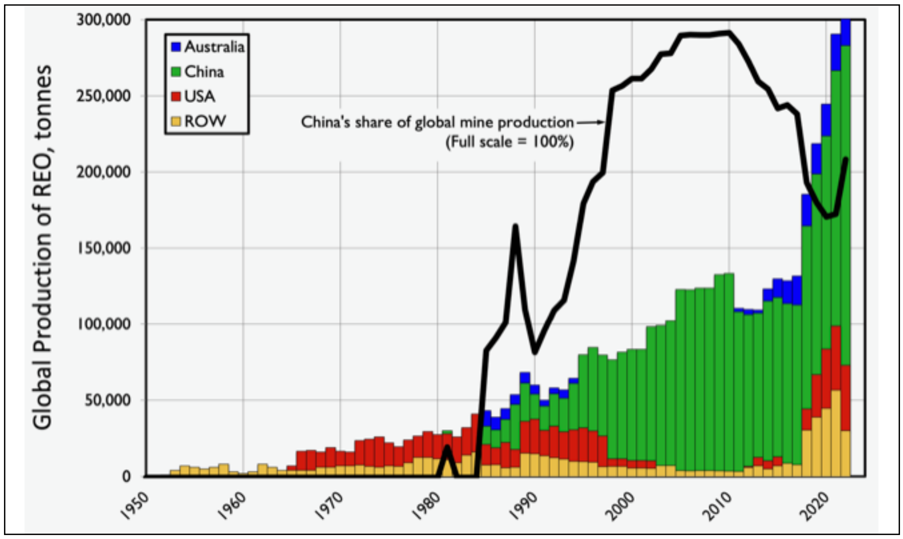

FIGURE 1 Principal national contributions to global rare earth oxide (REO) production from 1950 to 2022. Quantities are the total amounts of REO produced annually. The rest of the world (ROW) comprises smaller producers. China's percentage of total REO mine production is represented by the heavy black line. Data from annual USGS Mineral Commodity Summaries.

Recent Impacts of Materials Supply Challenges on the Energy Sector

Wind Energy

Since the mid-2000s, wind has been the second-fastest-growing source of energy for generating electricity in the United States, behind natural gas (EIA 2022).

Several generator technologies can be used in wind turbine systems, but they generally fall into two categories: direct-drive generators that turn at the same rate as the turbine blades and require powerful permanent magnets; or electromagnetic induction generators that require higher rotation rates, which are achieved by coupling them to the turbine blades through gearboxes.

Direct-drive systems are more efficient, quieter, and avoid the risk of gearbox failures that are the most common cause of downtime for induction generator systems (Faulstich et al. 2011). However, the magnets required for direct-drive generators are made from neodymium-iron-boron, with neodymium partly substituted by other rare earth elements (REEs) in many cases.

As wind energy started to emerge, China commanded a large and growing share of global REE mine production (figure 1), and it announced export restrictions in 2005. With questionable supplies of the REEs needed for the direct-drive technology, land-based wind turbines in Europe and North America almost exclusively used induction generator systems, with resulting impacts on efficiency, site selection, and reliability (King 2020). China's dominance of rare earth mining diminished from 2010 to 2020, and although it has recently regained some share of mining and still processes much of the ore extracted elsewhere, there is cautious optimism that a robust global supply chain will eventually emerge.

When the wind energy focus shifted from onshore to offshore installations, the technology was able to move to direct-drive systems that avoid the gearbox maintenance and repair issues that are so much more challenging at greater heights and in marine environments. Concerns about REE supply were allayed by the emergence of new sources and intense R&D efforts on magnet materials and generator designs that reduced the REE quantities required (particularly the heavy rare earths dysprosium and terbium), so the new offshore turbines can use direct-drive technology.

In this case, technology choices arising from supply concerns initially compromised the decarbonization impact of a clean energy technology, but materials supply and performance challenges are continuously being overcome, allowing for ever greater effectiveness.

Lighting

The mid-2010s saw an unanticipated collapse of the market for fluorescent lighting as it was rapidly overtaken by LEDs (Navigant Consulting Inc. 2012, 2014). LEDs represent a significant improvement in terms of energy efficiency, but the twin drivers for this revolution were the rising cost of producing fluorescent lamps (because of their reliance on the REEs europium and terbium) and the falling cost of LEDs (driven by improvements in the technology). The price per lumen for LEDs dropped below that of fluorescent lamps in 2013, and the "rare earth crisis" of that time, coupled with conventional free market forces, helped to accelerate this step in the clean energy revolution.

The wind and LED stories are linked by their needs for the same materials. Until 2013 fluorescent lamps were the largest global consumer of both europium and terbium; demand for these elements in lighting applications has slowed since then. Rare earth magnets used in large motors and generators are based on the compound $Nd_2Fe_{14}B$, and the inclusion of up to a few percent of dysprosium improves the performance of these magnets, especially at elevated temperature. Terbium has the same effect as dysprosium and has been used in magnets at increasing levels since the decline of its demand for fluorescent lighting. The reduction in demand for terbium in lighting thus helps to alleviate the shortage of dysprosium for magnets (King 2020).

Electric Vehicles

The revolution in electric vehicles started in 2008 with the introduction of Tesla's first commercial vehicle, the Roadster. At the time, 98 percent of global REE mining was in China, which was threatening ever more stringent export restrictions on the materials needed for high-strength permanent magnets.

Choice of energy storage system depends on several factors, with material cost and availability offsetting performance issues such as power density.

Tesla began with a distinctive marketing strategy. The Roadster was produced in small numbers and it was expensive; target customers were not particularly price-sensitive and the car competed against luxury sportscars with internal combustion engines—its key distinguishing features from a marketing perspective were acceleration and handling. Tesla continued to compete in the same market niche when it introduced the Model S and Model X.

All of Tesla's first three cars used induction technology for their tractor motors, avoiding the need for permanent magnets and concerns about rare earth supplies. Induction motors can produce greater torque and acceleration than permanent magnet (PM) motors, playing well into the market niche at which they were aimed. There are, however, a few downsides: induction motors are more complicated than PM motors, require more complex control software, are more failure-prone, and convert stored energy to mechanical work less efficiently.

Tesla's marketing strategy shifted toward the mass market with the introduction of the Model 3 in 2017 and the Model Y in 2020. Manufacturers' concerns about rare earth supplies had somewhat abated by this time, the target consumer was more focused on range (and hence efficiency) than acceleration, and the long-range versions of the new cars featured one PM motor with rare earth magnets (to drive the rear wheels) and one induction motor (for the front wheels). In 2023 Tesla announced that it had developed a new PM motor that uses no rare earth elements, potentially removing concerns about future REE supplies for EVs.

As other manufacturers have entered the EV market, they have made a variety of choices for their traction motors, reflecting different values placed on acceleration, range, reliability, and supply risks. Greater efficiency generally comes from PM motors, but performance, market penetration, and rapid deployment remain critical interests amid efforts to combat rising global temperatures and may be better served by attending to other concerns.

Technology choices are also important in the selection of onboard energy storage systems for EVs. Most of the attention is on lithium-ion batteries, which currently offer the greatest range, but several varieties of these contain varying quantities of cobalt, iron, and nickel in addition to lithium (Marom et al. 2011); nickel-metal-hydride remains a lower-cost, lower-performance option in some markets. Fuel cell systems based on hydrogen or natural gas add further options and may gain market share if battery materials face supply challenges. The choice of an energy storage system depends on several factors, with material cost and availability offsetting performance issues such as power density.

The Takeaway from These Cases

The cases of power generation, lighting, and electric vehicles show that questionable supplies of essential materials have mostly negative impacts on both the adoption of new technologies and the efficacy of the technologies' first generations. Rapid deployment of clean energy systems may be of greater benefit to the environment than pursuing the greatest possible motor efficiency or energy storage capacity using more ideal materials or technologies (Lesk et al. 2022). Efficiency can be expected to improve as the systems evolve.

What Are Critical Materials?

The concept of a critical mineral stems from a National Research Council report (NRC 2008), and the definition has also been applied to critical materials, which are distinct in certain respects from critical minerals. While critical minerals may be the ores from which critical materials are derived, they tend to be defined in terms of overall demand for the downstream materials across all their uses. Critical materials, on the other hand, are defined in the context of their applications, and a material may be critical for some of its uses but not for others. If a material is critical for a niche application that consumes only a small fraction of the global output, the minerals from which it is derived may not be classified as critical.

A critical material (or mineral) meets two conditions:

1. it is essential for a particular technology, corporation, business sector, or regional economy; and
2. it has some degree of supply chain fragility within a timescale of relevance.

Materials may be considered essential for a variety of reasons but usually rank highly if they embody specific properties such as catalytic activity, density, electrical or thermal conductivity (or lack thereof), magnetism, neutronics, photonics, mechanical strength, or combinations of these properties, any of which may be significant in particular clean energy technologies. The assessment of essentiality is typically only semiquantitative and is based on factors that include measurable performance indicators and substitutability, which is usually more a matter of "expert" opinion.

Supply chain fragility is also assessed semiquantitatively and depends on factors such as the capacity of the global supply chain to adjust to meet anticipated demands and its vulnerability to natural and other threats. Materials that depend on single global sources tend to have higher fragility scores than those available from a variety of sources; for those with only a single source, the potential for them to be cut off is a significant consideration. Materials that are coproduced with other materials are considered vulnerable (Nassar et al. 2015). Finally, coproduction tends to reduce the effectiveness of the supply-demand dynamic for less-produced or lower-valued materials, making them less responsive to traditional market forces and increasing their supply chain fragility.

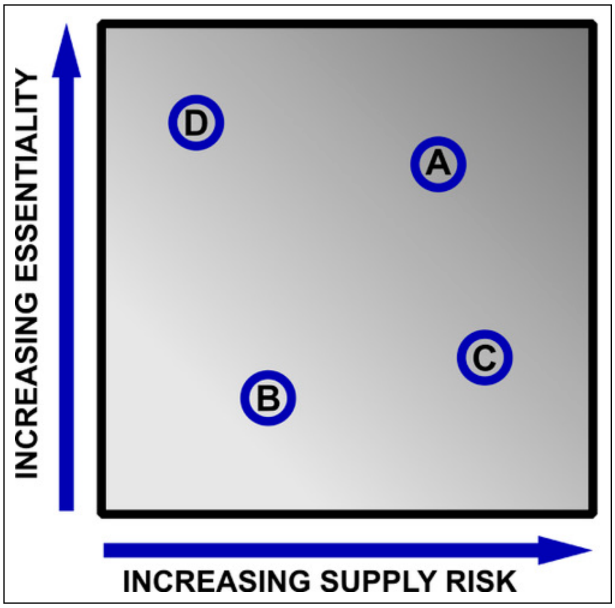

FIGURE 2 Classification of materials according to their supply risk and their importance to a particular application. Material A has greater supply risk and greater consequences from a supply disruption, so it is considered more critical than Material B. Material C has about the same level of essentiality as Material B, but a greater supply risk than any of the other materials. Material D has a greater level of essentiality than the others, but a lower supply risk. It is not clear how Materials C and D should be ranked against Materials A and B in terms of their criticality, or whether that is even a useful question.

Several studies have produced rankings of material criticality that are typically summarized in plots of the form shown in figure 2. The definitions of "essentiality" and "supply chain fragility" used in these studies, and the weighting of the different components considered, vary depending on the geographical region, industrial sector or product, and the concerns, preferences, or biases of those performing the studies (Schrijvers et al. 2020). Notwithstanding those variabilities, some consensus emerges based on specific applications of a material: Criticality studies of materials required for decarbonization or the development of clean energy technologies globally (APS 2011), in the United States (DOE 2010), and in Europe (Moss et al. 2013) agreed that rare earth elements are highly critical because of (i) their essential roles in making catalysts, light-emitting devices, and strong permanent magnets and (ii) their supply chain vulnerabilities associated with coproduction and China's dominance of their extraction and processing.

Many of the materials required for decarbonization of the energy sector fall into categories where short- or long-term shortages can be expected.

But rare earths are not the only materials that are critical for the transition to clean energy technologies. Lists of critical materials published over the past 15 years include some that focus on clean energy or decarbonization technologies and others that focus on regional economies. A consistent theme is the rise over a relatively short period in the number of materials identified as critical. The first list published by the US government addressed the needs for clean energy technologies and identified just six critical materials (DOE 2010); the most recent (USGS 2023) lists 50 across all sectors of the US economy, of which 37 relate to clean energy technologies.

Plots of the form shown in figure 2 have become popular and have certain uses, but they are not necessarily the best way to analyze the criticality of any particular material. They do not, for example, provide rigorous risk assessments associated with reliance on a potentially critical material (Gloeser et al. 2015), and they are most commonly retrospective, addressing historical supply and demand data, or relying on relatively simple projections if they address future needs. They also tend to focus on reducing materials criticality either by increasing supplies (addressing the horizontal axis) or inventing alternative materials (addressing the vertical axis) although these are not the only options, as explained in the next section.

How Criticality Emerges

When supply shortfalls are threatened, prices rise. This may stimulate increased production, but the process is less straightforward than one would hope.

When the demand for a material grows in response to a growing industry, existing sources may be able to increase their output to meet some of the demand in the short term but the capacity to do this can be quite limited. On the other hand, nonessential uses of the material are displaced, freeing up supplies for more critical uses, as seen in the case of REEs in fluorescent lighting. Meanwhile, the process of identifying and commissioning new sources can take as long as 20 years, risking the loss of a new technology's window of opportunity. And in some cases, the necessary mineral sources may fail to increase production if the material in question is not the primary revenue generator for its source mineral (Nassar et al. 2015), or the necessary geological resources may simply not exist.

Many of the materials required for decarbonization of the energy sector fall into categories where short- or long-term shortages can be expected. The materials that cause the greatest concern are those for which

1. the interplay between consumption, production, and price is disrupted so increased demand does not result in increasing supply. This applies particularly to materials that are minor byproducts of others and where there is geopolitical interference in the supply chain: both conditions apply to the rare earths.
2. there is a large time lag between increased demand and increased supply, so the time responses of supply and demand are out of phase with the shifting needs, with the result that the supplies do not emerge within the time window for adoption of a particular technology. This applies mostly to materials for which new sources must be found and/or developed to meet a growth in demand: it has repeatedly impacted supplies of cobalt over the last 50 years and will probably apply to beryllium if plasma fusion emerges as a viable energy source.

How Criticality Evolves

When a material becomes critical, efforts are made to increase supplies (from either primary sources or recycling) or reduce need by identifying substitute materials. Both of these approaches, however, usually take too long to meet the needs of emerging technologies. Manufacturers frequently find other ways to work around needs for materials for which there are doubtful supplies,

TABLE 1 Materials that are or may become critical for emerging clean energy technologies and whose limited supply may impede the development of such technologies. Data from USGS (2023).

USGS-listed critical materials, 2022

		Aluminum	Antimony	Arsenic	Barite	Beryllium	Bismuth	Cerium	Chromium	Cobalt	Dysprosium	Europium	Gadolinium	Gallium	Germanium	Graphite	Hafnium	Holmium	Indium	Iridium	Lanthanum	Lithium	Magnesium	Manganese	Neodymium	Nickel	Niobium	Platinum	Praseodymium	Samarium	Scandium	Tantalum	Tellurium	Terbium	Tin	Titanium	Yttrium	Zinc	Zirconium
Receding technologies																																							
Storage	Ni-M-H batteries									•											•				•	•													
Lighting	Fluorescent							•				•																						•			•		
Existing technologies with growth potential																																							
Magnets	NdFeB										•							•							•				•					•					
Magnets	SmCo									•																				•									
Magnets	AlNiCo	•								•																•	•									•			
Magnets	Ferrite				•																																	•	
Magnets	Electromagnets																																						
Solar PV	Silicon			•				•											•																•				
Solar PV	Cd-Te																		•														•		•				
Nuclear	Fission (Uranium)								•							•	•	•								•													•
Grid	Power mgmt			•										•		•																•							
Grid	Transformers																																						
Grid	Conductors	•																																					
Batteries	Li-ion									•						•						•		•		•													
Lighting	LED	•		•				•						•					•																		•		
Vehicles	Lightweighting	•				•																	•		•						•					•			
Combustion	High-temping	•						•	•								•					•					•	•			•					•			•
Potential or emerging technologies																																							
Solar PV	Perovskite																		•																•				
Nuclear	Fusion (plasma)				•	•			•													•				•											•		
Nuclear	Fission (thorium)					•			•							•	•	•								•													•
Hydrogen	Water splitting													•					•	•																			
HVAC	Magnetocalorics	•	•							•			•	•	•				•		•			•		•													
HVAC	Thermoelectrics		•				•																										•						

Other potentially critical materials

		Cadmium	Carbon fiber	Cesium	Copper	Fluorine	Iodine	Iron	Lead	Mercury	Molybdenum	Phosphorus	Rhenium	Selenium	Silicon	Strontium	Thorium	Uranium
Receding technologies																		
Storage	Ni-M-H batteries																	
Lighting	Fluorescent									•								
Existing technologies with growth potential																		
Magnets	NdFeB							•										
Magnets	SmCo																	
Magnets	AlNiCo				•													
Magnets	Ferrite							•								•		
Magnets	Electromagnets				•			•										
Solar PV	Silicon														•			
Solar PV	Cd-Te	•																
Nuclear	Fission (Uranium)																•	•
Grid	Power mgmt														•			
Grid	Transformers							•							•			
Grid	Conductors				•													
Batteries	Li-ion																	
Lighting	LED																	
Vehicles	Lightweighting		•															
Combustion	High-temping										•		•					
Potential or emerging technologies																		
Solar PV	Perovskite			•			•		•									
Nuclear	Fusion (plasma)				•	•					•							
Nuclear	Fission (thorium)							•									•	
Hydrogen	Water splitting																	
HVAC	Magnetocalorics							•				•			•			
HVAC	Thermoelectrics													•				

and solutions have been highly nuanced, focusing on improvements rather than revolutions in supply or materials use, and acceptable compromises on performance.

Technologies evolve most rapidly when they are new. Thus, for example, traction motors and batteries are undergoing rapid development as the market for EVs grows. In some cases research and development efforts are aimed at improving performance and in some they are driven by reducing reliance on critical materials, but every advance involves changes to the palette of materials—and changes the criticality landscape. Technology evolution also impacts recycling, as older devices that reach the end of their life after a few years of service may not match the compositions of current technologies.

Critical Materials in Emerging and Growing Clean Energy Technologies

Creating lists of critical materials has become a cottage industry since 2010 and there has been a steady growth in the number of materials considered critical over that time. USGS now publishes a list of minerals critical for the United States at least every three years. More than two-thirds of the 50 minerals on its most recent list (USGS 2023) are used in current or emerging energy production, storage, or utilization technologies.

Table 1 shows 37 energy-related materials from the USGS (2023) list and the clean energy technologies that they might impact. The table also identifies 17 additional materials, not currently listed by USGS, that *could* impact emerging clean energy technologies in the coming decades.

In almost all cases, Earth's crust contains sufficient mineral resources to provide the materials required to produce enough clean electrical power to meet immediate climate goals. But it is not clear that the necessary extraction rates can be achieved, environmental impacts from mining can be controlled, or ethical workforce practices can be assured (Wang et al. 2023).

As seen in the cases of wind, lighting, and EVs, multiple factors that either elevate or alleviate criticality can vary independently over time and occasionally converge to cause tipping points that precipitate supply shortfalls. This particularly impacts emerging technologies.

Efforts directed toward improving supplies or inventing alternatives may reduce the risks for some critical materials, but these strategies cannot respond with sufficient speed to avert supply chain failures once they occur. It is important to conduct proper risk analyses (rather than criticality analyses) for all the materials needed for a new technology and prepare appropriate supply chain strategies for them.

The best choice of material for an emerging technology (along with the design choices that follow from it) may not be the one that produces the best performance if it also causes unacceptable supply chain risks. Wind energy and EVs have demonstrated the value of wise materials choices and acceptable performance compromises and they point the way forward for other clean energy technologies.

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Energy storage is essential to a clean electricity grid, but aggressive decarbonization goals require development of long-duration energy storage technologies.

Energy Storage: A Key Enabler for Renewable Energy

Jeremy Twitchell, Di Wu, and Vincent Sprenkle


Jeremy Twitchell


Di Wu


Vincent Sprenkle

The job of an electric grid operator is, succinctly put, to keep supply and demand in constant balance, as even minor imbalances between the two can damage equipment and cause outages.

This balance is a highly complex undertaking that involves coordinating hundreds of generation units with the demands of millions of individual customers. Historically, this challenge was mitigated by predictability: the generation (supply) side had power plants that could be turned up or down as needed, while the load (demand) side had customers who generally had the same devices in their houses and used them in the same ways. Grid operators knew what was coming and could adjust production to accommodate it.

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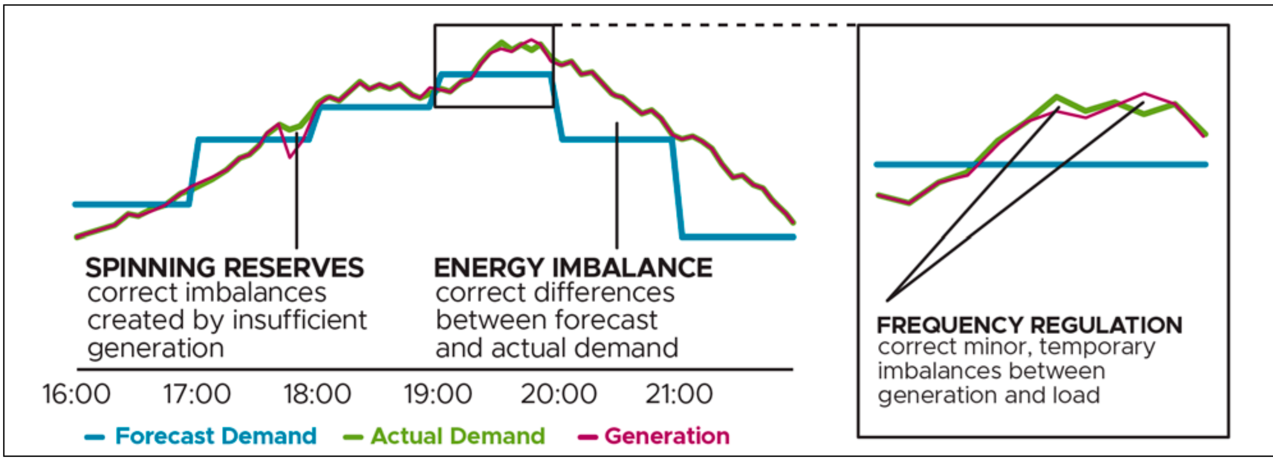

FIGURE 1 Sample illustration of electric ancillary services during peak hours, 4:00–9:00 pm.

Given recent changes in energy supply and demand, energy storage is of increasing interest to ensure reliable and sustainable provision. In this article we explain the current challenges to power supply and demand and then provide an overview of energy storage technologies. Following a summary of the modeling challenges associated with energy storage and recent advances in overcoming those challenges, we discuss systems and technologies needed to maintain a clean and reliable electric grid.

Current Challenges to Power Supply and Demand

Climate change and technological innovations that have made renewable generation financially competitive and increasingly accessible have fundamentally changed the nature of supply and demand. A rapidly increasing share of electricity comes from variable sources, distributed energy resources and electrical vehicles mean that generation can come from just about anywhere on the grid, and customer demands may vary widely.

Fortunately, technical innovations have also delivered new forms of electrical energy storage that can keep generation and load in balance. To maintain that balance, grid operators call on flexible ancillary services to reconcile differences between electric supply and demand. But the services vary in both the size of the differences that they remedy and the duration over which they are employed. Figure 1 illustrates how various ancillary services are used to keep supply and demand in balance during a portion of a 24-hour period, based on a sample day-ahead demand forecast, actual demand, and generation.

The figure shows how flexible resources such as energy storage can help to integrate variable sources of generation such as wind and solar. Moment-to-moment variability in the output of renewable resources requires frequency regulation to absorb peaks and fill in valleys to maintain generation and load balance. Longer-term variability in output (e.g., due to a cloudy day) requires activation of spinning reserves to replace the lost production. And finally, the variable output of distributed energy resources such as rooftop solar can vary the demands of individual customers, requiring energy imbalance resources to correct differences between forecast and actual demand.

Understanding Current Energy Storage Technologies

Energy storage devices are unique among grid assets because they can both withdraw energy from the grid during periods of excess generation and inject energy during periods of insufficient generation. These capabilities make storage an ideal source of both ancillary services and the grid flexibility necessary to incorporate variable energy resources such as wind and solar. However, determining how to optimally deploy energy storage is a challenge under traditional electric grid planning practices, and the rapidly changing grid is creating demand for new long-duration energy storage (LDES) technologies that have not yet been commercially proven.

Energy storage is distinct from other electric grid assets in three important ways:

- *Flexibility:* Because energy storage technologies can act as either a load (when charging) or a generator

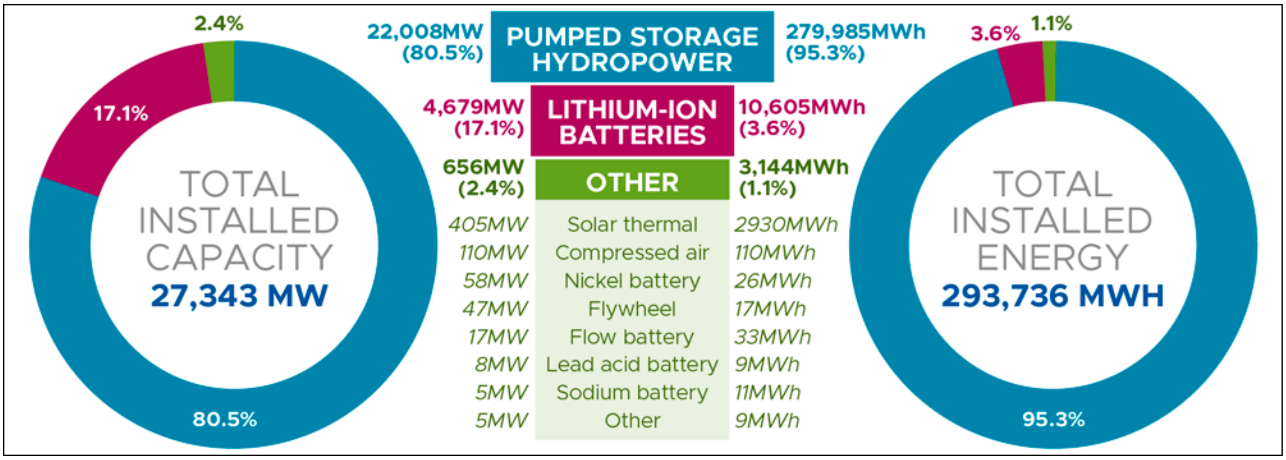

FIGURE 2 Installed energy storage capacity (left) and output (right) by technology in the United States, 2021 (data from EIA 2023). MW = megawatts; MWh = megawatt-hours.

(when discharging), they can provide a range of grid-balancing services.

- *Scalability:* Most energy storage technologies are modular, which allows them to be scaled down to a small device that supports the demands of a single customer or scaled up to a large project that supports the demands of thousands of customers.
- *Duration:* Unlike a power plant that can provide electricity as long as it is connected to its fuel source, energy storage technologies are energy-limited: they store their fuel in a tank and must recharge when that tank is empty.

Because energy storage technologies have different durations, they also have different measurement scales than other grid assets. A generator's capabilities are expressed in its maximum potential output, using kilowatts (kW) or megawatts (MW). But a storage asset's capabilities are generally expressed in terms of its kW or MW output as well as its total energy content, expressed in kilowatt-hours (kWh) or megawatt-hours (MWh).

Virtually all US energy storage projects constructed since 2013 have used lithium-ion batteries. However, despite that growth, pumped storage hydropower accounts for the majority of installed energy storage in the United States.[1] Figure 2 summarizes current US energy storage deployments in both total installed capacity and total installed storage content as of the end of 2022.

[1] Pumped storage hydropower pumps water to a higher elevation and then releases it to run back down through a turbine to generate electricity when needed.

Modeling Challenges

While energy storage can provide tremendous flexibility to integrate variable renewable generation in a distributed or centralized manner, it is challenging to model the optimal usage of an energy storage system (ESS) and fully capture its potential benefits from bundling services. Following are modeling challenges involved in identifying storage needs:

- *Operational characteristics:* The physical capability and operational characteristics of an ESS must be modeled so that it can be fairly evaluated against other resource options. Appropriate models are required to maintain a good balance between fidelity and simplicity.
- *Degradation effects:* An ESS is generally subject to degradation over time, which can affect its performance and reduce its lifespan. Models are needed to capture degradation impacts of different charging and discharging operation and inform the design of charging controls.
- *Use cases and applications:* The required modeling methods and formulation could vary by stakeholders with different objectives and use cases. The services to be evaluated, corresponding energy and power requirement, and reward/benefit calculation must be properly captured and represented. The problem becomes much more complicated when resilience and environmental benefits are considered in addition to economic benefits.
- *Regions and systems:* Modeling and valuing energy storage require a comprehensive understanding of

factors such as the generation mix, grid infrastructure, market structures and rules, distribution system capacity, and load growth rate, which typically vary from one region/system to another.

- *Operational uncertainties:* These are associated with wind and solar generation, electric energy and ancillary service price, and load. Assumption of a perfect forecast may overestimate the benefits of energy storage, so it is important to model operational uncertainties when evaluating the benefits of and developing control strategies for energy storage. Failure to account for uncertainty may result in a model that undervalues the flexibility benefits of storage in adapting to those uncertainties (Sioshansi et al. 2021).
- *Dispatch and control strategies:* An informed control strategy is crucial for realizing the benefits of an ESS. Advanced dispatch and control methods are required to maximize stacked value streams considering various couplings and constraints, such as trade-offs among services, short- and midterm temporal interdependency, degradation effects, and operational uncertainties.

Modeling is much more complicated when resilience and environmental benefits are considered in addition to economic benefits.

There has been a significant effort to develop modeling and optimization methods to tackle these challenges (Wu and Ma 2021). To model the physical capacity of an ESS, a scalar linear system is often used to simplify the dynamics of the energy state. This system is parameterized by constant efficiencies and static limits on charging and discharging power, energy, or state of charge. Nonlinear, high-fidelity models can provide a more accurate representation of ESS operations but at a cost of increasing complexity. Regarding degradation effects, models of varying complexity and accuracy range from fixed lifespan to loss-of-life-only and full models.

Advances in Strategies, Algorithms, and Other Tools

While the exact objective function and constraints typically vary from one storage project to another, modeling and valuation frameworks and problem formulations have been developed for most use cases and applications. Moreover, dispatch and control strategies and algorithms are available for co-optimization, rule-based control, mathematical programming, and hybrid control. There are also stochastic programming, risk-aware control, and learning-based methods to address uncertainties.

In addition, modeling and valuation tools developed during the past few years help various stakeholders identify value streams and evaluate the economic benefits of ESS (Siberry et al. 2022). There exist numerous similarities and differences among these tools, and it is often not easy for users to differentiate among tools and select the most appropriate to meet their specific needs.

To address this challenge, a model selection platform has been developed at Pacific Northwest National Laboratory to review and compare more than 60 energy storage modeling, valuation, and simulation tools developed by the US Department of Energy national laboratories and suggest the best-suited tools based on users' needs and requirements.[2] Users can filter tools based on a few high-level attributes, view a side-by-side comparison table of all tools, or take a quiz to find the best match based on their desired specifications. These tools continue to evolve and improve as the energy storage industry grows and matures.

Technology and Systems Needs

Frequency Regulation Markets

Before 2016, the average duration of utility-scale lithium-ion batteries installed in the United States was about 40 minutes (EIA 2022). At these shorter durations, frequency regulation markets were the only viable market for batteries. In fact, regional implementation (by the regional transmission organization PJM) of a frequency regulation market product designed to compensate batteries based on their unique characteristics played a key role in opening ancillary service markets to energy storage (Chen et al. 2017).

However, frequency regulation markets are relatively shallow compared to other electricity markets, which means they can accommodate much lower levels of par-

[2] PNNL Model Selection Platform, https://msp.pnnl.gov/

TABLE 1 Size of US frequency regulation markets, 2022. Based on data compiled by the authors from regional grid operators' annual reports and regulatory filings.

Market (in alpha order)	Average load	Frequency regulation market size
California Independent System Operator	24,092 MW	1,088 MW (4.5%)
Electric Reliability Council of Texas	44,831 MW	794 MW (1.8%)
Independent System Operator of New England	13,548 MW	91 MW (0.7%)
Midcontinent Independent System Operator	75,362 MW	435 MW (0.6%)
New York Independent System Operator	17,300 MW	300 MW (1.7%)
PJM Interconnection	92,774 MW	800 MW (0.9%)
Southwest Power Pool	48,864 MW	1,256 MW (2.6 %)

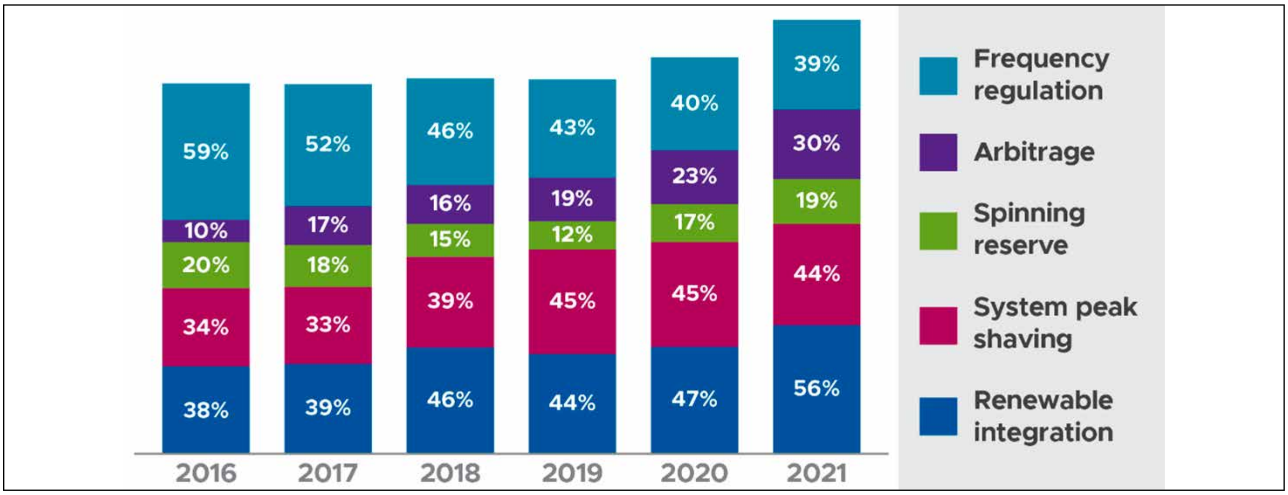

FIGURE 3 Reported energy storage use in the United States, 2016–21. Data from EIA (2022).

ticipation. Table 1 shows the sizes of frequency regulation markets in the seven US wholesale energy markets.

As the table illustrates, the size of each region's frequency regulation market relative to its overall energy market ranges from 0.6 to 4.5 percent. The size of these markets, coupled with competition from other energy resources that can provide frequency regulation, means that opportunities for energy storage to provide frequency regulation have declined in recent years. But at the same time, these changing grid needs, coupled with rapid cost declines, have caused battery storage technologies to evolve to support longer durations and their usage on the grid has changed, as explained in the next section.

Utility-Scale Storage

The Energy Information Administration (EIA) collects data on US utility-scale storage projects, including duration and planned uses. Figure 3 shows how reported uses changed for newly constructed storage projects from 2016 to 2021. Column percentages sum to more than 100 because most storage projects reported multiple uses.

As figure 3 illustrates, the share of newly installed storage systems providing frequency regulation declined from 59 percent in 2016 to 39 percent in 2021, while the share of those providing spinning reserves remained relatively steady. The share of new projects providing peak shaving rose from 34 percent to 44 percent over the period, renewable energy increased from 38 percent to 56 percent, and arbitrage projects tripled from 10 percent to 30 percent.

Both arbitrage and peak shaving involve discharging the battery during peak periods. The difference is that a peak shaving battery is built with multiple hours of duration to help the grid meet peak demands and earn additional revenue through capacity markets, whereas arbitrage involves a shorter-duration battery built purely for economics (charge during the lowest-cost hours and discharge during the highest-cost hours) and either operates in regions with no capacity market or accepts a derated capacity credit if available.

While renewable integration is not a defined grid service, the EIA data capture storage projects that are colocated with renewable generation to help "firm" the renewable output or that charge from excess renewable energy. The data show that there is a positive relationship between variable renewable generation and storage deployments and that, as the uses of energy storage evolve, so does the average duration of new projects (from about 40 minutes in 2016 to about 2.6 hours in 2021).

LDES Technologies for Variable Renewable Resources

LDES technologies will significantly reduce the costs of operating a power system powered solely by variable renewable resources (Dowling et al. 2020). In the event of mismatches between when energy is generated by a fully renewable-power grid and when it is consumed, two classes of LDES would be required to reconcile the mismatches, one up to 20 hours in duration and one with weeks of duration (Twitchell et al. 2023).

A review of several LDES studies identified a consensus that when an electric system reaches 80 percent variable generation, LDES of up to 100 hours would be required to maintain reliability, and a fully variable grid would require LDES of 1,000 hours or more (Albertus et al. 2020). Despite these recognized needs, however, a review of utility planning practices concluded that the common use of short time horizons prevents utilities from fully identifying the value of LDES (Sánchez-Pérez et al. 2022).

Significant research and development are required to provide LDES technologies in the quantities needed for electric system decarbonization. Federal LDES R&D programs include ARPA-E's Duration Addition to electricitY Storage (DAYS) program,[3] designed to support early-stage research into innovative technologies capable of providing 10–100 hours of energy, and the Department of Energy's Long Duration Storage Shot,[4] supporting the development and deployment of commercial storage products with 10–100 hours of duration at competitive costs.

On the commercialization side, iron-air battery developer Form Energy has signed deals with US utilities for three demonstration projects of its technology, which it claims will provide 100 hours of duration (Form Energy 2020, 2023). And ESS Inc., a US-based manufacturer of iron flow batteries with up to 12 hours of duration, has signed multiple agreements globally to deploy its technology.[5] Other technologies, including liquefied air and thermal storage, are also nearing commercial scale (LDES Council and McKinsey & Company 2021).

Summary

Energy storage is an enabling technology for rapid acceleration in renewable energy deployments. It enables flexibility to ensure reliable service to customers when generation fluctuates, whether over momentary periods through frequency regulation or over hours, by capturing renewable generation for use during periods of peak demand.

Progress in the integration of renewable energy requires both significant increases in the amount of energy storage on the grid and the development of new types of energy storage that can ensure reliability over days and seasons. While there is cause for optimism on this front, continued investment in research, development, and deployment of LDES technologies is crucial to enable electric grid decarbonization.

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Numerous existing and emerging technologies can help chemical process and petroleum refining industries decarbonize their operations.

Decarbonization of Chemical Process Industries via Electrification

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In 2018[1] the US manufacturing sector used 19.4 percent of the country's primary energy and emitted 17.5 percent of its total greenhouse gases (GHGs). The top two US energy-use processing industries—chemicals and petroleum refining—use nearly half of the manufacturing sector's primary energy and emit half of its GHGs. The majority of the process energy use in these sectors is for process heating (chemicals ~60 percent, refining ~90 percent).

Electrical energy constitutes only 22 percent of total US chemical process energy use, and nearly three-fourths of that percentage is for machine drives, process cooling, and refrigeration. Historically, most electricity has been generated from the combustion of fossil fuels, and for a unit quantity of energy its cost as electricity is nearly three times that of heat from combustion. As a result, almost all process heating needs are met either by the direct

[1] This is the latest year for which data are available from the Advanced Manufacturing Office of the US Department of Energy (https://www.energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2018-mecs). In this article, all the US manufacturing data are for the year 2018 unless specified otherwise.

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combustion of fossil fuels or through the use of steam raised directly or indirectly through the combustion of such fuels.

With emerging solar and wind, energy is directly harvested as electricity, making it important to examine the impact of replacing combustion heat with electrical energy. We discuss challenges and opportunities associated with the potential use of electricity in the US chemical manufacturing and petroleum refining industries.[2]

Electrification of the US Chemical Manufacturing and Petroleum Refining Sectors

According to the US Energy Information Administration (EIA 2022a), in 2022 total US electricity generation was 4,243 terawatt-hours (TWh), of which 580 TWh were from wind and solar using photovoltaics (PV). EIA estimates that by 2050 total US electricity generation from wind and solar will exceed 1,900 TWh—more than the total anticipated increase in electricity generation of 1,157 TWh. The generation of zero carbon electricity from sources such as hydroelectric and nuclear is expected to remain virtually unchanged.

Examining the electrification of the US chemical manufacturing sector against this evolving electricity generation landscape, we see two macrolevel barriers. The total process energy used by the two sectors in 2018 was 1,784 TWh. If we assume the process efficiencies to be similar if heat were provided by electricity, then the electricity demand in 2018 for these two sectors would have been 42 percent of the total US electricity generated that year and close to the anticipated solar and wind generation in 2050.

The first challenge is the strain this demand would place on electric power infrastructure (i.e., production, transmission, and distribution). The second stems from the fact that most large-scale chemical manufacturing and petroleum refining plants operate around the clock, whereas wind and solar electricity are variable in nature and their average available time ranges from 20 percent to 40 percent of a 24-hour period.

The variable renewable electricity (VRE) of wind and solar presents another challenge: the need for either massive energy storage or process plant redesign to enable load following. The latter would mean increasing plant size nearly threefold to meet the average production rate and add greatly to product cost. There would also be nontrivial design and operational challenges for such load-following processes.

The variable renewable electricity of wind and solar requires either massive energy storage or process plant redesign to enable load following.

But the changing energy landscape provides many opportunities for innovation. For example, units such as reactors and separators need to be redesigned with increased process intensification for improved productivity and energy-efficient operation. Chemical synthesis needs to be reinvented using electrochemical reactions under much milder processing conditions of temperature and pressure. And the potential of large-scale hydrogen generation through the electrolysis of water using VRE (so-called "green hydrogen") could act as an energy carrier, a reductant in various chemical reactions and an enabler for the use of byproduct CO_2.

Process Heating Through Electricity

The process industries evolved with the exploitation of fossil resources to meet their energy needs (Agrawal 2019). Given economic reasons and the ease of using a central boiler to generate steam to supply heat at multiple locations in a plant, fuel combustion became the norm.

Current Status

If all the steam and combustion heat used by the chemical manufacturing and petroleum refining sectors in 2018 were provided with resistive electrical heating, then, assuming similar efficiencies, this would translate to 1,512 TWh of electricity—about one-third of total US electricity generation in that year.

If, on the other hand, all this additional electricity were produced by natural gas power plants, then, given their efficiency at 50–55 percent, the net amount of

[2] In terms of global sales dollars associated with chemicals in 2021, the US share was only 11 percent, thus the global scope of the challenges discussed in this article is likely to be an order of magnitude higher (Statista, US chemical industry revenue 2005–21, Mar 10, 2023, update).

fossil combustion would nearly double, leading to an equivalent increase in GHG emissions. It is therefore essential to investigate process synergies based on electricity use, and to envision new unit operation designs to increase process efficiencies and greatly reduce electric power demand for heating.

One method to reduce the environmental impact of electricity use for heat is VRE. But although it would reduce GHG emissions, the intermittent availability of VRE presents a huge challenge because of the requirement for thousands of TWh of electricity storage.

Heat and mass flow between various units in a chemical plant are interconnected, so the entire plant must be considered rather than an isolated process unit for electrification.

For example, if VRE from solar or wind is on average available for 30 percent of a day, then at least 70 percent of daily energy (1,058 TWh of electricity) needs to be stored for around-the-clock operation of chemical plants. Battery storage, based on 100 kWh of the battery pack in a Tesla Model S electric car, would require the battery capacity of 10.6 billion Tesla Model S cars! (For reference, the total number of Tesla cars sold in 2022 was 1.3 million; Goldman 2023.) The actual amount that would need to be stored is likely one to two orders of magnitude greater because of daily and seasonal weather variations. Clearly, the use of VRE for process heating purposes would require prodigious innovations in electricity storage technologies.

Our Envisioned Options

Our vision for using electricity to provide process heat for the chemical manufacturing and petroleum refining industries is shown in figure 1. Because of the diversity of applications (far right), the temperature levels at which heat is needed span a wide range, from low (below 100°C) to medium (100–400°C) and high (above 400°C) (Lechtenböhmer et al. 2016). Most applications (e.g., distillation, melting, drying) involve low to medium temperatures, while certain endothermic reactors (e.g., ethane crackers and steam methane reformers) require heat at temperatures greater than 800°C.

As shown in figure 1, electricity offers multiple options for providing heat. For example, conventional resistive heating can be used to generate steam or warm hot oil or gas streams as heating media. These methods mostly use existing plant technology and should be relatively easy to implement, although, as noted above, electricity generated using natural gas combustion would nearly double GHG emissions. On the other hand, innovative methods and equipment design may be pursued to use secondary energy forms such as induction, dielectric, plasma, infrared, arc, and laser. But conversion of electricity to these secondary forms may entail efficiency loss, so process synergies and efficiency gains must accompany their use for heating applications to make them attractive.

Process Intensification Using Electricity

For certain heating applications, electricity may improve process efficiency and intensification. For example, the use of microwaves or other electromagnetic waves to directly heat a catalyst for reaction could eliminate unnecessary heating of the rest of the equipment and yield energy savings (Mallapragada et al. 2023).

Steam methane reforming (SMR) has been demonstrated with resistive heating of a Fe-Cr-Al alloy reactor tube at near ambient operating pressure and 800°C (Wismann et al. 2019). Such a reactor eliminates both combustion volume and the equipment associated with heat recovery in a conventionally fired SMR furnace flue. The study authors projected that the use of the electrically heated tube reactors would reduce the SMR volume by a factor greater than 200.

Conventional SMR and ethane cracking furnaces are more than 90 percent energy efficient as they recover heat from the flue gas by raising steam. This steam stream is absent from the electrically heated reactor, so if generated steam is needed for heating by other operations in the process, then energy savings may be minimal. In other words, in a chemical plant, heat and mass flow between various units are interconnected, and care must be taken to evaluate overall impact by considering the entire plant rather than an isolated process unit for electrification (Chavez Velasco et al. 2021).

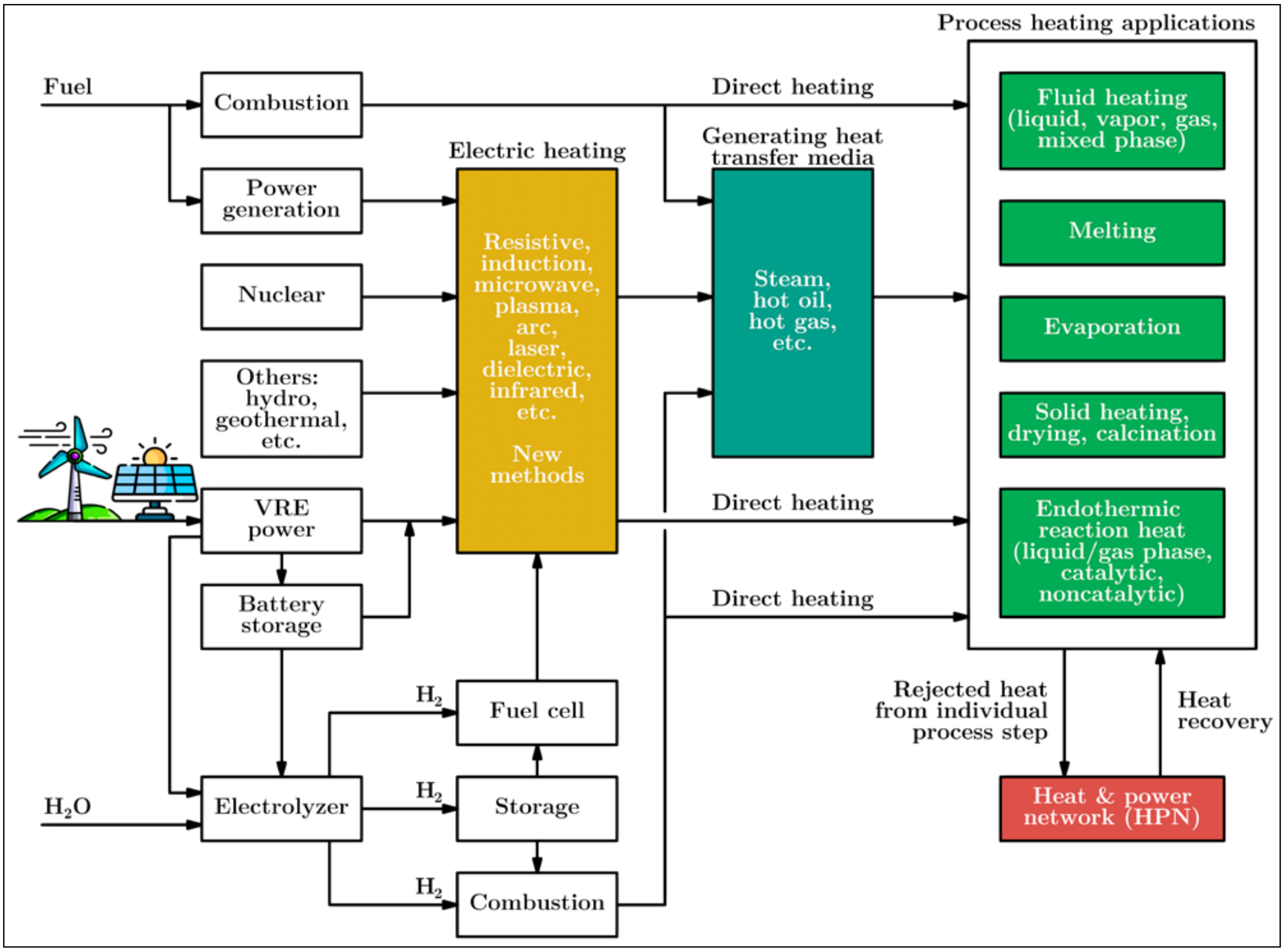

FIGURE 1 A framework for using electricity to supply process heat for chemical manufacturing and petrochemical refining plants. Diverse sources (far left) produce energy used for electric heating, direct heating, and generation of a heat transfer medium for process heating applications. Battery storage, electrolyzer, and hydrogen (H_2) storage are used in conjunction with variable renewable electricity (VRE) to support round-the-clock plant operation. Heat and power network analysis will enable energy optimization across multiple operations within a plant.

Electricity-Driven Separation Processes

Separation processes account for about 40 percent of the energy consumption in chemical manufacturing, and petroleum refining and distillation constitute most separation applications (NASEM 2019). It is estimated that 2.5 percent of US energy consumption is for distillation (Chapas and Colwell 2007).

Almost all of the above ambient-temperature distillations are driven by heat, and electricity can efficiently pump heat from the condenser to the reboiler. For most distillations, heat pumping may reduce energy consumption by a factor of 3 to 10, making it quite attractive in reducing energy consumption, fossil fuel–related GHG emissions, and VRE-related energy storage (Chavez Velasco et al. 2022).

Research and development are needed for the selection of energy-efficient distillation configurations and for the implementation and operation of heat-pumped distillation columns (Mathew et al. 2022). Additionally, where energy efficient and cost effective, pressure-driven separation processes such as membranes and pressure swing adsorption need to be pursued.

It is also worthwhile to consider heat pumps to upgrade heat from one unit operation for use at a higher temperature in another. Traditionally, heat exchanger network analysis is performed, but going forward it will be important to perform heat and power network analysis for the entire plant for optimal results (figure 1).

Possibilities for VRE Storage

One very efficient method of VRE storage is batteries with an overall efficiency of about 80 percent from storage to delivery. But with a low energy density of storage and self-discharge over time, batteries are more suitable for short-term storage.

An alternative way to store VRE is with a water electrolyzer and stored compressed hydrogen (H_2). The use of pressurized H_2 provides higher energy density and allows much longer storage, but it is less efficient than batteries because of losses first in the electrolyzer and then in the fuel cell. To produce 1 kg of H_2, 9 liters of fresh water and about 51 kWh of electricity are needed (Rissman et al. 2020). Demand for large quantities of electrolytic H_2 for process electrification could tax the clean water supply.

Compression or liquefaction of electrolytic H_2 provides higher storage density. However, with current technology, compressed stored electrolytic H_2, upon combustion, provides only about 63 percent of the energy used in its generation and storage, and when used with a fuel cell to supply electricity this number drops to about 45–50 percent.

Deficiencies in VRE availability could be offset by using natural gas turbines.

Thus, the preferred order of VRE use efficiency for continuous heating would consider batteries first, then H_2 combustion, and finally fuel cells. Conversion of electrolytic H_2 to other chemicals such as liquid ammonia and methanol has also been suggested to increase storage density and transportability but, compared to compressed H_2, such storage systems add equipment and energy inefficiencies.

A hybrid system of VRE and fossil fuels may reduce GHG emissions while decreasing the amount of energy to be stored. For example, VRE could be used when available with no energy storage. A hybrid steam boiler would be heated with renewable electricity when available and otherwise use efficient natural gas combustion, decreasing GHG emissions proportionally to the period of VRE availability.

Alternatively, supplementary VRE storage may be used. Battery storage may be sized based on average VRE availability during a 24-hour period. Any deficiency in electricity availability beyond that (e.g., due to extended weather patterns such as cloudy days for PV farms or low-wind days for wind turbines) could be offset by using natural gas turbines. Depending on the storage capacity of the batteries, an electrically heated SMR or ethane cracker could operate with a substantial reduction in GHG emissions and still enjoy process intensification with electricity. The use of VRE in conjunction with optimally sized storage is an interesting process system engineering problem.

Electrochemical Synthesis of Chemicals and Hydrogen

Chlorine and some small-scale chemicals (e.g., adiponitrile, ozone, and perchlorates) are produced via electrochemical route, but the use of electricity to produce most large-scale chemicals is rare.

Electrochemical processes for the production of ammonia and methanol and for CO_2 conversion are being developed. They operate at lower temperatures and pressures and are more amenable to VRE load following. However, energy inefficiency, long-term stability, durability under dynamic operating conditions, and the absence of electrocatalysts for high selectivity and yield are challenges that need to be addressed.

One exception is electrolytic H_2 generation, which is quite advanced—several dozen projects with a power rating between 100 MW and 1 GW are under development around the world (Mallapragada et al. 2023). Electrolytic hydrogen enables VRE storage for eventual supply as electricity or fuel for combustion, and it can be used as an energy carrier for fuel cell vehicles, transported long distances via pipelines, and used as a reductant in various reactions and processes that generate CO_2.

Electrification to Reduce or Eliminate CO_2 Release While Using Fossil Feedstock

As noted, primary energy use for process heat, cooling, refrigeration, and plant machinery operation releases most of the CO_2 from chemical and petroleum refining plants.

Endothermic chemistries such as SMR and ethane cracking release CO_2 because of combustion in their furnaces; only a few chemical processes, such as lime and hydrogen via reforming, directly generate CO_2 as a coproduct. Of the 332 million metric tons (MT) CO_2eq of GHG released from chemical plants in 2018, only 71 MT were coproducts of chemical synthesis; the remaining MT were due to combustion. For the petroleum refining sector, the entire 244 MT CO_2eq of GHG emissions were due to fuel use. Clearly, the coproduct GHG release of both sectors combined is a tiny fraction of the total 2018 US GHG emissions of 6,677 MT CO_2-eq.

There are two ways to mitigate coproduct CO_2. In one method, CO_2 is recovered from the product stream and either directly sequestered or upgraded to a usable chemical using zero carbon electricity. The second method is to change or modify the chemical synthesis to eliminate CO_2 formation. When feasible, this method is likely to be more energy efficient than the first.

A classic example of a chemical process that coproduces CO_2 is the production of ammonia. With an annual production of 16.41 MT in 2019, ammonia constitutes the second-largest chemical production in the United States (Statista 2023). On average, the emission intensity of an ammonia plant is 2.4 T of CO_2 per T of ammonia. Hydrogen for ammonia synthesis is generally produced from SMR. In addition to the CO_2 release in the SMR furnace flue gas, CO_2 is a coproduct of the water gas shift reaction to convert SMR carbon monoxide to CO_2 and H_2. The use of green H_2 in conjunction with nitrogen from a zero carbon electricity-driven air separation plant would avoid the release of CO_2, resulting in "green ammonia."

However, the use of electrolytic hydrogen in conjunction with VRE for CO_2-free chemical production comes with steep challenges in terms of the cost and volume associated with the electrolyzer and batteries, both of which require innovations for large-scale deployment. For example, a 1,000 T/day green ammonia plant would require 12.5 MWh of electricity per ton of ammonia, of which 10 MWh would be needed by the electrolyzer (DECHEMA 2017). Based on the DECHEMA data, the footprint of the electrolyzer to produce the needed amount of H_2 would be about 470 × 295 m^2, with an anticipated electrolyzer cost of about $500 million. To meet annual US ammonia demand, 48 such green ammonia plants would be needed. Challenges associated with the number of H_2 electrolyzer units and energy storage become apparent.

Electrification to Replace Fossil Feedstock

The two primary constituent elements of organic chemicals are carbon and hydrogen. If fossil resources are not to be used, then alternative sources will be needed for these elements. Green H_2 is available, and carbon could be sourced from lignocellulosic biomass or CO_2 emissions from processes. Each presents different opportunities, challenges, and outcomes.

Use of Biomass as a Feedstock

A benefit of using biomass as a feedstock is that the process from conversion to the end use of the chemical products enables no net release of CO_2 to the atmosphere. Generally, though, the supply of sustainable residual/waste lignocellulosic biomass that does not compete with food is limited. Furthermore, the collection efficiency of solar energy as biomass is quite low (less than 2 percent). So it is best to view biomass as a source of carbon and not as a source of energy or hydrogen (Agrawal et al. 2007; Agrawal and Mallapragada 2010). This also implies that during the conversion of biomass to chemicals and fuels, biomass carbon should be preserved and energy needed for the conversion supplied by zero carbon electricity.

Gasification and fast hydropyrolysis of biomass using green H_2 and zero carbon electricity may be used in creating a number of major organic chemicals.

Since a biomass molecule contains oxygen, its conversion to non-oxygen-containing organic molecules would need green H_2 to avoid the release of coproduct CO_2 and maximize the yield of the desired products by preserving carbon. Accordingly, gasification and fast hydropyrolysis of biomass using green H_2 and zero carbon electricity have been proposed as potential routes to creating a number of major organic chemicals (Agrawal 2019).

But the following challenges are associated with the use of lignocellulosic biomass: (1) seasonal availability and its low volumetric energy density limit long-distance transportation because of the associated carbon footprint, cost, and logistics; (2) biomass can contain up to 70 percent water, and drying before use is energy intensive; (3) the presence of char, tar, and ash during conversion often presents processing challenges; and (4) capital and production costs, even from standalone plants that do not use VRE or green H_2, are generally substantially higher than those of natural gas–based plants.

Nevertheless, compared to fossil resource–based chemicals, the use of renewable carbon in chemicals will reduce net CO_2 release through the lifecycle use and disposal of chemicals and could be quite attractive from an environmental perspective.

Green Hydrogen and VRE

The second option, converting CO_2 to chemicals in conjunction with green hydrogen and VRE, raises questions about cost and energy efficiency. In this process, H_2 is needed to remove oxygen (contained in the CO_2 as water) as well as H_2 atoms for incorporation in the chemical molecules. This leads to high demand for VRE and associated electrolyzers and energy storage.

> *It is imperative that processes be highly efficient to minimize the use of electricity.*

Consider the major building block chemicals: methanol, ethylene, propylene, benzene, toluene, and xylenes. Based on the DECHEMA (2017) data, 243 MT of CO_2 and 2014 TWh of VRE would have been needed for 2019 US production of these chemicals (Statista 2023). This electricity demand is nearly half the entire US electricity generation of 2019 (EIA 2022b). This route would put a huge stress on power generation, distribution, and storage, not to mention the volume of electrolyzers needed to produce green H_2.

Moreover, collecting CO_2 via a process that uses fossil fuel as an energy source (or as a reducing agent) and then converting the collected carbon to a chemical or fuel using zero carbon electricity is generally less energy efficient than directly using zero carbon electricity for the process, avoiding the release of CO_2 in the first place. When the reducing function is needed, H_2 generated from zero carbon electricity should be used. If there is still a need for a specific chemical, then a fossil resource should be considered for the conversion to the desired chemical. The energy needed to convert collected CO_2 to most chemicals that do not contain oxygen is greater than the energy supplied through the combustion of fossil fuel, and extra energy is required to separate and collect the CO_2 in the first place.

A Systems View

According to the EIA (2022a), by 2050 renewable electricity's share will grow from the current 21 percent to 44 percent of total US electricity generation. Almost all of this increase will come from wind and solar; zero carbon electricity from nuclear and hydroelectric are expected to remain flat. This is encouraging, as it implies that zero carbon electricity will become more cost effective and readily available for the large-scale electrification of the chemical manufacturing and petroleum refining sectors.

The Imperative of Efficiency

Because all the increase in zero carbon electricity will be due to wind and solar, it will be variable. It is therefore imperative that processes be highly efficient to minimize electricity use.

This reasoning is based on several factors. The cost associated with batteries and electrolyzers scales directly with the amount of electricity used. Any process energy inefficiencies will further increase the cost associated with these units. The estimated amount of electricity needed by the chemical manufacturing and petroleum refining sectors will be about half of current US electricity production, and this large amount of VRE is very likely to strain VRE harvesting and distribution. Considered in conjunction with the electrification of other sectors such as transportation, land for solar energy collection may compete with agricultural use (Miskin et al. 2019). Finally, availability of VRE may not be plentiful in all regions, and its inefficient use will have to be minimized.

Nearly 80 percent of the chemical industry's CO_2 emissions are associated with the supply of heat and power using fossil fuels. Replacing these energy needs with zero carbon electricity may dramatically reduce GHG emissions from chemical manufacturing—while maintaining current use of fossil resources as feedstock.

A Circular Economy

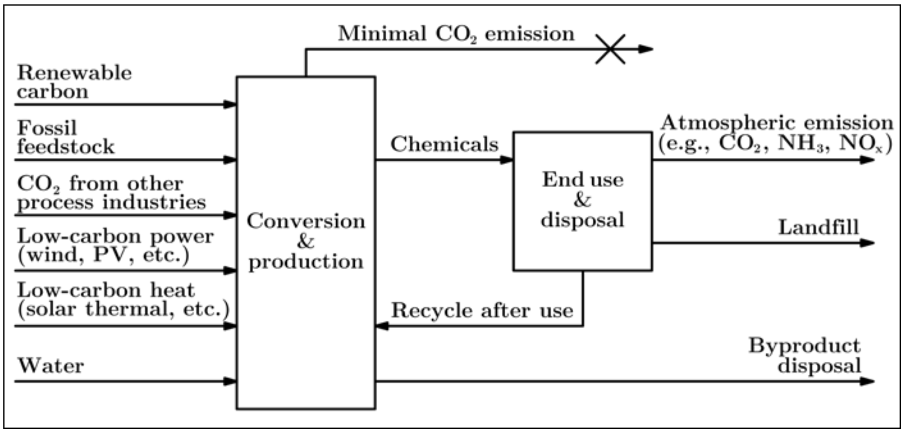

FIGURE 2 A chemical system allowing continued use of significant quantities of fossil resources as feedstock while dramatically reducing greenhouse gas emissions. PV = photovoltaic.

To further reduce GHG emissions over the production and use stages of chemicals, consider the life of chemicals after they leave the plant (figure 2). In a circular economy, a portion of chemicals (e.g., polymers) will be recycled to reduce the use of fresh feedstock. Some chemicals and their derivatives at the end of their use cycle could be safely buried in a landfill; for these products, the use of fossil feedstock in conjunction with low-carbon electricity will not contribute to GHG emissions. But a third portion will eventually be released into the atmosphere as a greenhouse gas. This portion includes the combustion of chemicals such as methanol, vaporization of some volatile chemicals during use, and release into the environment during their application and use (e.g., urea).

To avoid net GHG emissions associated with this third category of chemicals, an equivalent amount of renewable carbon (e.g., residual/waste lignocellulosic biomass) would be needed as a chemical feedstock. For certain large-volume chemicals, such as ammonia, that do not contain carbon atoms but are responsible for a large fraction of process CO_2 release, the use of zero carbon resources such as green H_2 must be pursued. Basically, for net zero GHG emissions during chemical production and use, thanks to zero carbon VRE and prudent recycling and disposal of chemicals at the end of their lifecycle, it may not be necessary to replace the entire fossil feedstock for chemicals production. This will likely result in a much lower requirement for renewable carbon. This system needs to be analyzed and evaluated.

Challenges and Opportunities

New equipment design may help achieve process intensification and reduced cost even when a unit quantity of fossil heat is replaced with a unit quantity of electricity. Heat pumping of above-ambient temperature distillations and use of electromagnetic waves to supply energy where it is needed (rather than heating the entire equipment) should be explored to use electricity advantageously and greatly reduce the total energy requirement.

The use of heat and power networks to optimize energy flow throughout the plant may enhance process synthesis. Integration of VRE to accommodate around-the-clock operation of chemical plants presents unique challenges and opportunities in innovation and analysis. Chemical plants that just load follow VRE and remain idle most of the 24-hour day not only will be costly per unit quantity of product but also could be challenging to operate and maintain. These concerns could be addressed with VRE use, storage, and periodic, limited use of energy/power from natural gas.

Concluding Observations

The lifetime of typical chemical plants is long—30 to 50 years or more—and it will take a great deal of innovation to implement new electrification ideas at existing plants. The direct use of electricity and secondary forms (e.g., electromagnetic waves of various frequencies, plasma) will introduce new physics in the design of chemical reactors and separation processes and spur new and exciting development in the analysis of such equipment.

Electrification will result in new dynamic behaviors of unit operations and affect associated sensors and control strategies. For example, an inductively heated steam boiler or a reactor could be heated much faster, or its output or temperature rapidly adjusted. The availability of both electrolytic green H_2 and byproduct process H_2 will enhance flexibility in the use of various types of carbon resources (Chen et al. 2022).

In summary, given the changing energy landscape and environmental concerns, the electrification of chemical manufacturing and petroleum refining sectors presents a generational opportunity for engineers. Successful implementation will depend on the 24-hour availability of hundreds to thousands of TWh of zero carbon electricity at low cost. Otherwise sustainable electrification will remain limited.

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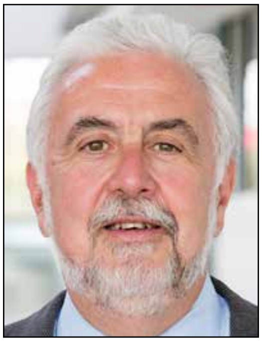
Renewable raw materials can be exploited as alternatives to fossil fuel–based liquid transportation fuels, electrical power, and chemicals.

Producing Transportation Fuels, Electrical Power, and Chemicals in a Circular Bioeconomy



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Timothy J. Donohue

Among today's greatest challenges is the development of sustainable and cost-effective ways to produce sufficient transportation fuels, electrical power, and chemicals while reducing greenhouse gas (GHG) emissions. In 2019 fossil fuels (petroleum, natural gas, and coal) supplied roughly 80 percent of the energy used in the United States, with the remainder derived from a combination of renewable resources (nuclear, wind, hydroelectricity, and biofuels; Kretchmer 2020).

Adding to the challenge is the ever-growing demand for numerous products derived from fossil fuels. Tens of billions of gallons of fossil fuel–derived hydrocarbons are used every year to generate liquid transportation fuels, electrical power, and petrochemicals. In the United States in 2021, liquid transportation fuels accounted for about 30 percent of fossil fuel use—combining the commercial and military needs of the aviation, marine, shipping, automotive, and industrial sectors—and the electrical power sector accounted for about 10 percent.[1]

Using raw materials as a source of fuels, electrical power, and chemicals could move society to a circular bioeconomy that minimizes waste while generating products, services, and processes from this and other renewable resources (Gallo 2022). Plugging abundant renewable raw materials into the

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[1] US Energy Information Administration, "US energy facts explained," Jun 10, 2022, https://www.eia.gov/energyexplained/us-energy-facts/

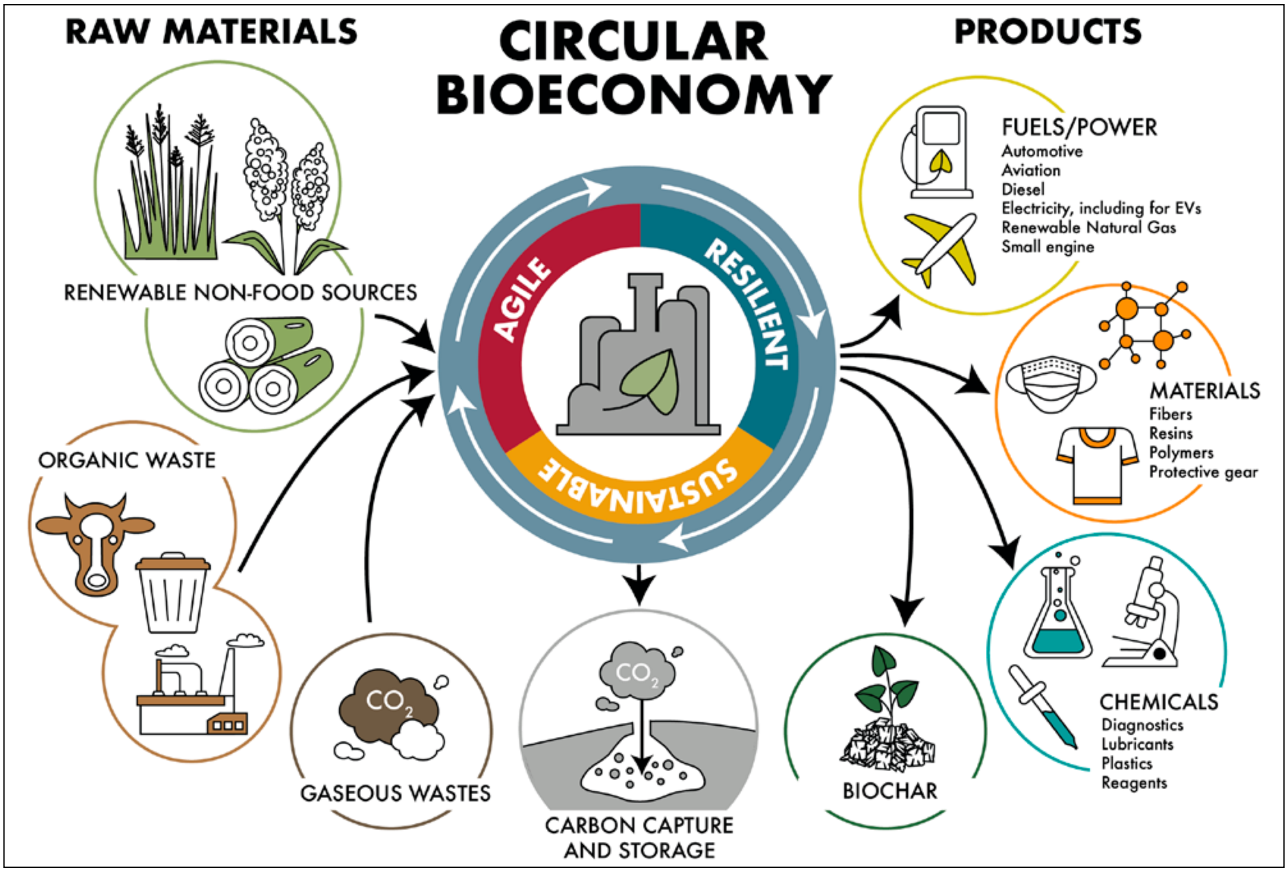

FIGURE 1 Elements of a circular bioeconomy. Left and bottom: Examples of abundant renewable raw materials (nonfood organic residues; carbon dioxide, CO_2) or processes (carbon capture and storage) that can power the circular bioeconomy. Right: Examples of products that can be generated from these abundant renewable raw materials (fuels, power, materials, chemicals, and biochar). EVs = electric vehicles. Credit: Chelsea Mamott, Wisconsin Energy Institute (WEI). Reprinted with WEI permission.

economy will require significant technical advances and changes in existing agricultural and industrial practices, but the environmental, health, social, and economic benefits are enormous (Northrup et al. 2021; Robertson et al. 2022).

Renewable Biological Sources

There is a growing call to develop methods to produce significant quantities of liquid transportation fuels, electrical power, and chemicals from abundant renewable resources. Successful efforts could reduce net GHG emissions, lead to a decarbonized industrial base, and provide other environmental, economic, and societal benefits. To achieve such goals, advances are needed to enable cost-competitive and low net GHG production of products to replace those derived from fossil fuels as well as the generation of new products from renewable raw materials.

Studies indicate that sufficient renewable raw materials are available to produce sizable amounts of liquid transportation fuels, electrical power, and other products currently derived from fossil fuels (Burger and van Nimwegen 2008; Lizundia et al. 2022). These renewable raw materials include billions of tons of organic residues in nonfood animal and plant material, purpose-grown crops (e.g., switchgrass, poplar) used for conversion into these products, manure, microbes, and residues derived from other agricultural, municipal, and industrial activity. There is also an opportunity to tap abundant gaseous carbon sources (carbon dioxide)—produced by the biological process of respiration, sequestered from the atmosphere, or released by fuel combustion—to help reduce net GHG emissions (Elhacham et al. 2020).

Approaches to a Circular Bioeconomy

The potential role of a circular bioeconomy (figure 1) in the 21st century industrial evolution is large. For example, it has been estimated that up to 60 percent of the inputs to the global economy could, in principle, be produced biologically (Chui et al. 2020).

Nonfood plant and animal residues, when combined with inedible materials generated by agriculture, food, biotechnology, or other industries, can provide a significant portion of the raw materials needed to feed a circular bioeconomy (Lizundia et al. 2022; Zhao et al. 2021). For instance, industries could convert plant and animal residues that are not suitable for or needed as food into numerous products (e.g., feed, fiber, chemicals, materials, pharmaceuticals, and food replacements or additives). Such practices can increase the future profitability of agriculture and reduce net GHG emissions from industrial synthesis of these products when compared to existing practices.

In addition, advances in breeding of so-called dedicated energy crops can increase biomass productivity and enhance above- and underground carbon sequestration from the atmosphere (Northrup et al. 2021). The ability to increase the yield and quality of biomass per acre from purpose-grown nonfood cropping systems on fallow, unreclaimed pastureland and acreage that is not suitable for food production is crucial to realizing the vision of a circular bioeconomy. There are also calls for the adoption of zero-carbon farming practices that can lower the net GHG footprint of crop production by reducing, or even avoiding, the use of fertilizer and pesticides since these agrochemicals have a high energy production cost, contribute directly or indirectly to GHG emissions, and can have other detrimental impacts on air, soil, or water quality (Northrup et al. 2021; Robertson et al. 2022).

Catalytic, biological, and hybrid technologies can be used to convert raw materials derived from existing industries (food, chemicals, pharmaceutical, biotechnology, and other sectors) into liquid transportation fuels, electrical power chemicals, and materials. This conversion can replace or supplement fossil fuel use as sources of these products while lowering the net GHG footprint of generating them (Liu et al. 2021; Nielsen and Keasling 2016; Schwartz et al. 2016).

Challenges of Renewables for Liquid Transportation Fuels

Given the growing global need to move people and products and current estimates of raw materials supply, liquid transportation fuels and electrical power generated by a circular bioeconomy cannot totally replace hydrocarbons derived from fossil fuels in the near future (Liu et al. 2021). It is therefore necessary to develop liquid fuels that fit the needs of different parts of the transportation sector.

For example, electrification can be a viable replacement for fossil-derived liquid fuels for most light vehicles, medium- and possibly heavy-duty trucks, and a significant fraction of rail transport (Tamor and Stechel 2022). However, for commercial and military air transport and ocean-going ships, there is a growing consensus that liquid fuels will be needed in the near to long term, because of the added weight of airline batteries and the long distances traveled by most marine transports.

Development and acceptance of drop-in fuels will minimize or prevent the need to design and deploy entirely new engine systems.

For air and marine transport, “drop-in” liquid fuels—derived from renewable resources (e.g., sustainable aviation fuel, renewable diesel, and renewable gasoline) that can be mixed with fossil-derived fuels—are needed until other non-GHG-intensive petroleum replacements can be developed. Of course, combustion of drop-in liquid fuels should release minimal particulates or pollutants to prevent unwanted environmental impacts of their use in different engines. And the renewable hydrocarbons in drop-in fuels should be cost-competitive and compatible with existing pipeline, shipping, and engine systems. Development and acceptance of drop-in fuels will also minimize or prevent the need to design and deploy entirely new engine systems.

Renewable natural gas (RNG) can be a major source of fuel for some vehicles and for electrical power. RNG is typically obtained by isolating and purifying the natural gas (methane) generated by microbial activity in anaerobic digestors, although landfill sites have recently become a significant source (Burger and van Nimwegen 2008; Keogh et al. 2022).

Many additional sources of RNG could be developed if anaerobic digestion of the raw materials in agricultural, wastewater, and industrial residue streams could be made cost effective (Krohn et al. 2022).

Renewable Chemicals and Materials in the Circular Bioeconomy

Technoeconomic analyses predict the benefits of generating liquid transportation fuels, electrical power, and chemicals from renewable raw materials as much as possible (Perez et al. 2022; Scarborough et al. 2018). In this vision, a circular bioeconomy can support the sustainable and renewable production of high-demand chemicals and materials (figure 1) (Liu et al. 2021).

Existing carbon capture and storage (CCS) technologies can sequester CO_2 underground either in plant roots (biological CCS; Northrup et al. 2021) or in geological formations (Raza et al. 2019). Emerging technologies can capture CO_2 and store it in insoluble material (the type used to reinforce concrete and other materials; Ragipani et al. 2022). Syngas, a mixture of carbon monoxide and hydrogen generated by industrial activity, could also be converted into useful chemicals and other materials (Sun et al. 2019). Deployment of these approaches at industrial scale would allow abundant gaseous carbon sources to be used as renewable raw materials in a variety of applications.

Public and private investments are essential to generate the game-changing advances in biology, chemistry, computation, and engineering needed for success.

The potential to convert organic matter into chemicals and materials is seemingly endless if one considers the combined use of existing or improved enzymes, genome-enabled synthetic biology to build new biosynthetic pathways, and new chemical catalysts. The suite of products that might be derived from these renewable raw materials include building blocks for synthesis of biodegradable plastics, lubricants, polyesters, adhesives, and new microbial foods. They may also be used to develop additives to stimulate growth or productivity of crops and animals; compounds with pharmaceutical, antimicrobial, or health-beneficial effects; and myriad other specialty (small-scale) or commodity (large-scale) chemicals (Donohue 2022; Jahn et al. 2023; Schwartz et al. 2016).

Industries in the circular bioeconomy would operate like petrochemical refineries where chemicals and materials can be lower-volume and higher-profit per unit products, generating revenue to lower the cost of liquid transportation fuels and electrical power (Huang et al. 2020; Wu and Maravelias 2019). In addition, recent advances in computational, catalytic, and genomic techniques can facilitate the development of renewable chemicals and materials that cannot yet be generated from fossil fuels in a cost-effective manner (Liu et al. 2021; Nielsen and Keasling 2016; Schwartz et al. 2016).

Technology, Investment, Modeling, and Communication Needs

There are differences in the readiness of individual technologies given the range of advances needed to satisfy the world's ever-growing need for transportation fuels, electrical power, chemicals, and materials. Anaerobic digestion, for example, is a fairly long-standing and well-developed technology. In contrast, the production of drop-in biofuels and chemicals from lignocellulosic biomass, other agricultural residues, or municipal waste is at a lower technology readiness level. While some technologies have been commercialized and deployed at industrial scale, improvements could remove existing technical bottlenecks and make these alternative approaches even more cost effective at industrial scale. Given these differences in technology readiness, it could be helpful to set priorities for scientific development and the transition to industrial deployment that would stimulate government and industrial investment in individual approaches.

To address knowledge and technology gaps, public and private investments are essential to generate the likely game-changing advances in biology, chemistry, computation, and engineering needed for success. Investments could include single investigator awards and center-scale initiatives that assemble teams to make breakthroughs that occur when researchers work across disciplines. Programs are needed to support high-throughput approaches, mining and modeling of large datasets by machine learning and other computational techniques, and the promotion of transitional research advances from field and laboratory studies to pilot and industrial scales. Biological, physical, computational, and engineering professional societies as well as practitioners, researchers, policymakers, and educators can both contribute to and reap the benefits of a circular bioeconomy.

Lifecycle analysis predicts that maximizing the economic and evironmental benefits of converting raw materials into products will depend on the strategic placement of refineries close to their sources and the infrastructure needed to move materials from producers to end users (Gelfand et al. 2013). This in turn will require integrating remote, satellite, and land-based tracking systems with other datasets. The data will inform models that can accurately predict the supply of raw materials, model the costs of purchase and transport to refineries, and forecast expenses to produce, purify, and distribute products at scale (Gelfand et al. 2013; Robertson et al. 2017).

Modeling of the economic, GHG, and other environmental benefits associated with the circular bioeconomy is needed to inform industrial, community, and consumer dialogue and acceptance of this new industrial ecosystem. The cost of building and operating a new generation of refineries means that public and private sector investors will need to be convinced about cost-effective access to raw materials and the technology to generate useful products.

Looking to the Future

A significant fraction of the raw resources needed to provide cost-effective renewable liquid transportation fuels, electrical power, chemicals, and materials can be derived from existing nonfood products of agricultural, industrial, or other societal activities. The siting of next-generation refineries close to the supply of raw materials can create economic opportunities for industries and communities. By producing liquid transportation fuels, power, and chemicals from local raw materials, rural communities that have traditionally not been part of the fuel and chemical industries can participate in a multitrillion-dollar-per-year economy.

In this model, the refineries that power a circular bioeconomy can become a cornerstone of a new industrial ecosystem for the country and the world. The new locally sourced energy ecosystem will be environmentally sustainable and more resilient to events that disrupt output from other refineries, and will provide economic opportunities to rural communities.

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Achieving a net zero carbon society demands a new approach that will use all clean energy generation options available.

Shifting the Paradigm:

Nuclear-based Integrated Energy Systems to Achieve Net Zero Solutions

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Governments and private industry around the world have established aggressive goals to achieve net zero carbon emissions for the power, industrial, and transportation sectors by 2050. These goals require a sharp paradigm shift in how energy demands are met. Research laboratories and private companies are developing holistic, integrated solutions that seek to efficiently utilize an array of clean energy generation sources to meet the growing demand for heat, steam, and electricity from nonemitting sources.

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Current State

Electricity demands in the United States[1] and across many developed countries (Ritchie et al. 2022) account for approximately one-third of overall energy use and about one-third of CO_2 emissions. Most energy demands have traditionally been met via generators that support a single energy sector. The chemicals and fuels industries draw some electricity from the grid, but most large industrial facilities independently cogenerate heat and power for their internal utility duties, contributing to ~20 percent of CO_2 emissions. Only recently has the transportation sector been more directly linked to the grid with the increasing adoption of electric vehicles, but it is still responsible for more than one-third of CO_2 emissions.

A coordinated, integrated approach can link energy demands across sectors to optimize energy generation and use while maintaining grid reliability and resilience.

The prevailing low-carbon generation sources for electricity, industry, and transportation ultimately will come down to economics, but it is increasingly clear that options analysis should include not only the energy intensity, reliability, resilience, and security of generation sources but also the associated energy storage needs and cross-sector energy supply possibilities.

The buildout of variable wind and solar electricity production has already negatively impacted traditional baseload power plants, requiring them to operate more flexibly to accommodate supply/demand mismatch. In the future, more baseload plants may be forced to turn down their output, potentially reducing their economic viability; divert energy to a secondary, off-grid electricity or thermal energy user; or permanently shut down, putting grid resilience at risk.

Abating emissions from industrial processes presents a greater challenge than decarbonizing the grid because of limited options for nonemitting sources of heat. Electrification may help (assuming electricity is sourced from nonemitting generators, including nuclear), but some processes require a direct heat source to maintain efficiency and economic competitiveness.

Similarly, today's transportation sector primarily relies on internal combustion engines that use liquid fuels. Although most light-duty electric vehicles (i.e., passenger vehicles) can switch to plug-in batteries with buildout of charging infrastructure, and electric buses and trains can support commuter systems, heavy-duty transport vehicles, maritime vessels, and aircraft cannot be easily electrified. For these vehicles, hydrogen fuel cells or synthetic liquid fuels produced with renewable carbon sources can significantly reduce greenhouse gases (GHGs) and other pollutants. These options will further increase the demand for nonemitting thermal and electrical energy sources.

Proposed Solution: An Integrated Energy System

Amid efforts to achieve net zero emissions across all energy generation and use sectors, grid reliability and resilience, as well as customer affordability, must be maintained.

An integrated energy system (IES) can offer solutions that leverage desirable attributes of each energy resource. This could include a shift from the single-output systems commonly used today (e.g., generators operating independently to support electric grid demand) to other configurations, such as multi-input multi-output (MIMO) systems integrating multiple resources to provide both heat and electricity to multiple energy users (Arent et al. 2021). While some CO_2-emitting multi-output (cogeneration) systems are in operation today, IES development efforts focus on providing heat and electricity to multiple energy users without CO_2 or other GHG emissions.

MIMO systems could be deployed in an energy park configuration connected to a regional grid balancing area; alternatively, they may operate as an independent microgrid. Through coordinated dispatch from the various installed generators, energy can be redirected to storage or coupled energy users (e.g., hydrogen production) as needed to ensure efficient use rather than reducing dispatchable output when the installed variable generation is sufficient to meet demand.

Nuclear energy is the primary source of nonemitting thermal energy and can flexibly provide clean heat and electricity. Deploying nuclear and renewables in a more tightly coordinated, integrated approach can

[1] Lawrence Livermore National Laboratory, Energy Flow Charts, https://flowcharts.llnl.gov/

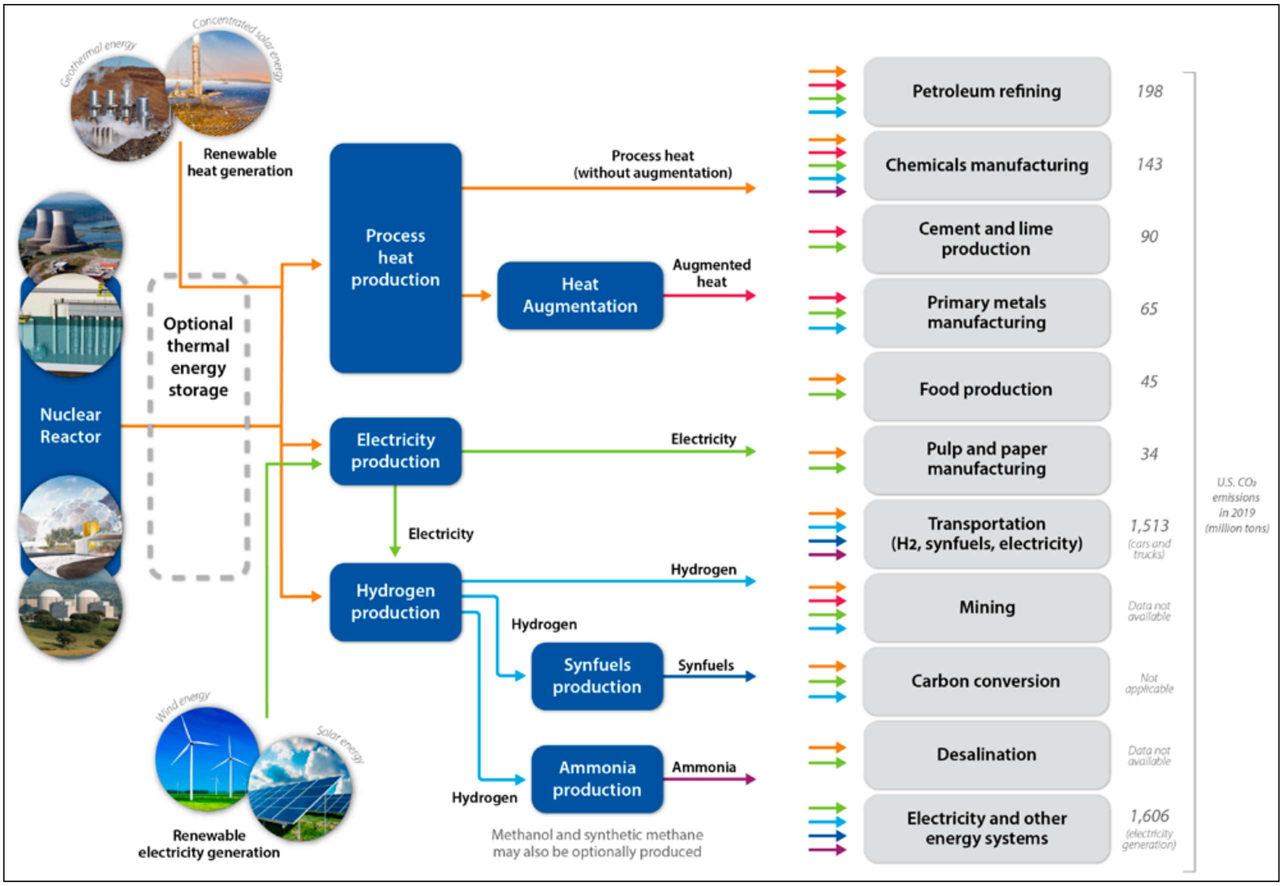

FIGURE 1 Illustration of possible energy generation and use options for an integrated energy park, showing energy flows and input requirements for energy users. Adapted from Foss et al. (2021).

link energy demands across the electric, industrial, and transportation sectors to optimize energy generation and use, maintain the grid reliability and resilience offered by thermal generators, and support decarbonization of industry and transportation.

A variety of options can be pursued for an integrated energy park (figure 1). Prioritization of options may depend on opportunities to reduce emissions from a selected process (based on both process scale and overall market size; McMillan et al. 2016), reduce operational costs relative to competing technologies, enhance domestic industrial opportunities, or other factors, such as ensuring access to clean water in regions experiencing water scarcity or enhancing social, environmental, and energy justice. This paper focuses on use of nuclear energy alongside renewables in these conceptual energy parks.

Commercial implementation of technologies is strongly dependent on cost, deployability within a desired timeframe, and technology availability at the desired scale. The science-based development of IES involves three key pathways:

- *Energy system and process modeling, simulation, and analysis:* These are required to characterize and optimize the intersection of multiple energy use sectors from both a technical and economic perspective.
- *Component development, testing, and demonstration:* Experimental facilities are required to validate the modeled behaviors. Facilities designed to reflect real system responses support validation of simulation results to build confidence and assurance in the proposed system design.
- *Process and system monitoring, control, and maintenance:* Process monitoring and control must be demonstrated at each development scale (bench, pilot, or engineering) in preparation for prototype deployment to ensure safe, reliable, and secure system operation before commercialization.

Status of Development

Multiple technologies that can support nuclear-renewable IES are under development around the world. Many of these technologies are operating commercially as independent units today, but they are not integrated to create a multi-application clean energy park.

Nuclear Energy Systems

Nuclear energy has been powering the US grid since the Experimental Breeder Reactor-I first did so in 1951. Current US fleet plants are all light water reactors (LWRs), most of which produce about 1 gigawatt of electricity (GWe) and provide steam outlet temperatures of ~300°C. The field of reactor design options is, however, poised to change with the development of microreactors (~10s MWe), small modular reactors (~50–300 MWe), and non-water-cooled advanced reactor (AR) technologies that provide higher temperatures and offer higher power generation efficiency. Each of these systems offers different IES opportunities.

Light Water Reactors

The current US LWR fleet faces economic challenges in regions of the country where subsidized renewable energy buildup and low-cost natural gas have reduced the wholesale price of electricity to levels that are difficult for nuclear power plants to clear the market throughout the year. For several large-scale nuclear plants, particularly those in deregulated markets, these challenges are leading to early plant closures (before plant license expiration) (Szilard et al. 2017).

Advanced nuclear reactors can extract heat at higher temperature to drive industrial processes.

Recent studies have demonstrated the value of flexible operation of grid-connected LWRs (Boardman et al. 2019; Epiney et al. 2019; Frick et al. 2019). IES configurations offer enhanced flexibility with continued operation at nominal power levels by dynamically apportioning energy to meet grid demand while sending excess energy to yield a secondary product, such as hydrogen, at a market-competitive price. These analyses helped promote LWR hydrogen demonstration projects at multiple US nuclear plant sites in partnership with the US Department of Energy: Constellation's Nine Mile Point Nuclear Station (New York), Energy Harbor's Davis-Besse Nuclear Power Station (Ohio), and Xcel Energy's Prairie Island Nuclear Generating Plant (Minnesota).[2] Nine Mile Point reached a major milestone in March 2023 with operation of a 1.25 MWe low-temperature electrolysis system to produce 560 kg of hydrogen per day.

Advanced Nuclear Reactors

Numerous AR concepts are under development by private industry, in many cases with support from federal research laboratories. These concepts focus on inherent safety, waste minimization, generation of cost-competitive electrical power, and nonproliferation, but the characteristic most relevant to IES is the potential to extract heat at higher temperature to drive industrial processes.

The three primary technologies being pursued in the United States are liquid metal (sodium-cooled) fast spectrum reactors, high-temperature gas-cooled reactors, and molten salt reactors. The potential to achieve much higher temperatures (500–750°C) with ARs opens possibilities of meeting the thermal and electricity needs of multiple industrial users while reducing industrial emissions.

Renewable Energy Options

Multiple renewable generators may be integrated with nuclear energy to establish clean energy parks. Options may include wind, solar (photovoltaic [PV] or concentrated solar), geothermal, biomass, or hydropower. Some of these generators (wind, solar PV) produce electricity directly, while others could be integrated via a thermal energy manifold that distributes heat as needed to electricity or secondary product production.

Energy Storage

Energy storage—electrical, thermal, and chemical—may play a key role in coupling diverse technologies to ensure that energy is delivered when needed and of the desired quality. Many IES require both thermal and electrical integration; however, coupled energy users may require heat augmentation to achieve the needed quality.

[2] Other demonstrations have been proposed, but contracting has not been completed.

In addition, many industrial applications operate best at steady state. If an IES dispatches energy alternately between the grid and the industrial user, then energy storage components may be required to manage flexibility of operation without deprioritizing any coupled users (Knighton et al. 2021). Stored energy may support peak power production in deregulated markets for system-wide profit maximization (i.e., storage when electricity production exceeds demand, causing the electricity selling price to be low or negative, and sale when the price is high). Stored energy can also smooth the transition of energy use between process applications that operate on different characteristic time scales.

One of the most versatile energy carriers is hydrogen, which enables chemical energy storage. It can be compressed, stored, transported, and later combusted to produce electricity, or it can become feedstock for many of the processes shown in figure 1.

Interface Technologies

IES may require thermal integration, electrical integration (behind the grid), or both, with each option posing different technical, operational, and regulatory challenges. Researchers are working to advance at-scale demonstration of suitable integration technologies to accelerate IES deployment.

Thermal interconnection can be accomplished using heat exchangers and heat transfer loops. Design considerations include materials compatibility, working fluid characteristics, operational temperature, and temperature limitations. Interconnections must provide efficient heat transfer without creating unnecessary interdependence among subsystems.

Intermediate heat transfer loops can effectively isolate the nuclear island from heat users, eliminating the potential for radioactive contamination of products for both normal and off-normal operations. Isolation can also reduce the number of components and subsystems required to adhere to nuclear quality levels in coupled facilities, thus reducing overall system cost.

In some applications it may be necessary to boost the temperature of the heat transfer media. This can be accomplished using electric heating, a fired heater (including hydrogen-fired), compression, or heat pumping. Chemical heat pumps can achieve very high temperature amplification if the cost-benefit is justified (Gupta et al. 2022).

Some IES configurations benefit from power transactions behind the grid—before the electrical switchyard. Such interfaces can increase the efficiency of energy delivery to coupled users and may also reduce operational costs.

Industrial Energy Applications

The manufacturing industry uses about 25 exajoules of energy per year, of which approximately 20 percent is from electricity (with about one-third produced onsite for captive use), 40 percent from steam (all generated onsite), and 40 percent from fossil-fired combustion as a source of either direct heating (as in a cement kiln) or indirect heating (as in fired heaters) (Ruth et al. 2014). Over 90 percent of the primary energy required is derived from combustion of fossil fuels. Hydroelectric dams and biomass combustion in concentrated heat and power plants are still the main sources of nonfossil energy used by the industrial sector.

Over 90 percent of the primary energy required for industrial energy applications is derived from combustion of fossil fuels.

A key tenet of IES is apportioning energy between power production and heat provision to industrial applications to both enhance energy use efficiency and reduce industrial CO_2 emissions by using nonemitting generation sources. The US manufacturing industry can be broken down by electrical duties, heat or steam duties and temperature requirements, and heat transfer media and methods for direct heating (Pellegrino et al. 2004; summarized in Bragg-Sitton et al. 2020). Key markets include feedstock drying, petroleum distillation, biomass and coal pyrolysis, hydrotreating, steam cracking, oxidative coupling, and calcination.

Nuclear energy has the potential to provide heat (primarily via steam and indirect heating) and electricity to meet many industrial process needs. Use of high-temperature ARs would reduce the need to augment steam heating, but these designs require additional development time. In the near term, heat augmentation technologies represent a key opportunity that could enable utilization of LWRs for high-temperature process applications.

Hydrogen Production

Hydrogen (H_2) can be used to incorporate clean energy in existing or new industries, and nuclear-supported H_2 production is versatile as both an energy carrier and a feedstock for numerous industrial applications. Today, hydrogen is mainly used in petroleum refineries and for ammonia production. In the future, it may also be used as a combustion fuel, to refine iron ore, and to power gas turbines.

> *Hydrogen may be used in the future as a combustion fuel, to refine iron ore, and to power gas turbines.*

Two types of H_2 generation technologies are used currently: (1) hydrocarbon cracking, reforming, and shifting with steam and (2) water splitting (Boardman 2021). Reforming technologies convert fossil fuels and biomass into hydrogen, emitting the carbon in the feed material as CO_2. Water splitting technologies, which do not result in carbon emissions when the source of heat and electricity is carbon-free, fall into two categories: chemical looping, which involves formation of an aqueous mineral acid followed by high-temperature acid decomposition, or electrolysis—low-temperature water electrolysis (LTE) and high-temperature steam electrolysis (HTE). With HTE, the additional heat reduces the amount of electrical work needed and thus increases the H_2 production efficiency—HTE can be 20–50 percent more efficient than LTE.

The choice of nuclear reactor design to support hydrogen production ultimately depends on the cost of producing electricity and heat relative to the capital and operation and maintenance costs of the H_2 plant. In addition, high reactor outlet temperatures yield high thermal-to-electricity efficiencies, further enhancing H_2 production efficiency (McKellar et al. 2018).

Coordination of Multiple Regulatory Entities

In the United States, civilian nuclear reactors are licensed and regulated by the US Nuclear Regulatory Commission. Its role is to protect public health and safety related to nuclear energy generation as well as other radiological sources. Industrial facilities are bound by the code of federal regulations under the National Energy Policy Act, Environmental Protection Agency, Occupational Safety and Health Administration, and codes and standards for building and operating potentially hazardous process operations. Industrial siting and operations generally fall under individual state agencies, and the Federal Transportation Agency or Department of Commerce oversees the transport of chemicals and fuels. All industrial practices are subject to the International Organization for Standardization.

Nuclear-based IES must demonstrate that nuclear-industry integration will not increase the risks of operating the nuclear facility. Preliminary probabilistic risk assessments—completed for integration of a generic pressurized or boiling water reactor with a large-scale HTE plant—support the colocation of hydrogen production at a nuclear plant without increasing safety risk (Vedros et al. 2020). A Hydrogen Regulatory Research Review Group, comprising laboratory researchers, nuclear plant operators, architectural engineering firms, and licensing experts, is also evaluating potential technical and safety risks for nuclear-hydrogen integration (Remer et al. 2022); its work supports nuclear-integrated H_2 production demonstration facilities in clearing regulatory hurdles at current fleet nuclear plants.

Modeling, Simulation, and Optimization Tools

The laboratory-developed Framework for Optimization of ResourCes and Economics (FORCE) ecosystem of tools supports design, analysis, and optimization of novel IES solutions.[3] Key tools include:

- Reactor Analysis and Virtual Control ENvironment (RAVEN), to process raw market data to create synthetic data that represent the market and its stochastic nature
- Holistic Energy Resource Optimization Network (HERON), to stochastically optimize both the individual IES component sizes and real-time dispatch of IES resources to the grid or coproduct markets
- Tool for Economic AnaLysis (TEAL), used in conjunction with HERON for multiyear financial opti-

[3] For additional information about the US DOE Integrated Energy Systems program and the FORCE tool suite, see https://ies.inl.gov/SitePages/FORCE.aspx.

mization of the IES in agreement with the financial figures of merit appropriate to the type of market

- HYBRID, a repository of transient process models, with detailed models of various nuclear reactors, energy storage, and ancillary processes (e.g., water desalination, H_2 production) that can be used to understand dynamic behavior, integration, and control of IES across time scales
- Feasible Actuator Range Modifier (FARM), a RAVEN plug-in used to ensure that control actions requested by the dispatch optimizer do not violate operational constraints for various hardware components
- Optimization of Real-time Capacity Allocation (ORCA), for real-time IES control and optimization
- Dynamic Reliability Analysis Framework and Toolbox (DRAFT), which uses HYBRID operational data to construct component reliability and failure probability data, which are used in HERON to differentially motivate dispatch decisions.

Analysis tools are available for public use via GitHub.

Potential benefits of deploying integrated assets can only be assessed based on their technical and economic performance relative both to the current state of the art and to independently operated systems that produce the same products for the market. As such, nuclear-based IES performance might be evaluated relative to comparably scaled renewable generators coupled with energy storage systems, or to natural gas combined cycle systems with coupled carbon capture and storage, ensuring that both the benchmark systems and the integrated systems can achieve equivalent emissions reduction and system reliability.

Case Studies

Numerous case studies conducted for application of nuclear energy in IES support further development of the dynamic models and tools. A few of these case studies are summarized below.

Hydrogen Production

Steady-state and dynamic analyses of nuclear-supported H_2 production have been completed both for current fleet and advanced nuclear systems. One of the earliest demonstrations of the FORCE toolset was for a collaborative study among Constellation (previously Exelon), Fuel Cell Energy, and national laboratories to evaluate the potential of using existing nuclear plants in the US Midwest to produce hydrogen via HTE while continuing to support grid electricity demands (Frick et al. 2019). The analysis indicated that during times of low grid pricing (ample supply), H_2 production is more profitable to the plant. When grid demand and grid electricity pricing are high, selling energy to the grid is more profitable.

Hydrogen storage provides additional flexibility in plant operations, ensuring that both grid and H_2 demand can always be met. The 2019 FORCE analysis indicates a potential revenue increase to the evaluated nuclear plant of $1.2 billion over a 17-year span with optimally sized HTE and storage systems. This work resulted in Constellation's decision to demonstrate H_2 production at Nine Mile Point, which started operation in March 2023.

Sustainable Fuels

Sustainable fuels (synfuels) can be produced from carbon and H_2 chemical building blocks, including methane (a substitute for natural gas), olefins (as substitutes for diesel and jet fuel), and oxygenates (as substitutes for motor gasoline). The most common pathways to produce synfuels are methanation, the Fischer-Tropsch process, and the methanol-to-gasoline process.

Synthetic fuels produced from clean hydrogen and a renewable carbon resource or CO_2 sourced directly from the atmosphere are sustainable.

Synthetic fuels produced from clean hydrogen and a renewable carbon resource or CO_2 sourced directly from the atmosphere are sustainable. Biomass can also be converted directly into sustainable fuels using emission-free hydrogen to hydrotreat pyrolysis oils. Development of these nonemitting pathways to liquid hydrocarbon fuels supports decreased atmospheric CO_2 and reduced emissions from hard-to-abate transportation systems (Wendt et al. 2022).

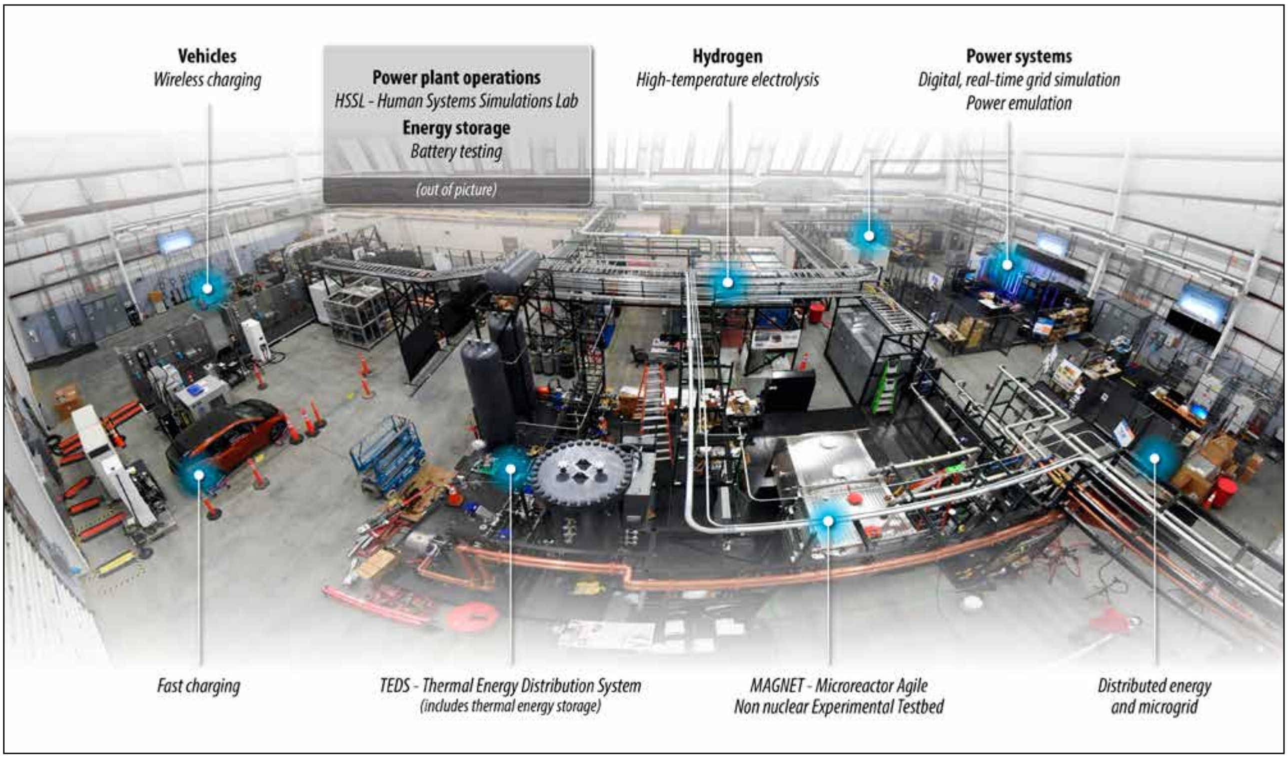

FIGURE 2 Overhead view of the Dynamic Energy Transport and Integration Laboratory (DETAIL) at Idaho National Laboratory.

Carbon Conversion Product Pathways

Use of nuclear energy to support carbon conversion pathways (e.g., converting coal feedstock into higher-value products versus combustion for electricity) provides alternative revenue opportunities to communities that rely on exports of fossil fuel resources to support their economy. Initial analysis of a carbon conversion refinery for the Appalachian region focuses on optimizing the chemical process for coal conversion to products based on market needs (Worsham et al. 2022).

Energy Storage

The influx of solar and wind power has increased net demand variability on the grid. Energy storage in an IES can be used to shift power production to periods when demand is high or when variable power generation is low, or to transfer energy to industrial users (Saeed et al. 2022).

A recent study compared utility-scale battery storage with hydrogen and thermal energy storage systems (Knighton et al. 2021). Results indicate that the best option is situational and depends on a variety of factors, most importantly the time scale. Batteries are consistently better for short storage durations, typically less than 4–6 hours. At longer time scales, hydrogen and thermal energy storage can be more economical. Because the cost of energy storage is significant, it can be justified in the electricity sector only when there is a substantial differential between the selling price of electricity during normal and peak demand periods.

Experimental Systems

Laboratory testing and demonstration of individual or coupled technologies are needed to evaluate IES performance characteristics, integration approaches, and system control options. Scaled testing also provides data for validation of computational models used in broader system design and optimization before demonstration on a nuclear system. Advancing technologies from lab to commercial scale can entail unique challenges that can impede deployment if not addressed.

Nonnuclear, electrically heated test facilities can be useful for characterizing system integration approaches and controllability of system operation under normal and off-normal operating conditions. The Dynamic Energy Transport and Integration Laboratory (DETAIL) at Idaho National Laboratory (figure 2) has multiple experimental systems integrated both thermal-hydraulically and electrically. A Microreactor Agile Nonnuclear Experimental Testbed (MAGNET) supports testing of various microreactor concepts, and the Thermal Energy Distribution System (TEDS)—a network of valves, pipes, and heat exchangers—moves thermal energy between connected subsystems, serving as the backbone of DETAIL. TEDS can also deliver thermal energy to HTE systems for H_2 production.

Real-time digital simulators enable electrical integration of DETAIL with systems at other laboratories (PowerGrid International 2023) and/or customer sites to extend IES demonstration capabilities. A battery storage and charging laboratory and a microgrid test facility demonstrate how each system can respond to changes in demand or supply on the grid. And integration of DETAIL and the Human Systems Simulation Laboratory allows demonstration of control approaches for industrial use of nuclear-generated thermal energy and/or steam, in addition to electricity production, and will provide valuable information on the human factors aspects of operating integrated systems.

Advancing Technology through Collaboration

Both developed and emerging economies around the world are seeking diverse energy generation and delivery options as they pursue a net zero future. Global partnerships among energy planners and technology developers are necessary to accelerate adoption of clean energy pathways that will increase electricity access, energy security, and environmental sustainability in both developed and developing regions. These collaboration platforms provide opportunities to share experiences in clean energy technology options, operational or deployment challenges, project financing, and community engagement.

In addition, IES research brings together nuclear and renewable technology developers and energy users to evaluate opportunities and establish a new paradigm for clean energy deployment. Stakeholder engagement is essential to ensure that research and development (R&D) is well positioned to support rapid technology advancement. As such, industry expert groups have been established to engage in laboratory research activities, providing feedback on key gaps to commercial IES deployment, for both current fleet LWRs and future ARs.

Summary and Path Forward

Achieving a net zero carbon society demands a new approach that will best utilize all clean energy generation options. Integrated energy systems are imperative for meeting clean energy needs across all energy sectors. They couple diverse energy generation sources, including variable renewables, with high-capacity clean energy generated by nuclear plants and fossil plants that capture and manage carbon emissions. These systems ensure more efficient energy use and increased revenues for plant owners by supporting multiple product streams while ensuring power grid reliability and resilience.

The path forward requires a concerted private-public effort in which innovative technologies and system integration are reduced to practice through modeling and simulation; technology testing, proving, and scale-up; and financial structures that help overcome the risks taken on by first movers and commercial adoption. Technology performance and reliability testing will reduce the technical, safety, and financial risks inherent in disruptive technologies and physical/temporal systems integration.

Successful deployment of the integrated clean energy solutions proposed here will require true partnership among research organizations, technology developers, energy users, investors, policymakers, and communities.

The clean energy transition away from fossil fuel dependence cannot leave communities behind. Nuclear and renewable-based integrated energy systems can usher in job creation and economic development through deployment of new infrastructure and industry.

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Deployment of advanced reactors, clean hydrogen, and fusion energy requires private-public partnerships, investment, streamlined regulations, international cooperation, and policy support.

New Generation Resources:
Advanced Reactors, Fusion, Hydrogen

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Decarbonization of the global economy in the near term necessarily focuses on current energy options for industrial and consumer applications. In addition, new carbon-free energy resources with higher power density are essential for a full energy transition and continued energy evolution (Smil 2021). In this article we examine opportunities and challenges to be addressed for advanced nuclear, hydrogen, and fusion energy.

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Setting the Stage for Nuclear, Hydrogen, and Fusion Energy

Advanced nuclear reactors,[1] poised to come online within a decade, may augment baseload power options while also managing costs through modular fabrication, new fuel cycles, and distributed installation (IEA and NEA 2020). For hydrogen, a new national strategy advocates for the accelerated development of low-carbon and clean hydrogen production for targeted sectors such as manufacturing, heavy-duty transportation, and long-duration energy storage (DOE 2022a). Nuclear fusion, while less mature, has compelling potential as the natural progression of advanced nuclear energy for delivering broadly available, safe, carbon-free energy with limited waste products (Gonzalez et al. 2022; NASEM 2021).

New energy solutions are unlikely to succeed without community acceptance and understanding of environmental impacts.

Nuclear and fusion systems are energy sources, while hydrogen is an energy carrier—and can, like electricity, support the use of various energy sources. The three approaches vary significantly in their readiness for deployment, but each offers valuable characteristics for a future carbon-free energy portfolio.

All new energy resources require extended periods of development, including resolution of technical challenges, demonstration of economic feasibility and cost predictability, public acceptance, safety and regulatory certainty, utility acceptance, and grid integration.[2] New resources also offer an opportunity to address environmental concerns and energy justice from an early stage of development. Without community acceptance and other aspects of energy justice, as well as an understanding of environmental impacts, new energy solutions are unlikely to succeed (Hoedl 2019).

A proposal now under review to site advanced nuclear reactors at former coal plants is one example of how a blend of government, industry, and community engagement can support energy evolution (Hansen et al. 2022). New analysis tools can also support local planning efforts to inform options for future power plant siting and energy source access (Omitaomu et al. 2022).

Needed Technology Development

Advanced Nuclear Reactors

Advanced nuclear systems, including small modular reactors, are closest to achieving both demonstration facilities and commercial deployment. These reactors include a variety of designs and capabilities, ranging from 10 to 100s of megawatts.

Light water reactor (LWR) designs have a more defined path to commercialization in the United States because they share similarities with already licensed and operating reactors.[3] Non-LWR designs require significant investment in research and development to qualify fuels and materials; qualification requires validation of modeling and simulation tools, and potentially component testing.

Fuel development for advanced nuclear systems ranges from improvements to LWR fuels to new forms based on alternative fuels and cladding, all with differing levels of technology readiness (Carmack et al. 2017). Coated particle fuels, for example, are undergoing testing and changes that could benefit performance; they are being explored to support development and demonstration of high-temperature reactors (Demkowicz et al. 2019). Additionally, the development of new materials for reactor structures is necessary for harsh advanced reactor environments (Zinkle et al. 2016). Computing, modeling, and simulation capabilities are advancing nuclear systems with both new (Alexander et al. 2020; Martineau 2021) and existing models such as MELCOR at Sandia National Laboratory.[4]

[1] Advanced reactors are nuclear fission reactors with technologies that provide significant improvements over current light water reactors in performance, passive safety features, thermal efficiency, and expanded applications.

[2] International Energy Agency, "Net zero by 2050: A roadmap for the global energy sector" (https://www.iea.org/reports/net-zero-by-2050)

[3] One example is NuScale's standard design certification for an integrated assembly of 12 small modular reactors, submitted to the US Nuclear Regulatory Commission (USNRC 2017).

[4] MELCOR (a portmanteau from *melting core*) is a computer code developed at Sandia "to model the progression of severe accidents in nuclear power plants" (https://energy.sandia.gov/programs/nuclear-energy/nuclear-energy-safety-security/melcor/).

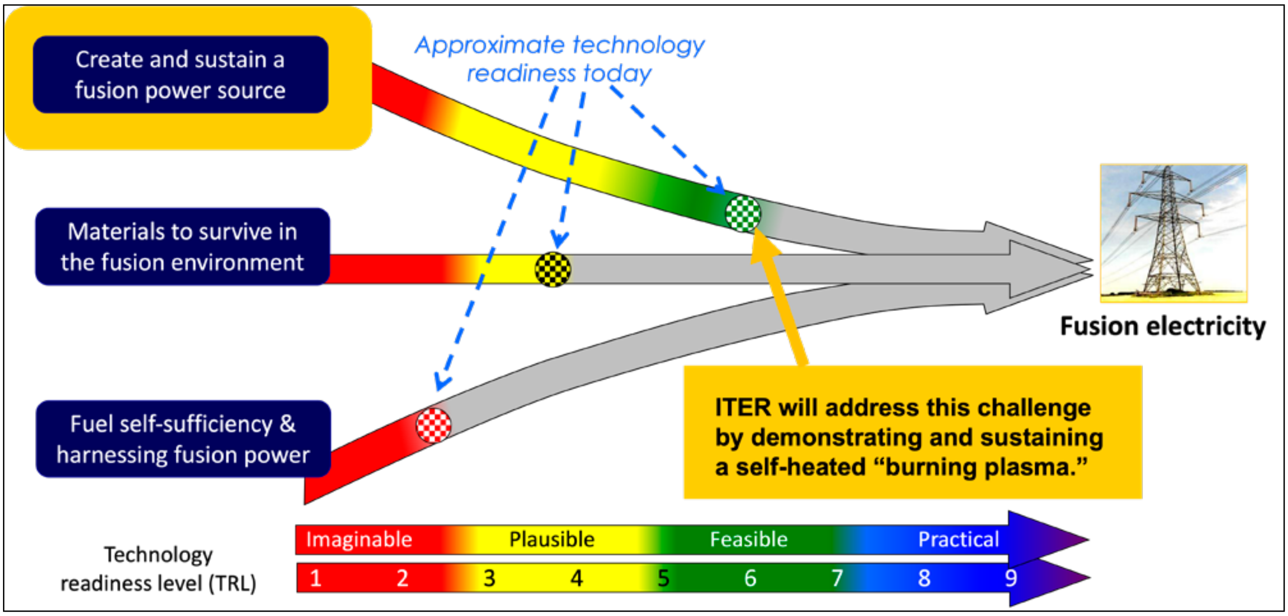

FIGURE 1 To achieve practical fusion energy, three major challenges must be resolved: Produce and sustain a fusion power source, develop new fusion materials, and resolve fusion fuel self-sufficiency and efficiency. ITER will address the first challenge by achieving a self-heated, self-sustaining "burning plasma."

Hydrogen

Hydrogen (H_2) can be extracted from fossil fuels and biomass, from water, or from a mix of both; however, thermal processes using natural gas or coal are currently the primary source of H_2 production (IEA 2019). To contribute to decarbonization, economical, low-carbon or carbon-free production techniques must be developed to yield "clean hydrogen" (IEA 2019).

The DOE Hydrogen Shot[5] seeks to reduce the cost of clean hydrogen by 80 percent—to $1 per kilogram in a decade. Technical challenges must be resolved related to H_2 distribution, storage, dispensing, and safety. Long-term distribution of pure hydrogen through the existing natural gas pipeline infrastructure is limited because of hydrogen's corrosive impact on materials (Topolski et al. 2022). Long-term storage materials for hydrogen must also be addressed, and safe end-use solutions must be developed for diverse applications.

In short, the infrastructure required for clean hydrogen is similar to the scale of conventional fossil fuel infrastructure. One important difference is that hydrogen can be produced in a centralized facility or at distributed end-use locations (DOE 2017).

[5] https://www.energy.gov/eere/fuelcells/hydrogen-shot

Fusion

Fusion could be a compelling energy source, and there has been exciting technical progress over the past decade:

- The ITER facility in southern France is demonstrating that it is possible to achieve millimeter-scale engineering precision for assembly of power plant–scale fusion reactor components (Bigot 2022).
- Early in 2022 the Joint European Torus (JET) in the United Kingdom documented the generation of 59 megajoules of sustained fusion energy, more than doubling its 1997 record and providing confidence in the physics underlying ITER (Gibney 2022).
- The National Ignition Facility at Lawrence Livermore National Laboratory achieved ignition (Bishop 2022) late in 2022, demonstrating a "Q" of around 1.5 (the energy produced by the target divided by the energy that went into the target) (Zylstra et al. 2022).

Investment in the private fusion industry has grown to about $5 billion, with more than 30 companies now established worldwide (Windridge 2022). Still, significant technical challenges must be solved for fusion to be a practical, economical energy source (figure 1). ITER will address one of these challenges: the production and

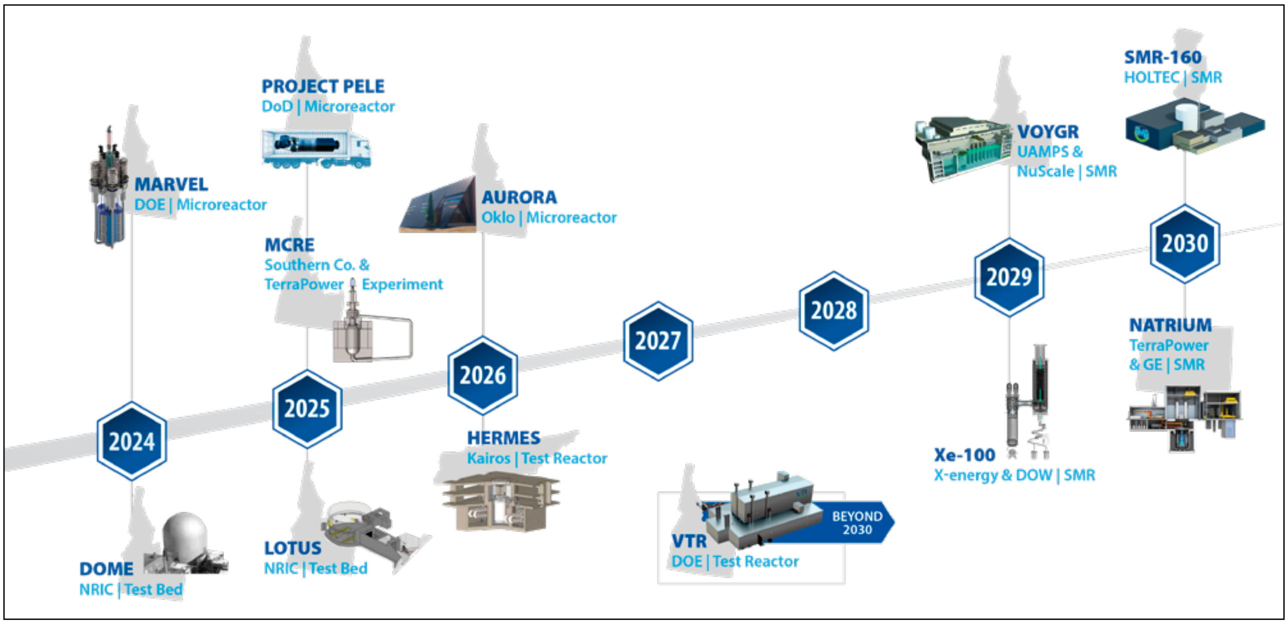

FIGURE 2 US advanced reactor demonstration timeline, 2024–30. The shadowed state behind the reactor indicates the reactor site location. DoD = US Department of Defense; DOE = US Department of Energy; DOME = demonstration of microreactor experiments; GE = General Electric; LOTUS = Laboratory for Operations and Testing in the United States; MCRE = molten chloride reactor experiment; NRIC = National Reactor Innovation Center; SMR = small modular reactor; UAMPR = Utah Associated Municipal Power Systems; VTR = Versatile Test Reactor.

control of a self-sustaining fusion power source with a Q of up to 10. The development of materials that can survive fusion power plant conditions and the establishment of a sustainable fusion fuel cycle are at much earlier stages of technical maturity. While ITER will contribute to solving these challenges, additional investment is needed. All three challenges must be resolved to construct and operate a pilot plant that demonstrates a safe, affordable, and reliable fusion energy system (FES Advisory Committee 2020).

Economic Factors: Cost, Supply Chains, Infrastructure

Advanced Nuclear Reactors

Nuclear fission energy has been deployed in the United States at a large scale for over 40 years and now delivers nearly 20 percent of the country's electricity generation (EIA 2023) and about 50 percent of its carbon-free electricity (DOE 2022b). However, cost predictability is a persistent issue.

Small modular reactors (Liou 2021), developed in response to the challenges of deploying large-scale reactors (NEA and OECD 2016), provide benefits such as reduced capital costs, more reliance on passive safety, and greater flexibility for deployment. A broad range of designs is under development, with a variety of fuels and coolants (MIT 2018). While these designs reduce overall manufacturing and construction costs—and offer new options for remote site installation—cost competitiveness is still uncertain and there remain issues with fuel supply chain development. The Department of Energy Advanced Reactor Demonstration Program,[6] which supports deployment of first-of-a-kind advanced reactors, will provide important data on competitiveness, but ultimately deployment of multiple advanced reactors will be needed to evaluate cost consistency.

Further, many advanced reactors use High Assay Low Enriched Uranium (HALEU), which is not produced in the United States. National investment is needed to establish the required infrastructure for this fuel (MIT 2018). In November 2022 DOE announced a cost-shared award for the first domestic production of HALEU for advanced nuclear reactors (DOE 2022c). Figure 2 illustrates an advanced reactor deployment timeline.

[6] https://www.energy.gov/ne/advanced-reactor-demonstration-program

Hydrogen

Economical clean H_2 production could be accelerated by new carbon-free energy sources, such as advanced reactors. Innovations in other industries, including transportation, chemical and steel production, and pipeline infrastructure, could also affect hydrogen's economic feasibility (DOE 2022a).

The hydrogen energy value chain to the end user will largely consist of three stages: production, distribution/storage, and dispensing. The final dispensed price and carbon footprint of hydrogen are the combination of costs incurred and CO_2 generated during these stages (Sujan 2022). Additional factors—such as economic profit margins, H_2 purity, taxes, incentives, environmental policies, public-private partnerships, upstream feedstock carbon footprints, end-use productivity, and resiliency—must also be considered.

Fusion

Fusion will have to be competitive with other firm energy resources, such as advanced reactors and hydrogen. And fusion power plants must offer utilities compelling options at a sufficient scale and availability (NASEM 2021). Some posit that fusion is likely to follow a trajectory similar to that of nuclear fission, with costs decreasing as efficiency improves (Griffiths et al. 2022).

Current R&D focuses on resolving technical challenges and establishing viable solutions for the sustained operation of a fusion pilot plant. Private fusion companies are exploring compact options for future fusion devices that may prove more economical. The bottom line is that a pilot fusion power plant must not only demonstrate technical features for future power plants but also give confidence to utilities that the economics for the technology will be acceptable for commercial deployment.

The Role of Utilities

Utility acceptance is a key factor in the deployment of any new energy source. Many utilities already own and operate nuclear fission reactors, and the recently established DOE clean H_2 hubs (part of the department's Energy Earthshots[7]) should accelerate utility acceptance of hydrogen. Engaging utilities during the development of fusion energy has been identified as an important step for utility acceptance (NASEM 2021). Similarly, public acceptance of a new energy source is as important to deployment as is the technology development. Recommended methods for public acceptance include early engagement and consent-based siting (Kasperson and Ram 2013).

[7] https://www.energy.gov/policy/energy-earthshots-initiative

Safety and Regulation

Advanced Reactors

Regulatory frameworks need to be modernized to reflect the unique characteristics of advanced reactors and eliminate unnecessary delays (Meserve 2020). This includes streamlining licensing processes and establishing standardized safety criteria. Licensing for advanced reactors is being pursued through existing regulations largely established for light water reactors. The US Nuclear Regulatory Commission (USNRC) is pursuing new rule making to develop a risk-informed, technology-inclusive regulatory framework for advanced reactors (USNRC 2023a). Advanced LWRs, and in particular small modular LWRs, have a simpler path to commercialization since the USNRC has many years of experience with LWRs (Federal Register 2023; USNRC 2022). In addition, the industry-led Licensing Modernization Project has been approved by the USNRC for use with current regulations to provide a path for advanced reactors that are ready for licensing before 2027 (Grabaskas et al. 2019). This is important for the Carbon Free Power Project, for example; it notified the USNRC that it intends to submit a combined license application for the NuScale SMR in 2024 (CFPP 2022).

Regulatory frameworks need to be modernized to reflect the unique characteristics of advanced reactors and eliminate unnecessary delays.

Hydrogen

Efficient, safe deployment of hydrogen requires infrastructure solutions that are well aligned with the needs of the end user, whether for industrial applications or consumers.

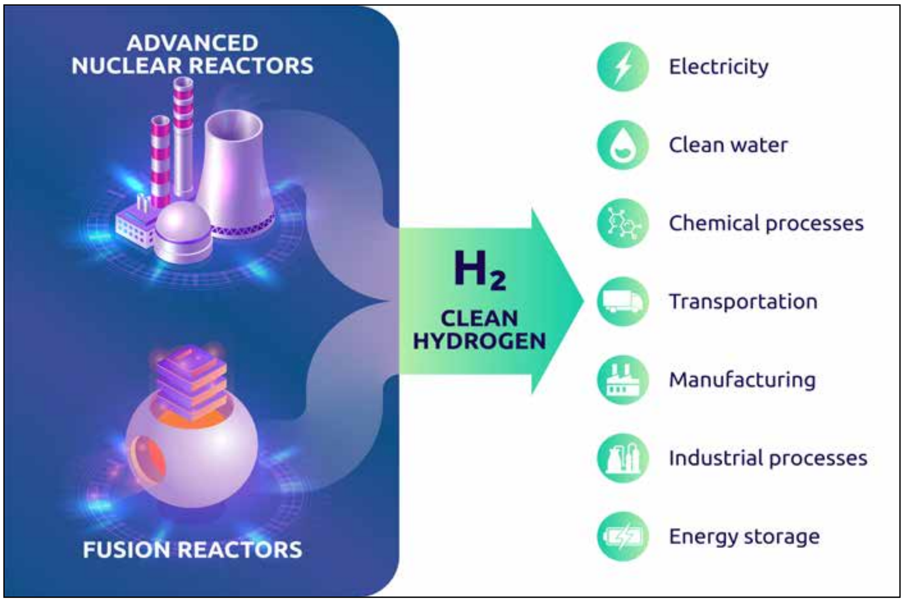

FIGURE 3 Advanced reactors and eventually fusion reactors could contribute to clean hydrogen production for a variety of applications (right column) in an integrated energy system.

Because hydrogen is more flammable than methane and other hydrocarbon fuels, its use may require the installation of sensors and instrumentation specifically configured for fuels containing hydrogen. In addition, hydrogen can affect materials and systems differently than other gases. Solutions that use liquid hydrogen will introduce challenges with the safe handling of cryogenic fluids and therefore federal and local regulatory agencies[8] will need to coordinate in establishing and maintaining H_2 standards.

Regulatory compliance and oversight will be critical in all phases of the H_2 value chain, from production through off-take usage. While some standards and regulations are in place, gaps remain in areas such as offshore transportation, sales and distribution, fuel certification, and residential and commercial heating (Ehrhart et al. 2021).

Fusion

The USNRC (2023b) is developing a licensing framework for fusion, to be completed by 2027. This is a challenging undertaking since many fusion technologies are still at a low level of technology readiness, and the fusion configurations in development vary widely. Many, but not all, concepts assume a deuterium-tritium fuel cycle. There are also concepts for fusion-fission hybrids, primarily for destruction of long-lived transuranics (Shlenskii and Kuteev 2020).

Fusion systems can produce copious neutrons, activating reactor structures and requiring longer-term management solutions. Work is needed to ensure availability of “low-activation” materials that are easier to dispose of than those currently used in a nuclear system (Jones et al. 1999; Petti et al. 2000). Safe operation scenarios must be demonstrated, and regulatory certainty is needed both for the development of appropriate down-selection of fusion system approaches and for utility owner-operator acceptance (EIA 2023).

The Path Ahead

The cost- and time-efficient deployment of advanced reactors, clean hydrogen, and fusion requires a coordinated effort involving private-public partnerships, sustained investment, a tailored regulatory process, international cooperation, and policy support.

The private sector brings expertise in business models, financing, and commercialization, while the public sector offers research, development, and demonstration capabilities. Technical challenges must be resolved, cost and supply chain issues addressed, safety and licensing established, and community support secured for these resources to be viable contributors to carbon-free power generation and other applications. Government and regulatory agencies will need to provide pathways for collaborations that maintain the attributes necessary for market competitiveness. Figure 3 illustrates how these new energy resources can contribute to a clean energy ecosystem.

The potential for flexible application, combined with higher energy density, makes the development of these resources especially valuable in a future integrated clean energy system (Bragg-Sitton et al. 2020; DOE 2020). Integrated clean energy systems can deliver more value

[8] In addition to the EPA and OSHA, these will include the Pipeline and Hazardous Materials Safety Administration (PHMSA), Federal Motor Carrier Safety Administration (FMCSA), Federal Highway Administration (FHWA), National Fire Protection Association (NFPA), American Society of Mechanical Engineers (ASME), and Compressed Gas Association (CGA).

than the sum of a single resource. Consider an advanced or fusion reactor that provides electricity during peak demand and produces hydrogen during times when demand is low.

Given deployment timelines, we envision that advanced reactors will both provide a carbon-free power source for grid distribution and support localized industrial processes, such as clean hydrogen production. Hydrogen's flexibility lends itself to serving industrial processes that are particularly difficult to decarbonize, such as ammonia for fertilizer. Fusion could follow advanced reactors with delivery of firm baseload power; it could also be used to help manage the nuclear fuel cycle via transmutation of waste. The goals of long-term decarbonization and new clean energy source development are deeply compatible.

Acknowledgment

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Peer-to-peer trading benefits the grid through reductions in peak demand, reserve requirements, and operating costs as well as improved reliability.

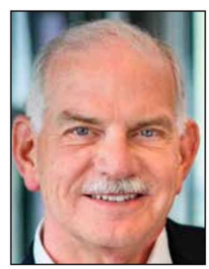
Peer-to-Peer Trading in Support of Decarbonizing the Electricity Sector

Wayes Tushar, Chau Yuen,
Tapan K. Saha, and H. Vincent Poor


Wayes Tushar


Chau Yuen


Tapan Saha


Vincent Poor

Electricity generation is the largest source of carbon dioxide (CO_2) production, contributing about 40 percent of global energy-related emissions (Luderer et al. 2019). But the electricity sector has the potential to reduce CO_2 generation by electrifying the building, industry, and transport sectors—most of which now depend on fossil fuels—and providing electricity from renewable energy sources.[1] In this article we describe the prospects and

[1] For instance, the 2022 Integrated System Plan draft of the Australian Energy Market Operator notes that a fivefold increase in distributed photovoltaics (i.e., rooftop solar) is necessary for the country's decarbonization efforts (AEMO 2021).

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benefits of peer-to-peer trading to help decarbonize the electricity sector.

Introduction

An initiative for decarbonizing the electricity sector that is gaining momentum involves engaging *prosumers*—electricity consumers who also have production capabilities (Tushar et al. 2020)—with distributed energy resources (DERs).

Using prosumers' resources at the edge of the grid—the point in the electricity network at which electricity users are connected—to decarbonize the electricity sector will necessitate prosumers' seamless and active participation in market management and sharing (Peck and Wagman 2017). At present, such participation is mostly passive: prosumers sell their excess energy to the grid through feed-in tariff schemes at a price set by the utility. This is not a sustainable model for prosumers' active participation in the energy market because of limited monetary benefit and lack of independence in managing resources (Tushar et al. 2018). Furthermore, in some places there is a restriction on prosumers' DER exports to the grid, reducing the potential benefits to the prosumer.

Energy management through P2P trading enables prosumers to fulfill energy-related objectives in a distribution network by sharing resources.

Decarbonizing the electricity sector through prosumers' active participation requires innovations in how prosumers interact with the grid and make decisions about sharing their resources with other stakeholders, such as electricity consumers and retailers in the network. One emerging market mechanism that has proven its capability to encourage electricity sharing is peer-to-peer (P2P) trading (Cui et al. 2019).

P2P trading is an energy management technique that enables prosumers in a distribution network to share resources and information with one another and other stakeholders to fulfill various energy-related objectives, such as decarbonization of the electricity sector and electricity cost reduction. Energy resources that can be shared through P2P trading include electricity from solar generation (Chen et al. 2021), negawatts (Tushar et al. 2020), and battery capacity (He et al. 2021). The more such sharing is enabled in the electricity network, the less reliance on fossil fuel–based electricity. For these reasons, efforts in P2P research and development have been extensive (for details on P2P trading, see Azim et al. 2021c; Tushar et al. 2021a).

The Fundamentals of P2P Trading

P2P trading, as a form of transactive energy (Shahidehpour et al. 2020), provides a platform for prosumers to use economic and control mechanisms for sharing their energy resources and flexibility services in a local electricity market. With this arrangement, (i) prosumers can reap substantial revenue compared to existing feed-in tariff schemes (Tushar et al. 2021) and (ii) the grid can benefit from reductions in peak demand (Kanakadhurga and Prabaharan 2021), reserve requirements (Andoni et al. 2019), and operating costs (Mengelkamp et al. 2018) as well as improved reliability (Morstyn et al. 2018).

Layers of the P2P Network Structure

The P2P network structure needs two interactive layers: virtual and physical (figure 1).[2] The virtual layer, built on a secure information system, handles the exchange of information and negotiations to buy and sell orders among the participating prosumers (or peers), who all have access to the virtual layer. The physical layer handles the transfer of electricity and may be either a dedicated physical structure to facilitate P2P sharing in a locality or a traditional distribution network provided and maintained by an independent system operator.

Types of P2P Markets

P2P markets can be categorized as coordinated, decentralized, community, and retailer-enabled. In all of these forms, a constraint on the underlying distribution is that the export and import of power cannot violate the network's statutory (operational) limits. Negotiations between P2P peers follow different market rules depending on the roles of various stakeholders and their approaches to coordination and communication.

[2] For detailed descriptions of the elements of the P2P network structure layers, see Tushar et al. (2021).

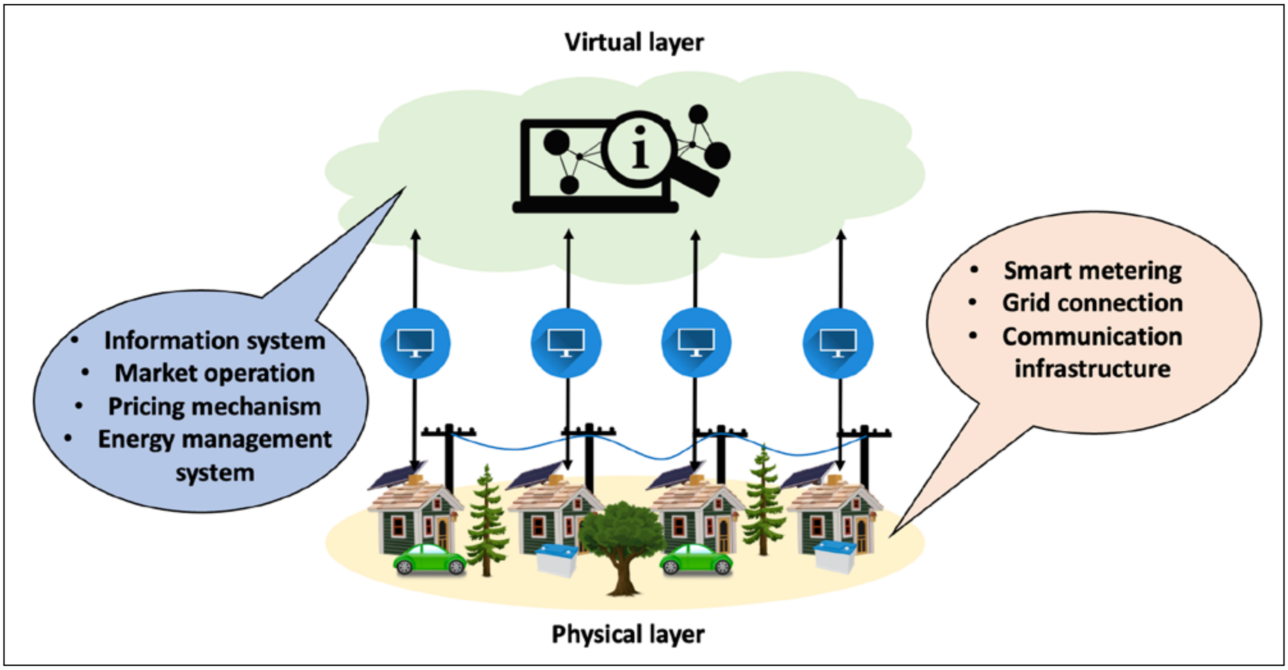

FIGURE 1 The virtual and physical layers of a peer-to-peer network and their elements. Adapted from Tushar et al. (2021a), where the details of different elements are also explained. Images are royalty-free and taken from https://pixabay.com/.

In a *coordinated* market, a centralized entity or coordinator is responsible for the trading and communication between peers in the network and directly controls their export and import limits for P2P sharing (Tushar et al. 2021a). The peers influence the market outcome by independently deciding energy and price before allowing the centralized entity to control the export and import of energy. This arrangement can improve the social welfare impacts of P2P sharing (Zhou et al. 2020) if the coordinator sets the export and import limits of each participant for that purpose. However, if the number of participants becomes very large, the computational burden can become unmanageable (Papadaskalopoulos and Strbac 2013).[3]

In a *decentralized* market, participating prosumers decide on their energy trading parameters and share the resources among themselves without a centralized coordinator. As prosumers are in full control of their decisions about energy sharing, their privacy is preserved. The scalability of decentralized P2P markets is remarkable, but it is challenging to maintain the same efficiency as the coordinated market and these markets have poorer social welfare outcomes compared to coordinated markets. This is because in a decentralized market, prosumers are interested in maximizing their own benefits, which does not necessarily maximize social welfare outcomes. Examples of decentralized P2P markets are discussed in Sorin et al. (2019).

In a *community* market (Moret and Pinson 2019), resource sharing among the participants is handled by a community manager, without directly controlling prosumers' resource exports and imports. With very limited information exchange between the community manager and participants, a community-based market ensures a very high level of prosumer privacy and enables prosumers to maintain their autonomy in decision making.

In a *retailer-based* P2P market (Tushar et al. 2021b), peer participation follows the same framework as in the decentralized market, but a retailer can facilitate prosumers' sharing with available resources to participate in either the spot or retail market by expediting the bidding of surplus energy in prosumers' batteries. Both prosumers and retailers can improve their revenues compared to coordinated, decentralized, and community markets.

These P2P market structures enable prosumers to share their resources in a local electricity network and contribute to decarbonizing the electricity sector. But their contributions toward decarbonization may vary depending on what type of resources they share.

[3] To learn more about the coordinated market, see Lüth et al. (2018).

Types of P2P Resource Sharing

Since 2017 the feasibility of P2P trading and its benefits for electricity customers have been demonstrated extensively through pilot projects and scientific research. Based on state-of-the-art P2P trading, three types of electricity resources can be shared in a local electricity network by prosumers with DERs.

Electricity

In P2P electricity trading, locally generated electricity—predominantly from rooftop solar (photovoltaics, PV)—is shared in a community, reducing consumption of electricity from fossil fuel–driven generators. This approach facilitates decarbonization at cheaper rates and lowers electricity bills for both prosumers and consumers (without DERs).

The need for fossil fuel–driven electricity can be substantially reduced by allowing consumers to manage their energy consumption through negawatt trading.

A P2P trial in Western Australia shows how P2P electricity trading can help a community to achieve decarbonization. In the city of East Village at Knutsford near Fremantle, Powerledger (2022) has successfully set up a RENeW Nexus project to enable 40 residential houses to share their electricity via P2P trading.[4] The participating properties rely on fossil fuel–driven generators for only 32 percent of their total electricity demand; they meet the remaining 68 percent of demand through P2P trading of renewable energy and thus contribute to decarbonization. P2P trial projects in Asia, Europe, and the United States similarly demonstrate decarbonization via P2P electricity trading (Tushar et al. 2021a).

Negawatts

Negawatts are negative watts, the amount of power that a prosumer can save through efficient consumption.

In the P2P exchange of negawatts, a prosumer negotiates with peers to decide on a price to reduce its demand by alleviating energy consumption and then trades that demand with peers to maintain a fairly steady demand level among customers in the community. Negawatt trading can help electricity customers reduce their reliance on fossil fuel–based electricity even when the supply of renewable energy is limited (Azim et al. 2021a).[5] For example, if the supply of renewable energy is limited, consumers need to buy energy from fossil fuel–based generators to meet their additional demand. Through negawatt trading, overall demand in a community can be reduced and thus reliance on fossil fuel–based generation minimized.

Japan's Yokohama Smart City Project illustrates successful implementation of negawatt trading. In this demonstration project, experiments with various types of electricity customers (e.g., high-rise office buildings, urban centers, housing complexes, shopping centers, and small to medium-size factories) showed that about 71 percent of the customers were willing to participate in negawatt trading by taking different power conservation measures. Options included reduced use of air conditioning systems and the scheduling of electricity-related activities (e.g., washing machine use, heating of swimming pools, and electric vehicle charging) for non-peak periods (Honda et al. 2017). There was a direct correlation between successful negawatt trading and the trading system's responsiveness to individual customer preferences (Honda et al. 2017).

The Yokohama project showed that the need for fossil fuel–driven electricity can be substantially reduced by allowing consumers to manage their energy consumption through negawatt trading.

Storage Capacity

One of the most common renewable energy resources is rooftop solar. At present, during sunshine hours, prosumers with rooftop solar use the resulting power for household activities, and excess power is directly exported into the grid. But without effective management, simultaneous power exports can result in voltages and currents in the distribution network well beyond

[4] Powerledger RENeW Nexus, https://www.powerledger.io/media/renew-nexus-enabling-resilient-low-cost-localised-electricity-markets-through-blockchain-p2p-vpp-trading

[5] More information about negawatt trading is in Tushar et al. (2020).

TABLE 1 Summary of how different peer-to-peer (P2P) trading strategies contribute to electricity sector decarbonization

Type of P2P trading	Summary	How it contributes to decarbonization	Further reading
Electricity	Prosumers with excess electricity share the surplus with other customers in the network	Reduces dependence on fossil fuel–driven electricity by increasing the share of renewable energy in the community	Tushar et al. (2021a)
Negawatt	Participants share their rights to trade energy and thus enable customers with urgent need to meet demand with renewable energy	Facilitates flow of renewable energy in the community through appropriate reduction in demand	Azim et al. (2021a) Tushar et al. (2020)
Storage capacity	Participants share battery capacity with one another for charging and discharging	Stores excess renewable energy to use during periods of low renewable energy generation	He et al. (2021) Tushar et al. (2016) Yang et al. (2021)

statutory limits, compromising the network integrity and even disrupting its operation.

The most popular solution to unmanaged power exports is to use battery storage at either the individual household or community level. But battery storage is expensive. P2P trading of storage capacity has become a viable mechanism to provide access to battery storage to mass electricity prosumers.

In P2P storage trading, owners of storage devices negotiate with other prosumers in an electricity network to agree on rent per unit of storage capacity to be shared with peers. Depending on what type of storage is shared, the framework for negotiation may vary. For example, in one community several household owners share their small-scale battery storage with a facility controller, which ensures the consistent availability of routine functions such as apartment elevators and streetlights (Tushar et al. 2016). This kind of model can facilitate decarbonization by using shared storage to store renewable energy for use by the facility controller at times when the supply of electricity from rooftop solar is very low or null.

Another model for storage capacity sharing via P2P is medium- or large-scale storage shared by community members. Participating entities either cooperate (Yang et al. 2021) or compete (He and Zhang 2021) with one another to access some fraction(s) of the community storage capacity, maximizing their use of renewable energy and contributing to decarbonization of the electricity sector at the community level.

Table 1 summarizes strategies for P2P sharing of different resources and how they contribute to decarbonization.

Future Considerations for P2P Trading and Decarbonization

As P2P trading continues to demonstrate its potential for shaping the electricity network and decarbonization, new technologies are emerging to complement its capabilities and mitigate its limitations. In this section we focus on the concept of the dynamic operating envelope and decentralized finance and discuss how P2P trading can benefit from integrating them into its capability portfolio for decarbonization.

Dynamic Operating Envelope

In a power system, a limit to the amount of electricity that a customer can import from or export to the grid enables the trading of electricity without violating the network's statutory limits.

Traditionally, network operators keep the export and import limits to fixed levels considering the worst-case load and generation limits, not necessarily based on the actual network capacity. Because of these export and import limits, prosumers need to coordinate with the network operator before exporting electricity, to conform with the requirements. This hinders prosumers from trading according to their maximum capacities.

Recently, however, a new concept, the *dynamic operating envelope* (Liu et al. 2021), has emerged to relax prosumers' export/import limits. It allows the network operator to dynamically set the export (or import) limits, enabling prosumers to operate freely as long as they operate within the "envelope" of these limits (Milford and Krause 2021).

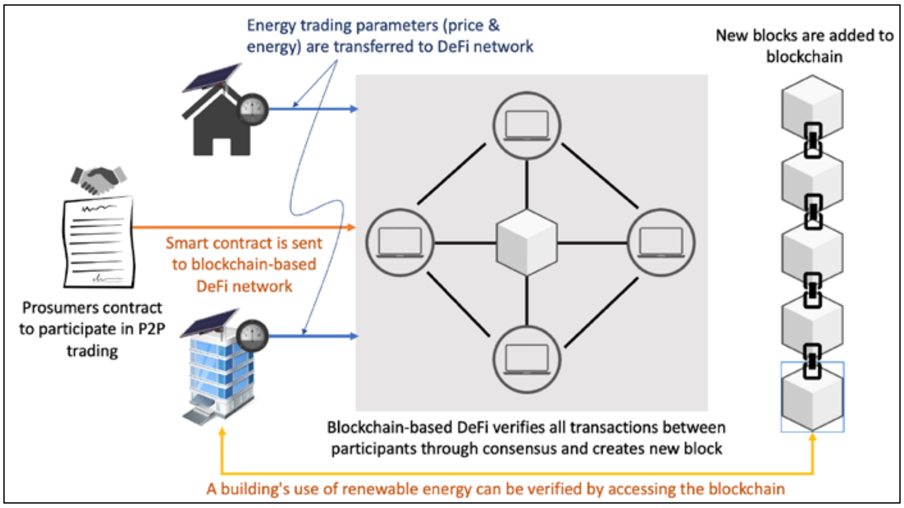

FIGURE 2 How a blockchain-based decentralized finance (DeFi) network can help houses and buildings track their 24/7 use of renewable energy in peer-to-peer (P2P) trading and reduce carbon taxes. Images used in the figure are royalty-free and taken from https://pixabay.com/.

A dynamic operating envelope calculates the export limit per user in real time. For example, depending on the condition of the network, a prosumer with a 7 kW (or larger) system would be permitted to export close to its limit during some parts of the day without approval from a third party or controller. This flexibility can increase the flow of renewable energy from prosumers' DERs into the electricity mix and thus contribute to decarbonizing the electricity sector.

In the context of P2P trading, the flexibility of the dynamic operating envelope can be very useful in terms of increasing prosumers' participation in trading by stimulating their independent decision making and increasing revenue. For example, in many parts of the world, the export limit of rooftop solar is capped at 5 kW (Azim et al. 2021b) based on traditional operating envelopes. This means that, even if a household or small business owner installed a large PV system (e.g., 7 kW capacity), it would not be allowed to export more than 5 kW. If it attempted to do so, the inverter would be cut off from the system. Sometimes, even stricter restrictions are imposed (e.g., a maximum export limit of 3.5 kW; Liu et al. 2021) to ensure network integrity during peak PV generation hours.

However, P2P trading that can incorporate a dynamic operating envelope in its decision-making paradigm is yet to be implemented. One way to include this capability in the trading framework might be to develop a hierarchical decision-making algorithm in which, as the first step, each prosumer would receive the maximum dynamic operating limit in each time slot from the network provider and manage its supply and demand to set the power it is willing to trade. Once the maximum power amount that each prosumer can export safely to the network is determined, then, in the final step of the algorithm, prosumers would initiate P2P trading among themselves.

Decentralized Finance

Decentralized finance (DeFi) is an emerging financial model suitable for P2P financial transactions. It uses secure distributed ledger technology (e.g., blockchain; Hassan et al. 2019), which uses a consensus mechanism to verify financial transactions and removes the involvement of third parties in the transactions (Chen and Bellavitis 2020). Anyone with an internet connection can create an account in the system and trade with another entity.

By registering for DeFi, each P2P participant can track their generation and consumption of renewable energy 24/7—which can help offset carbon taxes (Papadis and Tsatsaronis 2020)—and receive certificates for contributing to decarbonization. With such certificates P2P participants may get tax rebates, qualify for special mortgage programs, have better occupancy rates, and receive higher rental rates (Awair 2019). Figure 2 shows how contributions to decarbonization by different buildings/households can be tracked through a DeFi platform.

It is relevant to note that DeFi does not provide anonymity (Sharma 2022). Although a prosumer may hide their identity from other entities in a P2P network by using an anonymous name, they are traceable by organizations such as the government and law enforcement with the legal authority to access the accounts if needed. Such traceability reduces the probability of cheating in financial transactions and can build confidence among prosumers to use such a trustless system for trading.

Conclusion

We have discussed how peer-to-peer trading of renewable energy can help reduce CO_2 emissions in the electricity sector. We posit that this energy-sharing technique can also be used for sharing alternative resources of an electricity network, such as negawatts and battery storage capacity, to contribute to decarbonization by increasing the flow of clean electricity and reducing the need for fossil fuel–driven electricity.

Implementation of a P2P network comes with the technical challenges of maintaining the network's reliability and securing financial transactions. We have identified two emerging technologies with capabilities to address these challenges. Integration of these techniques into P2P trading schemes may enable and enhance the capability of P2P trading in decarbonizing the electricity sector.

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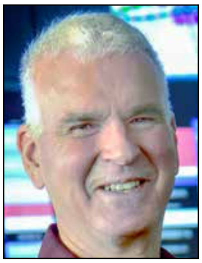
As the power grid becomes both more essential and more vulnerable, new approaches are needed to ensure its resiliency.

The Electric Grid and Severe Resiliency Events

Thomas J. Overbye, Katherine R. Davis, and Adam B. Birchfield



Thomas Overbye

Katherine Davis

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Large-scale electric grids worldwide are in a time of rapid transition due to a variety of changes, including the addition of large amounts of renewable and distributed resources, the electrification of transportation, the need for more energy storage, increasing use of advanced technology for monitoring and control, smarter distribution systems, and sophisticated electricity markets. It is an exciting time, and one with many engineering challenges.

While the future could be quite bright, this time of great transformation is also a time of potential peril. Societies around the world are increasingly dependent on a reliable, nearly ubiquitous supply of electricity. The impact of the loss of a portion of a large-scale electric grid ranges from minor inconvenience when the outage is brief and limited in scope to potentially

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catastrophic when it covers a large region for a long duration.

Grid Reliability and Resiliency

In 2010 the North American Electric Reliability Corporation (NERC) and the US Department of Energy (DOE) used the term *high-impact, low-frequency* (HILF) *events* to denote risks that could cause long-term, widespread blackouts (NERC and DOE 2010); HILFs may also be called Dark Sky or Black Swan events (e.g., Paté-Cornell 2012). Recognizing that such events ultimately affect grid resiliency, here we use the term *severe resiliency events* (SREs).

> *A future pandemic could affect the electricity grid workforce, making it difficult to continue operating the transmission grid and resulting in blackouts.*

"Keeping the lights on" involves designing and operating electric grids[1] with the goal of achieving two related but different concepts: reliability and resiliency (Kezunovic and Overbye 2018). For large-scale grids, reliability has two core concepts: (1) adequacy (enough electricity supply) and (2) operating reliability (the ability of the high-voltage grid to withstand contingencies such as the loss of a transmission line) (NASEM 2017). Reliability mostly concerns smaller, more routine events, with the goal of keeping all, or almost all, of the grid intact.

Resiliency is also about keeping the lights on, but is more pertinent to this article's focus on more severe events. In this paper the most germane definition of resiliency is from the North American Transmission Forum (NATF 2022): "The ability of the system and its components (both equipment and human) to 1) prepare for, 2) anticipate, 3) absorb, 4) adapt to, and 5) recover from non-routine disruptions, including… [HILF] events, in a reasonable amount of time."

An event's magnitude, the scale, location, and duration of grid exposure to the event, and other factors all determine the impacts of the event. Impacts and thus the desired system response are based on the power system's electrical characteristics, which inform exactly what must be done to prepare for, anticipate, absorb, adapt to, and recover from such events.

In this article we explain severe resiliency events and provide some guidance on how their risks can be reduced and their impacts mitigated.

Severe Resiliency Events

SREs combine large size and long duration with potentially catastrophic societal impacts. They can occur initially in the electricity grid and then spread to other sectors, start in another sector and spread to the electricity grid, or simultaneously affect both (Bose and Overbye 2021). They include events that cause grids to have cascading failures, such as what happened in the North American Eastern Interconnection on August 14, 2003, when localized problems in Ohio resulted in a blackout affecting 50 million people in eight states and southeastern Canada (USCPSOTF 2004).

Types of Threat Events

The 2010 NERC-DOE report considered four types of HILFs: (1) cyber or physical coordinated attacks, (2) pandemics, (3) geomagnetic disturbances (GMDs), and (4) high-altitude electromagnetic pulses (HEMPs) caused by the detonation of a nuclear weapon in or above the atmosphere. While any of these could involve catastrophic scenarios, they exist on a frequency and severity continuum, with the more common occurrences often classified as reliability events. For example, vandalism at a few transformers in a single electrical substation, causing thousands to lose electricity for a few days, is a reliability event, whereas a large-scale coordinated attack that disables large portions of an interconnected power system for weeks or even months, affecting millions, is an SRE.

The covid-19 crisis is a resiliency example, akin to the NERC pandemic scenario, affecting the electricity grid workforce, making it increasingly challenging to continue operating the transmission grid and resulting in blackouts. Thus SREs, and associated risk reduction and mitigation measures, need to be considered on a reliability-resiliency continuum. Other SRE classes include severe weather, earthquakes, major operational errors, volcanic events, tsunamis, and wildfires

[1] The term *grid* encompasses both the equipment used to deliver electricity and the many associated components such as control and cyber systems.

(NASEM 2017). A recent SRE was winter storm Uri in Texas in February 2021—it came close to blacking out all of the Electric Reliability Council of Texas system (FERC and NERC 2021).

An increase in the frequency and virulence of SREs and the potential involvement of external systems and infrastructure are also notable features. The US Cybersecurity and Infrastructure Security Agency (in the Department of Homeland Security) defines 16 critical infrastructure sectors whose assets, systems, and networks are so vital that their destruction or loss would devastate national security and welfare (CISA 2023). Electric energy is the uniting factor among all 16 sectors.

Natural vs. Human-Induced Events

SRE risk reduction and mitigation require consideration of the nature of the event and its relative risk. For example, approaches to protect against one class of events could be quite different than for other classes, and some (e.g., earthquakes, hurricanes) are prevalent in some areas but not others.

A key distinction is between natural and human-induced events. Natural events, like GMDs, severe weather, and earthquakes, have underlying causes that generally cannot be prevented. Resiliency efforts for natural events involve predicting and preparing, taking steps to reduce impacts on infrastructure, limiting the scale and cascade of impacts, and expediting repair.

Human-induced events may be unintentional or intentional. Unintentional events due to lack of training or flaws in system design or operation may produce cascading, broad-range impacts. The predictability of these events is quite low, since known flaws are (presumably) corrected. Much like hidden bugs in software, the potential for these events could be hiding in many aspects of the system, particularly as components and control schemes get faster-paced and more complex. Efforts to enhance resiliency in this category mainly focus on preventing them from happening through detailed reviews of system design and operational practices, including personnel training.

Unintended problems may be more likely to occur at the boundaries or interdependencies of different subsystems, which are individually robust but have hidden failure modes when combined with a larger system. For example, during winter storm Uri in February 2021 (FERC and NERC 2021) electric outages compounded existing problems at natural gas processing facilities and increased the shortage of electric generation, an effect that could have been reduced with proper coordination of critical load designations.

Intentional human-induced events are the work of malicious actors seeking to cause disruption to the grid. Resiliency to these types of events may be the most challenging because they are due to an active intelligent effort to maximize the impact and duration of an event, perhaps timing it when society is particularly vulnerable (e.g., during a cold weather event). The assets and subsystems affected are not arbitrary and are meant to cause significant disruption. Unfortunately, public discussion of grid vulnerabilities to such disturbances may help an adversary better plan attacks, and unlike cyber vulnerabilities that may be rapidly patched, some grid vulnerabilities (e.g., to cyberphysical coordinated attacks, HEMPs) are not easily rectified.

Prepare, Anticipate, Absorb, Adapt, Recover

Engineered critical infrastructure systems are built from, and depend on, interdependent systems of systems, with computational, physical, and human components. In direct or indirect ways, they all depend on power and energy. Hence, protecting against SREs of any origin to avoid operational impact requires new approaches that cross traditional silos for careful design and implementation of solutions.

> *Unintentional human-induced events may result from lack of training or flaws in system design or operation.*

The goal of enhancing electric grid resiliency is to minimize, in a cost-conscious manner, the likelihood of long-duration blackouts, reduce their magnitude, and recover as quickly as possible. Using the NATF (2022) approach, coupled with the feedback component from NASEM (2017), grid resilience involves the following: (1) prepare as much as possible through both long- and short-term planning, (2) anticipate what is happening before and during the event through situational awareness, (3) design the grid (including its associated control and cybersystems) to be robust and able to absorb shocks, (4) adapt as needed during the event, (5) recover as quickly as possible, and (6) learn from what occurred

FIGURE 1 Resiliency process. Adapted from NATF (2022).

and improve (figure 1). The effectiveness of all six steps depends on the first: what is done to prepare well before an SRE occurs.

Simulation and Assessment

Simulations and assessments contribute to resilient system design. For example, could different grid architectures reduce the impacts of certain points of failure (e.g., critical substations) (Nagpal et al. 2022)? Simulation results can be used to determine needed procedures to address potential events. Not every event can be fully anticipated or mitigated, but realistic plans must be developed beforehand. Scenario development and operational planning require a wide range of research—even in the aggregate, such research is almost always significantly less expensive than even one of the events it seeks to mitigate.

To know how to respond to events, an initial assessment is crucial to identify and predict events and their impacts. The value of the assessment is enhanced with high-fidelity models and corroborating data, and learning from the data (and experience) when models are inadequate or absent. Most assessment simulations are inherently interdisciplinary, particularly in efforts to accurately represent events such as earthquakes or hurricanes.

For more common events, such as hurricanes, the risks are well known. But to some extent each event class has its own characteristics and relative risks, and requires its own mitigation strategies (Veeramany et al. 2016a). For instance, recent work discusses HEMP impacts and mitigation (EPRI 2019) and illustrates how models can break down during HEMP simulations (Overbye et al. 2022a).

For many SREs, however, the risks are not precisely known, although there are some useful commonalities in ways to improve their simulation and assessment. For instance, the development of better approaches to simulation can reduce convergence issues in simulation software. But simulations can be challenging because some types of events may not have occurred in a particular region—or at all—and even within a particular event class there can be significant variability.

An ongoing challenge in efforts to improve electric grid resiliency is the availability of grid models and data for research. Models of the actual grid are, of course, available to engineers in the electric utility sector and can be used in many SRE simulations. But development of advanced simulation tools, for example, needs to be done by researchers.

Because of security concerns stemming from the September 11, 2001, terrorist attacks on the United States, agencies such as the Federal Energy Regulatory Commission have designated much electric grid information useful for SRE analysis as critical energy infrastructure information (CEII), meaning that it cannot be freely shared (FERC 2001). To address this problem, over the last several years geographically based synthetic grids have emerged (NASEM 2016). These fictional grids are free from CEII classification and designed to mimic the complexity of actual large-scale electric grids, with appropriate geographic coordinates so they can be coupled to other infrastructures and SREs (Birchfield et al. 2017; Xu et al. 2018). This is a useful compromise to provide realistic complexity to develop and test simulation tools without disclosing CEII-sensitive data.

Geographically based synthetic grids are useful in efforts to determine earthquake risk (Veeramany et al. 2016b), and a combination of real and synthetic grids has been used to study an AC interconnection of the North American East and West grids (Overbye et al. 2022b). Figure 2 shows a detailed synthetic grid denoting different nominal transmission line voltages for the contiguous United States.

Protection, Control, and Reinforcement

A key aspect of SRE mitigation is to avoid cascading blackout scenarios, in which localized events can rapidly affect an entire interconnection (Dobson et al. 2007; Schäfer et al. 2018). While some disturbance phenomena propagate at nearly the speed of light (e.g., traveling waves from faults on a transmission line), most do so on much slower time scales because of grid interactions with the electromechanical coupling of rotating inertia. Protection and control systems also affect the way disturbances propagate. So, although grids are subject to many disturbances, most are quickly isolated, resulting in little or no loss of load.

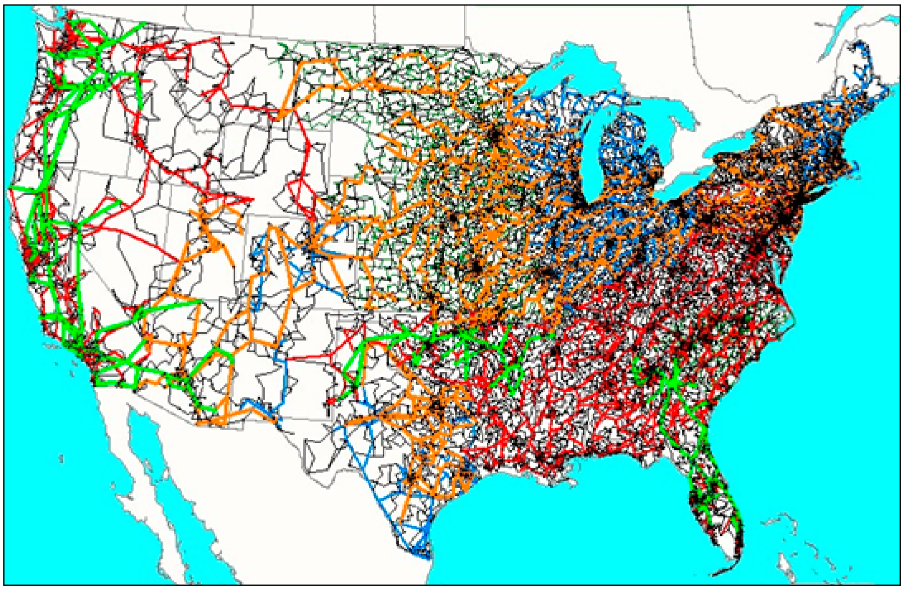

FIGURE 2 Synthetic grid for the contiguous United States. Colors correspond to different nominal transmission line voltages: green = 765 kV, orange = 500 kV, and red = 345 kV. Source: Texas A&M University Electric Grid Test Case Repository (electricgrids.engr.tamu.edu).

The challenge in assessing SREs is to ensure that even when subjected to a large disturbance, the bulk grid remains intact. One way to achieve this is intentional islanding, in which a grid is quickly broken up into a number subgrids operating independently (Biswas et al. 2020; Senroy et al. 2006). Such an approach could allow continued operation in parts of the grid, enabling faster recovery.

Enhancing the grid is also about infrastructure reinforcement, with designs that improve the system's ability to absorb disturbances. Some effective enhancements are expensive, as is the case with replacement of wood transmission towers with more wind-resistant steel or concrete, undergrounding of transmission lines, or implementation of stronger standards for distribution structures (e.g., National Electric Safety Code Rule 250C or 250D; Jurgemeyer and Miller 2014).

Inherent resiliency in the design of the grid lays the foundation for operational resiliency (i.e., withstanding an SRE in real time without significant degradation). The ability to respond—at any stage: before, during, or after an event—requires good situational awareness (Endsley 1995) of the grid and related control systems, and assessment of hazards. This certainly applies to electric grid SRE simulations of unusual operating conditions (Overbye et al. 2021).

Modeling, situational awareness, and response—the three pillars of power system resiliency—work together to support the grid's operational and infrastructural resiliency.

- *Modeling* involves testbed simulation of the system with its threats and defenses.
- *Situational awareness* requires vulnerability and risk analyses, monitoring, inference, and detection.
- *Response* includes mitigations, defense, outreach, and training.

There is a direct link between the first two and effective response.

Studies of SREs must also consider how to measure and quantify risk avoidance. This is important because it is difficult to quantify something that hasn't yet happened, and therefore difficult to justify investment for protection and defense against it. It is more straightforward to quantify the cost impacts of historical events.

Defense against large-scale cyber disruptions has been a key driver of research in this area (NASEM 2020; for discussion of specific needs, see Gunduz and Das 2020, Sun et al. 2018). A coordinated approach for next-generation energy management systems begins planning before an event and carries the model and associated data through the entire analysis cycle—before, during, and after an event (Sahu et al. 2023). This is known as *event lifecycle security*.

For example, at the early stage, the goal could be to improve cyberphysical situational awareness, which is based on the model and preventive risk analysis. Next, monitoring and verification combine different data sources (including cyber and physical) to identify or infer system vulnerabilities. Then the models and data are combined to support online preventive cyberphysical risk analysis with current state information to understand how expected system behavior matches observations. Last, these analyses provide recommendations for response and mitigation, for use in next-generation energy management systems.

A next-generation energy management system based on the three pillars of power resiliency would facilitate new capabilities for online control actions that couple cyber and physical domains. The integrity and security of the data flow pipeline are crucial for grid resiliency, so such next-generation energy management systems will track and secure the grid cyberphysical critical infrastructure from monitoring to analysis to control.

Conclusion

Since the creation of the first grids in the 1880s electricity has played an indispensable role in the development of modern societies. This transformation continues, with rapidly increasing use of renewables, expansion of computing power and artificial intelligence, and massive integration of consumer-based grid edge technologies, including the electrification of transportation.

With the new opportunities provided by this transformation, there are also challenges in how to define and respond to severe resiliency events. The emergence of new technologies for incorporation in the grid may suggest optimism for the future, but they also require defense against a variety of SREs. A change in paradigm is needed—as are changes to traditionally designed solutions. Detailed modeling of SREs using realistic electric grid models is essential, with consideration of the end-to-end lifecycle of each event.

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The Gulf region can leverage its energy history, infrastructure, capacity, and expertise to lead the energy transition.

The US Gulf of Mexico Region:
Leader in Energy Production and the Energy Transition

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Beginning with some of the earliest American oil wells in the mid-19th century and continuing with the first true offshore oil rig in the 1940s, the US Gulf of Mexico region is steeped in history as an energy production hub with global influence. Initial oil exploration in Texas and Louisiana progressed from windfalls to a sophisticated balance of risk and reward across the region, spurred by engineering advances and geologic expertise that shifted prospects to new topographies and, eventually, deeper waters.

The progression of the energy industry in the area paralleled immense growth in port infrastructure, development of a technically skilled work-

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force, and the expansion of numerous top engineering institutions. As a result, the Gulf is a crucial region for national and international energy production with established infrastructure and a world-class experienced workforce.

How will the Gulf region leverage its energy history, expertise, and capacity to lead a sustainable and just energy transition?

This article addresses three Gulf Coast capabilities that are key to enabling this country's bright energy future: carbon capture and storage, hydrogen, and experienced, resilient communities. We discuss strengths and challenges in each area.

Carbon Capture and Storage

Building on its long legacy of leadership in hydrocarbon exploration, production, and refining, the Gulf Coast region is well positioned to play a leading role in carbon capture and storage (CCS). Offshore CCS is still in the early stages of development, but the region's leadership in the upstream industry can make it a frontrunner in offshore CCS for the United States.

Carbon storage in the form of CO_2-enhanced oil recovery (EOR), a vital bridge technology for carbon sequestration, has been practiced in the Permian basin for over 50 years. The oil and gas industry has significant experience in the large-scale injection of CO_2 into the subsurface.

Data and Characterization

Much of the experience and many of the technologies and processes developed by the oil and gas industry can be transitioned to CCS projects. These include a broad range of modeling, measurement, and monitoring tools for reservoir surveillance and management strategies for pressure maintenance. The Gulf of Mexico is one of the most well-explored basins for hydrocarbon potential, with thousands of square miles of integrated 3D seismic data and thousands of well logs that allow for a detailed assessment of regional CO_2 storage potential (Meckel et al. 2021).

But some site characterization challenges need to be addressed (NASEM 2019). Data sparsity is typically a significant challenge for CCS, particularly for regionally extensive aquifers, which will be the primary CO_2 storage resource as opposed to oil and gas reservoirs. Increased data density will reduce geologic uncertainty and enhance model calibration and forecasting.

Economies of Scale and Storage Capacity

The industrial landscape of the coastal areas of Texas and Louisiana hosts clusters of coal- and natural gas–fired power plants, refineries and petrochemical complexes, and gas liquefaction, cement, and other stationary industrial emission sources. The Gulf Coast region therefore has the highest CO_2 emissions in the country, accounting for nearly 20 percent of total US emissions. This large volume provides economy of scale for large CCS projects, while the concentrated CO_2 sources provide "low-hanging fruit" for rapid CCS deployment as CO_2 capture is typically the most significant component (generally 60–70 percent) of the overall project cost.

The Gulf's thousands of square miles of 3D seismic data and thousands of well logs enable detailed assessment of regional CO_2 storage potential.

Two major projects in the Gulf Coast region illustrate existing capacities:

- The first industrial CCS project was completed in 2013 to capture about 1 million tons per year of CO_2 at the Air Products hydrogen plant at Port Arthur, TX. The CO_2 was transported for EOR to the Hastings Field, about 25 miles southeast of Houston.
- The Petra Nova CCS project, started in 2017 and located southwest of Houston, is the largest US postcombustion CO_2 EOR project. It is designed to capture approximately 90 percent of the CO_2 from a 240 MW slipstream of flue gas and sequester approximately 1.4 million metric tons of this greenhouse gas (GHG) annually for EOR at the West Ranch oil field, near Vanderbilt, TX (Olalotiti-Lawal et al. 2019).

The experience gained from these projects to capture CO_2 from industrial emissions, transport, and sequester it will be critical for the large-scale expansion of such efforts.

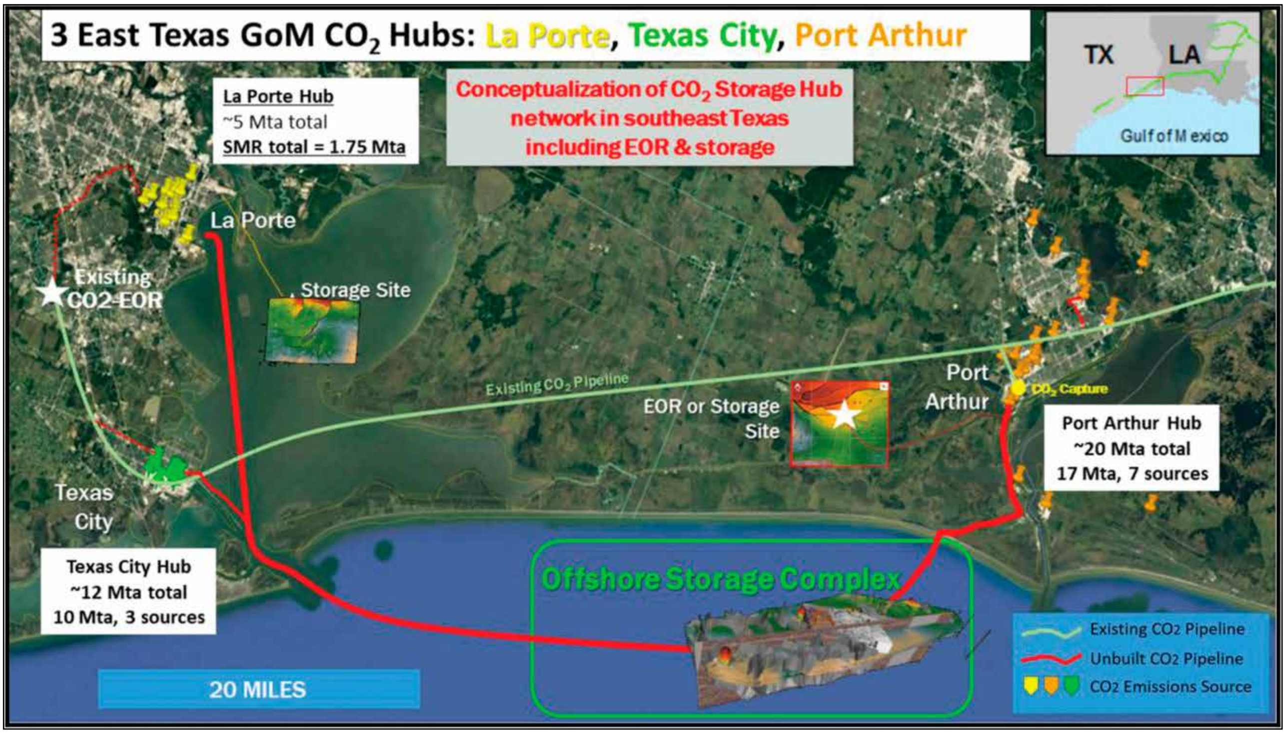

FIGURE 1 Conceptual diagram of potential carbon capture and storage hubs in Southeast Texas. EOR = enhanced oil recovery; GoM = Gulf of Mexico; Mta = megatons per year; SMR = steam methane reforming. Reprinted with permission from Meckel et al. (2021).

The storage capacity of on- and offshore saline formations along the Gulf Coast is estimated to be over a trillion tons of CO_2, making it the largest in the United States (NETL 2015). The estimated capacity in the greater US Gulf region can accommodate decades of annual regional emissions. The near-offshore state waters of Texas and Louisiana offer a further advantage due to their single land ownership and distance from major population centers.

Decarbonization Hubs

The Gulf region offers the potential for multiple hubs that could accelerate decarbonization on a national basis. The CCS supply chain includes transport to a suitable location for permanent storage or conversion to valuable products such as fuels, chemicals, and materials, and the region already has a mature CO_2 pipeline network across multiple states (figure 1; Meckel et al. 2021).

At-scale deployment of CCS through the development of industrial hubs will support the development of integrated capture, storage, and transport. Such hubs would provide a mechanism to focus investments for infrastructure, accelerate innovation to minimize or eliminate GHG emissions, and engage stakeholders in building public confidence in CCS technology. With its experienced workforce and technical expertise, the oil and gas industry can provide the necessary human capital to build and operate these CCS hubs.

Several large corporations have announced significant investments to develop the greater Houston area into a low-carbon hub, and many CCS-favorable characteristics of the Texas coastal region also apply to Louisiana.

Importance of Community Engagement

Although the Gulf Coast region is uniquely positioned to offer leadership in the large-scale implementation of CCS, gaining public support and confidence will require outreach efforts and engagement across a broad range of stakeholders, including policymakers, industrial groups, nongovernmental agencies, and, most importantly, Gulf Coast communities.

Several demonstration projects of the Regional Carbon Sequestration Partnerships sponsored by the US Department of Energy have established that CCS operations are safe and environmentally sound.[1] But

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[1] Regional Carbon Sequestration Partnerships, https://netl.doe.gov/sites/default/files/2022-05/RCSP%20Infographic_20220512.pdf

storage integrity and the potential for induced seismicity remain significant public concerns that need to be addressed, along with trustworthy monitoring, verification, and accounting of greenhouse gases to ensure air quality. Cost-effective regulatory regimes are necessary for widespread deployment of CCS.

Hydrogen

The Gulf Coast is the world's leader in the hydrogen (H_2) economy, with more than 1,400 miles of H_2 pipelines (figure 2)—90 percent of the nation's and a third of global pipelines—and more than a third of US H_2 production (Parfomak 2021).

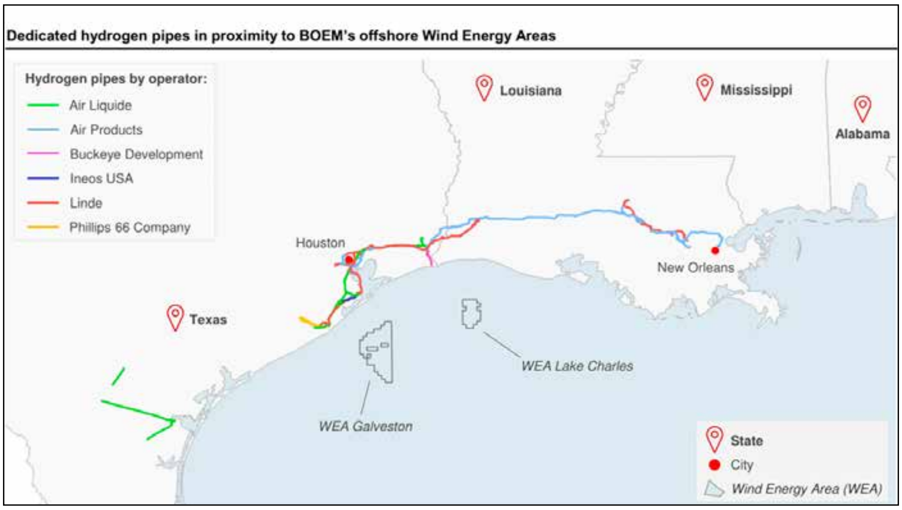

FIGURE 2 Gulf Coast hydrogen infrastructure. BOEM = Bureau of Ocean Energy Management. Source: Aegir Insights (2023).

Most current production is of "gray" hydrogen,[2] which has a high carbon footprint. It is produced using steam methane reforming (SMR) of natural gas, a process that produces hydrogen, CO_2, and carbon monoxide as byproducts. In addition, the Gulf Coast region hosts just over half of the US natural gas processing capacity, providing an advantageous feedstock nearby.

The region also has substantial salt cavern storage capacity and the experience base to safely store H_2 in the world's only three salt domes used for such storage (with a total capacity of 5–8 billion cubic feet). Salt dome storage has proven safe and has a high round-trip efficiency and long-term (multiday to multiweek) storage capability.

With over 47 percent of US petroleum refining capacity, a sizable end-use market exists for produced hydrogen (figure 2). An early opportunity to diversify end use at scale involves blending H_2 with natural gas, currently underway for power generation and as fuel for industrial heating. Moreover, the region is pioneering autothermal reforming in combination with carbon capture to develop low-cost, low-carbon ammonia and H_2, and its ability to export hydrogen—as liquefied H_2, as fuels such as ammonia and methanol, or as liquid organic hydrogen carrier—is unrivalled.

[2] Gray hydrogen is produced without capturing the carbon dioxide; blue hydrogen is produced when CCS is included with the production of gray hydrogen; green hydrogen is made from water electrolysis powered using renewable electricity; purple hydrogen is made through electrolysis using nuclear energy.

The combination of existing H_2 infrastructure, port capacity, and knowledge and experience developed primarily in the growing liquefied natural gas market make the region a strong candidate to lead the forthcoming international hydrogen market.

Challenges and Opportunities

Expansion of H_2 use will require improvements to the infrastructure (including pipelines) and technological advances such as burners to accommodate higher amounts of H_2. But the critical challenge facing the Gulf Coast region in advancing and leading the H_2 economy remains decarbonization of hydrogen production while keeping costs low.

One area being examined through front-end engineering design studies and pilot demonstrations is the retrofitting of carbon capture units to SMR facilities to enable production of "blue" hydrogen.

An alternate path to producing low-carbon-intensity H_2 from natural gas through methane pyrolysis (leading to "purple" hydrogen) is making early-stage commercial headway in the region, but it is contingent on advancing a value-added carbon byproduct of the process.

The ultimate goal for the low-carbon H_2 economy is to generate "green" hydrogen (or high-density H_2 carriers such as methanol and ammonia) through electrolysis (or photocatalysis) of water through the use of renewable energy. Texas has the largest wind electricity generation (primarily through onshore wind) with 26 percent of the nation's capacity, more than 14 GW of solar capacity (over 10 percent of the nation's solar capacity), and more than 10 percent of the installed US grid-based battery capacity.

With the potential to generate 510 gigawatt-hours of offshore wind energy per year in the Gulf Coast area alone, seawater and wind energy provide tantalizing opportunities to rapidly expand a renewable low- or zero-carbon hydrogen economy. The most significant challenge for this effort is the development of earth-abundant, sustainable catalyst platforms to allow the direct conversion of seawater to hydrogen.

No matter the source of hydrogen, significant enablers for the Gulf Coast are the extensive pipeline network, ample and proven storage of hydrogen in naturally occurring salt caverns along the Coast, extensive markets for H_2 use, and expertise to scale the growing production, storage, and use market for hydrogen.

Community of Experience and Resiliency

The Gulf region is home to globally preeminent assets for the energy transition, including equipment and infrastructure, fabrication capabilities, innovation capacity, the ability to take innovations to scale, and, especially, technically experienced people.

The Gulf Coast offshore oil and gas industry produces about 2.3 million barrels of oil equivalent per day and supports 345,000 US jobs.[3] The industry has a proven record of innovation, progressing from drilling at a maximum water depth of 300 feet in the 1960s to over 8,000 feet today. Some 7,000 offshore structures have been constructed in the Gulf over more than half a century.[4] With the decommissioning of older platforms and a transition to newer, more complex platforms, more than 1,500 remain active (BOEM 2023), primarily off the Louisiana coast but also off the Texas, Mississippi, and Alabama coasts.

Despite this wealth of resources, the region must overcome challenges threatening its ability to lead in the energy transition. Mississippi and Louisiana rank as the two poorest states (Davis 2021); Texas, Louisiana, Alabama, and Mississippi rank among the lowest in terms of racial and ethnic equity in health care (Radley et al. 2021); and Texas, Mississippi, and Louisiana are three of the four lowest-performing states in educational attainment.[5] If the Gulf states are to be leaders in energy transition, the region's communities must be healthy, well educated, and able to make good technology-informed decisions.

The National Academies' Gulf Research Program (GRP) was created in 2013 in the aftermath of the *Deepwater Horizon* incident and oil spill. The criminal settlement agreements require the GRP to address human health and environmental protection issues associated with offshore energy production and transportation in the Gulf of Mexico and the United States' outer continental shelf.

The GRP aims to fill critical gaps not addressed by other programs and to concentrate on impactful activities that align with the National Academies' key capabilities. Figure 3 illustrates the five pillars that are the focus of the GRP's work: offshore energy safety, health and resilience, environment, data, and education. The GRP also supports programs that cut across the pillars to integrate activities.

Though headquartered in Washington, DC, the GRP is heavily invested in local and regional activities and partners in the Gulf. Following are some examples of this work:

- the Gulf Scholars Program, which supports Gulf colleges and universities in preparing undergraduate students, particularly among underrepresented groups, to prepare the next generation to address critical challenges in the region;
- science policy fellowships, pairing scientists with host offices of federal, state, or nongovernmental organizations to facilitate the process of bringing science into policymaking; and
- place-based projects and programs for K-8 youth.

GRP research efforts include

- enhancing community networks that improve coastal environments, health, and wellbeing;
- studying the effects of climate change on environmental hazards in overburdened communities;
- improving public health data systems to address health equity challenges for at-risk communities in the US Gulf region;
- a workshop on investing in resilient infrastructure in the Gulf (NASEM 2022); and

[3] National Offshore Industries Association, https://www.noia.org/

[4] Bureau of Safety and Environmental Enforcement, Platform/rig information, https://www.data.bsee.gov/Main/Platform.aspx

[5] World Population Review, Least educated states, https://worldpopulationreview.com/state-rankings/least-educated-states

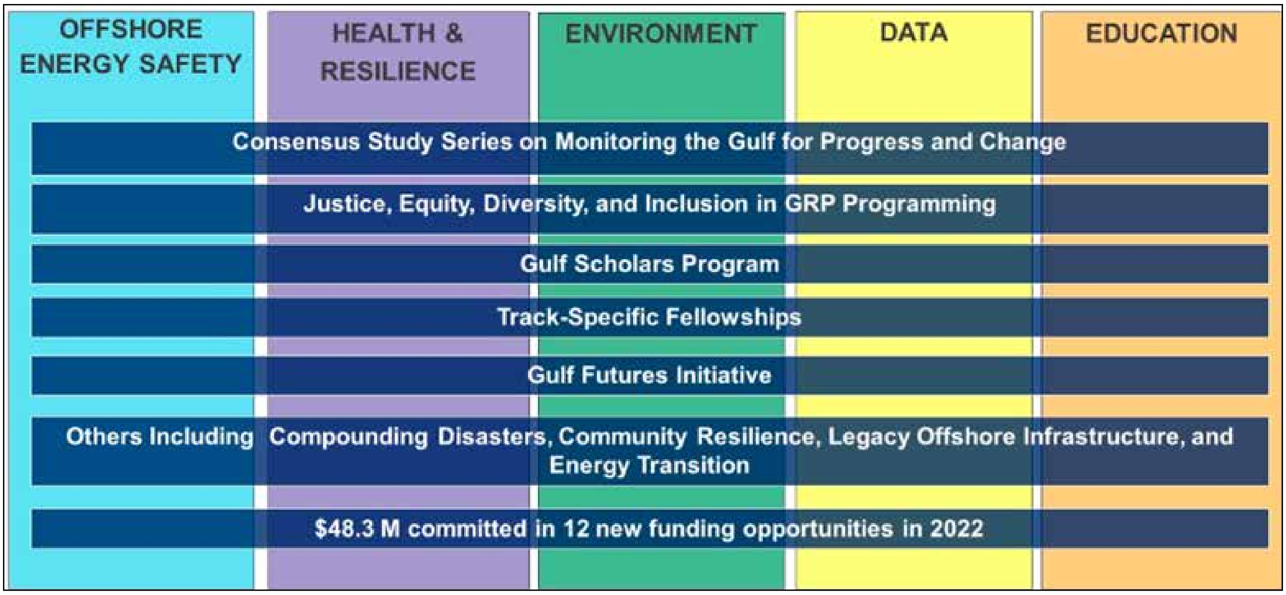

FIGURE 3 The five pillars of the National Academies' Gulf Research Program (GRP) focus areas, and examples of cross-cutting activities that integrate the areas.

- a workshop on navigating the energy transition in the region.[6]

Conclusion

The science, engineering, and technology challenges associated with transitions in energy production, demand, and sources are complex and daunting. The Gulf region's leadership strengths for the energy transition include its extensive infrastructure, experienced human resources, resilient culture, and proven ability to take innovation to commercial scale.

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[6] Proceedings of this workshop will be available summer 2023, at www.nap.edu.

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What are the most significant concerns and technical uncertainties for business leaders who allocate capital for the energy transition?

The Energy Transition:

Energy Industry Concerns as Reflected in Consulting Companies' Analyses

Thomas F. Degnan Jr.

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Commitments to a net zero carbon goal have increased dramatically over the past several years. However, countries are generally falling short of commitments made in the 2015 Paris Climate Accord. Despite analyses showing feasible pathways to achieving a delta global 1.5°C cap using current technology, there is a widely held belief that the world will exceed the Paris target.

The root causes of society's potentially missed climate change targets go beyond the need for scientific breakthroughs, energy technology innovation, or financing. An important additional factor is the perception of energy industry decision makers of the impacts of other constraints.[1]

Introduction

My meta-analysis of studies by consulting firms in the energy and environmental sector shows a prevalence of three constraints:

- access and availability of critical raw materials,
- adequate technical personnel to address permitting requirements and carry out the necessary capital projects, and
- concerns related to the scalability of sustainable technologies.

[1] Government decision makers and policymakers are also subject to the constraints discussed in this article, albeit to a somewhat lesser extent. I focus here on industry concerns.

Uncertainty associated with efforts needed to address these constraints likely influences resource commitments by CEOs and boards of directors of major organizations in the energy sector.

Balancing the allocation of capital investment and human resources while addressing shareholder financial expectations and responding to the growing negative public perception of fossil fuels is a daunting challenge for business leaders.

The history of previous "energy transitions" has been well chronicled (Smil 2016, 2017). What differentiates the current energy transition, to net zero carbon, is that it is not motivated by either energy resource scarcity (as was the case in Britain's transition from wood to coal) or significant improvements in energy efficiency (as in the transition from the steam engine to diesel) but by the prospect of an environmental cataclysm.

Delays in addressing this potential cataclysm are due mainly to societal denial that climate change is real. Confounding factors are uncertainties associated with measuring and attributing emissions, confusion between weather effects and climate change, and an erroneous sense that impacts will become evident only in the "distant" future.

Costs and Savings

This next energy transition could be expensive—not only in dollars but also in its draw on non-earth-abundant materials and human resources.

Cost estimates to achieve a net zero carbon (NZC) global economy range from $125 trillion (Climate Champions 2021) to $275 trillion over the next 30 years (McKinsey Global Institute 2022), equating to $9.2 trillion in annual average spending on physical assets, $3.5 trillion more than today. In relative terms, that increase is equivalent to half of global corporate profits and one-quarter of total tax revenue in 2020 (Krishnan et al. 2022).

However, McKinsey projects that expenditures—for the capital, labor, and other resources needed both to construct a new energy infrastructure (e.g., for wind, solar, renewables) and to deconstruct the existing energy infrastructure as appropriate to achieve NZC emissions—should increase GDP by only 0.9 percentage point over maintaining the status quo (McKinsey Global Institute 2022). The International Monetary Fund (Stanley 2021) and International Energy Agency (IEA 2021b) similarly estimate the necessary incremental investment over the next decade at 0.6–0.9 percent of cumulative output.

On the other hand, a recent analysis concludes that a rapid green energy transition will likely produce $5–15 trillion in net savings and that, by 2050, rapid conversion of the energy system will cost an average of $5.9 trillion a year (Way et al. 2022). In contrast, maintaining the status quo will average $6.3 trillion annually. The study projects an 80 percent likelihood that an NZC energy economy will be cheaper than continuing with the fossil fuel–based system. Another study estimates that the total global cost of doing nothing to pursue the 1.5°C maximum global temperature increase target could be $125–800 trillion between now and 2100 (Wei et al. 2020).

In the analyses considered here, costs will accrue nonlinearly, with most of the expenses or cost benefits realized in the first 10–15 years.

Unfortunately, many sustainable energy technologies are currently economically challenged or viewed by some as politically unsavory.

The comparative costs of doing nothing should also account for societal impacts such as the effects of fossil fuel combustion on public health (Kopel and Brower 2019). But the costs of health impacts—such as respiratory disease attributable to fossil fuel combustion products (NOx, CO, SOx)—are very difficult to quantify in dollars.

Finally, studies have concluded that several paths to an NZC global economy are technically achievable using current energy-producing technologies (IEA 2021b; Jacobsen 2020; Kelly 2021). No major scientific breakthroughs are required, but there are unarguably many economic and logistical advantages to be gained from technology improvements. Unfortunately, many sustainable energy technologies are currently economically challenged (e.g., carbon capture and storage) or viewed by some as politically unsavory (e.g., nuclear, geoengineering, and offshore wind in some locations).

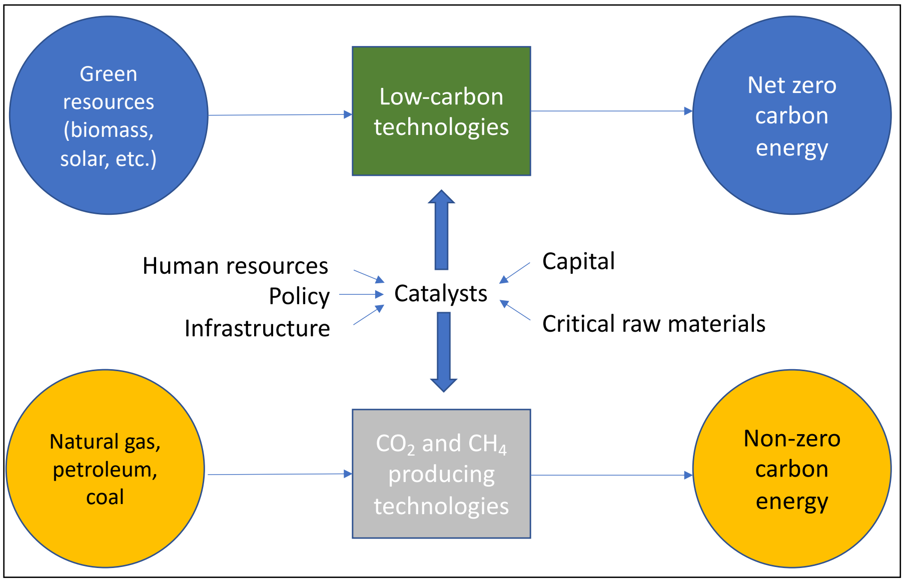

FIGURE 1 An oversimplified model of today's energy transition. CH_4 = methane.

The implications of the war in Ukraine and the global pandemic increased attention to the energy security risks associated with the current energy system. As a result, energy security has displaced energy sustainability as the more important priority for leaders in the Organization for Economic Cooperation and Development, at least for the near term. But most of the capital investment and resources required to move to a net zero carbon society by 2050 must be made in the next 10 years.

Except for coal and coal-fired power plants, existing fossil-fueled energy infrastructure has been difficult to replace. Nearly all new sustainable energy supplies have been additive: growth in energy-producing capacity via renewables has been on top of existing fossil fuel–based capacity. Nuclear power plants have been shuttered in Germany and the United States, but when energy shortages have occurred, natural gas and even coal-fired power plants have been brought back online.

Petroleum refining capacity has remained constant or slightly increased over the past decade even as the number of refineries has diminished and fuel manufacture has shifted geographically. As global energy demand is expected to grow by about 1.2 percent per year over the next two decades, oil and gas together are likely to remain critical in the global energy mix, accounting for 52 percent of the energy basket in 2040 (Mukhergee et al. 2019).

Wind and solar costs in many regions have declined to parity with—and are now often lower than—comparable costs for the most economical fossil fuel–produced electricity on an energy-delivered basis. Nevertheless, many nonfossil technologies remain grossly uneconomic, including green hydrogen, carbon capture and sequestration, and ambient air CO_2 capture. Even where they are economical, sustainable energy systems struggle to achieve the same functionality, reliability, and efficiency as fossil fuel–based systems.

An (Over)Simplified Energy Transition Model

While the objective of net zero carbon is technically achievable—and there seems no alternative than to pursue it—progress is confounded by society's slower-than-needed response. Indeed, to draw on a chemical analogy, a net zero carbon society is thermodynamically achievable but kinetically limited.

Continuing the chemical analogy, the "catalysts" are human resources, policy, infrastructure, capital, and access to critical raw materials (figure 1). However, there are parallel reaction paths: the current energy system (bottom row of figure 1) must be maintained while the net zero path (top row) is accelerated. Both reactions draw on the same catalysts, and balancing the catalyst allocation in the most cost- and capital-efficient manner is the challenge facing decision makers in the energy industry.

Key Concerns for Industry Decision Makers

Apportionment of the resources (i.e., catalysts) necessary for the energy transformation is primarily the responsibility of decision makers in the energy industry (CEOs and boards of directors). Lawmakers and senior government officials provide subsidies, institute new regulations, and set expectations, but it is energy industry leaders who make critical cost-benefit decisions in capital and human resource deployment.

It is therefore imperative to understand how these leaders visualize the future and what factors are most important in their decision making. Their thinking is

TABLE 1 Analysis of significant concerns among decision makers in the energy industry, based on surveys of 10 consulting groups and the International Energy Agency (IEA).

Consulting group, company, or agency	Critical raw materials	Scalability	STEM skills & experience	Regulatory policies	Supply chain	Mergers & acquisitions	Environ-ment, social, & governance (ESG)	Access to funding	Shifts in consumer spending
Accenture	XXX	XX	XXX	XX	X	X	XX	X	XX
Analysis Group		X	XX	X	XX	X	X	X	
Aon	X	XX	X	XX	X	X	X		X
Bain & Company	XX	XX	X	XX	X	XX	X	XX	XX
Booz Allen Hamilton		XX	XX	X	X	X	X	X	X
BCG (Boston Consulting Group)	XX	XX	X	XX	XX	XXX	XX	XX	X
Deloitte	XX	XXX	XXX	XX	XX	XX	XX	X	XX
IBM	XXX	XX	XX	X	XX	X	X		X
McKinsey & Company	XXX	XX	X	XXX	XXX	X	XX	XX	XX
PricewaterhouseCoopers (PWC)	XXX	XXX	XXX	XX	XX	XX	XX	XX	X
International Energy Agency (IEA)	XXX	XXX	X	XXX	X		X	X	
Ranking	1	2	3	4	5	6	9	7	8
Tally	5XXX+ 3XX	3XXX + 7XX	3XXX + 3XXX	2XXX + 6XX	1XXX + 5XX	1XXX + 3XX	5XX	4XX	4XX

Key
X - minor factor (topic of company blog or mentioned on website, but not a major area of emphasis)
XX - important factor (consulting services, group focused on area)
XXX - major area of concern (one or more significant reports; major area of focus for companies and consultants)

Sources available from the author on request.

influenced not only by shareholder sentiment but also by the ability of their company to operate within government constraints (e.g., regulations, tax structure).

Surveys of the Top 10 Energy and Environment Companies

To determine the critical factors that influence key decision makers, I drew on surveys regularly conducted by respected consulting companies in the energy and environment space.

According to Forbes, the top 10 management consulting companies in energy and environment are Accenture, Analysis Group, Aon, Bain & Company, Booz Allen Hamilton, Boston Consulting Group, Deloitte, IBM, McKinsey & Company, and PricewaterhouseCoopers (Sairam 2022). All have published extensively on the topic of energy transitions, and most have a long history of working closely with client firms in the energy field. The information produced by these management consulting companies has a significant advantage: it is public and candid, gleaned from anonymous responses of energy industry decision makers.

My assessment of management responses (cited in published reports, blogs, and press releases) reported by these top 10 consulting companies (table 1) plus published IEA reports revealed three concerns as especially significant:

- access to critical natural resources;
- availability of experienced technical personnel, especially engineers; and
- scalability of technology (i.e., the ability of both new and existing energy technologies to be commercialized and deployed at scale).

	Copper	Cobalt	Nickel	Lithium	Rare earth elements	Chromium	Zinc	Platinum group metals	Aluminum
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	◍	○	●	◍	●	○	◍
Hydro	◍	○	○	○	○	◍	◍	○	◍
Concentrating solar-thermal power	◍	○	◍	○	○	●	◍	○	●
Bioenergy	●	○	○	○	○	○	◍	○	◍
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	◍	○	◍	○	○	◍	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	◍	○	○	●	◍

Note: Shading indicates the relative importance of minerals for a particular energy technology (● = high; ◍ = moderate; ○ = low).

FIGURE 2 Critical mineral and metal needs for clean energy technologies.

Access to Critical Resources (Metals)

Understandably, at or near the top of the list of executive technical concerns is the availability of and access to critical raw materials, including copper, nickel, cobalt, aluminum, rare earth elements (necessary for high-performance magnets and motors), and chromium (figure 2). Copper is particularly significant as electrification sufficient to meet NZC targets requires an unprecedented 60 percent increase in the global supply of copper (Pickens et al. 2022). Higher prices should stimulate growth in the supply of copper, but political, social, and environmental challenges to this increased supply are also likely to grow.

Nickel is "critical" or "very important" to 6 of the 10 major energy sectors.[2] Russia sources 20 percent of the global nickel supply, which is no longer exported to Western markets because of sanctions. Nickel has unique properties essential to the operation of geothermal energy, batteries for electric vehicles (EVs) and energy storage, hydrogen, wind, concentrating solar power, and nuclear. Many applications require only small amounts of nickel, but they are critical to efficiency and durability (Nickel Institute 2021).

Cobalt is essential for EVs and battery storage. The IEA projects that demand for cobalt will grow by 500 percent between 2020 and 2040 (Mishra 2022). The Democratic Republic of Congo provides about 70 percent of the world supply, but its questionable environmental and governance history adds to the supply uncertainty. Diversification is possible (Australia has large deposits), but infrastructure and supply chain development will take time—likely a decade or more.

Fortunately, although metals and minerals are unavoidably energy intensive and often environmentally challenging to produce, in many cases they can be recovered and recycled.

Scalability

Deployment of new technologies and broader deployment of existing sustainable energy technologies must pass scalability tests, a major source of uncertainty. Scalable technologies must conform to either of two models. The first is the classical economy of scale model, where capital costs decline with size and breadth of deployment. Capital projects typically follow the two-thirds rule:

$$\text{capital expense} = k\,(\text{project size})^{2/3}$$

where k = \$/capacity (in m^3, ft^3, etc.).

In this model, the plant or facility, and thus the technology, becomes more affordable as its breadth and size increase.

The second model involves a modular approach, where the strategy is "design one, build many." It is often proposed for small modular (nuclear) reactors (Liou 2021).

[2] The 10 sectors are solar, wind, hydro, concentrating solar-thermal, bioenergy, geothermal, nuclear, electricity networks, EVs and battery storage, and hydrogen.

In both models, technical confidence grows with deployment. Investors often refer to the "valley of death" in startups; in technology development and deployment, unproven technologies have to traverse a "valley of uncertainty" before they are accepted and widely deployed.

The time required to scale from technology concept to commercial deployment varies greatly. For example, new software or digital inventions can scale in a matter of months, but capital-intensive technologies can require decades.

Renowned economist Edwin Mansfield (1968) analyzed the time intervals between invention (i.e., patent issuance) and commercialization of 37 inventions across selected industries. Most of these discoveries were related to capital-intensive industries (e.g., chemicals, energy processes, new products like plastics) rather than information-based or digital (table 2). The average discovery-to-commercial time was just over 13 years, and the median was 10. It is worth noting that some of the inventions with the shortest interval to commercialization (Freon refrigerants [CFCs], tetraethyl lead octane enhancer, and DDT) were the most societally regrettable because of their dramatic negative environmental impacts.

There is no comparable study of the commercialization of digital inventions, although some references cite a range of 4 to 12 months (Wardynski 2022). The most ubiquitously cited example of concept to first commercial demonstration is the iPhone, which took 30 months (Silver 2018).

The iPhone example notwithstanding, moving a capital-intensive new technology to the commercial stage in less than a decade remains an immense challenge. Widescale adoption and deployment can take just as long. The first diesel engine was commercially manufactured in 1897, and the first passenger vehicle with a diesel engine was launched by Mercedes-Benz nearly 40 years later, in 1936 (Smil 2013). It was not until the 1960s that diesel engines became the preferred power source for commercial trucking and marine shipping industries—even though the diesel engine was unquestionably superior to the steam engine and the gasoline-spark engine in terms of energy efficiency, reliability, and durability.

Clearly, technical superiority is not always the most significant driver for change. It remains difficult for emerging technologies to displace existing technologies that society finds familiar, convenient, and reliable.

TABLE 2 Estimated time between invention and commercialization: 37 inventions, selected industries (average = 13.4 years; median = 10 years). Adapted from Mansfield (1968).

Product	Interval (years)
Fluorescent lamp	79
Gyrocompass	56
Zipper	27
Electrostatic precipitation	25
Distillation of hydrocarbons w. heat and pressure (Barton)	24
Television	22
Jet engine	14
Crease-resistant fabrics	14
Radar	13
Tube and tank process	13
Continuous cracking (Dubbs)	13
Fluid catalytic cracking	13
Gas lift for catalyst pellets	13
Xerography	13
Dacron	12
Continuous cracking (Holmes-Manley)	11
Nylon	11
Turbojet engine	10
Long-playing record	10
Safety razor	9
Houdry catalytic cracking	9
Catalytic cracking (moving bed)	8
Wireless telegraph	8
Hardening of fats	8
Radio (oscillator)	7
Power steering	6
Self-winding watch	6
Cross process	5
Magnetic recording	5
Distillation of gas oil w. heat and pressure (Barton)	3
Clean circulation (Dubbs)	3
DDT	3
Plexiglass, Lucite	3
Tetraethyl lead gasoline additive	2
Freon refrigerants	1

While entirely new energy technologies are not required to achieve net zero carbon, they will be desirable to address the needs of difficult-to-decarbonize energy consumers. These include aviation, long-distance transport and shipping, chemicals production, production of carbon-intensive structural materials such as steel and cement, and provision of a reliable electricity supply that meets varying demands: "In 2014, difficult-to-eliminate emissions related to aviation, long-distance transportation, and shipping; structural materials; and highly reliable electricity totaled ~9.2 Gt CO_2 or 27 percent of global CO_2 emissions from all fossil fuel and industrial sources" (Davis et al. 2018).

It is difficult for emerging technologies to displace existing technologies that society finds familiar, convenient, and reliable.

The demand for energy for difficult-to-decarbonize segments is projected to increase substantially over the next 30 years. Capital investment today in the infrastructure to support these segments will determine achievement of NZC targets.

Another sector that will be difficult to decarbonize is the residential sector—not just home heating (where heat pumps are making inroads) but gas-fired stovetops, ovens, fireplaces, and ornamental lighting.

Scalability also, of course, relates to the ability of a technology to be deployed widely. For example, offshore wind technology is scalable in Europe but has been challenged by a number of factors in the United States, where there are only two functioning offshore wind farms (Block Island Wind in Rhode Island and Coastal Virginia Offshore Wind), although several others are at various stages in the permitting process. The two US wind farms have a combined generating capacity of 42 MW; in contrast, Europe has 123 operating wind farms in 12 countries with a collective production capacity of 28.4 GW.

Engineering Skills and Experience

In addition to challenges associated with capital, critical raw materials, and technical readiness, lack of engineering skills constrains implementation of the energy transition.

Lawmakers have focused on reducing permitting times for new projects and streamlining environmental and community approval processes, but the underlying problem is a lack of qualified engineers to conduct the studies, issue the reports, and certify safety and environmental suitability. As a result, approvals for clean-energy projects are lagging. As the *New York Times* recently reported, "more than 8,100 energy projects—the vast majority of them wind, solar and batteries—were waiting for permission to connect to electric grids at the end of 2021, up from 5,600 the year before, jamming the system known as interconnection. On average, it takes roughly four years for developers to get approval for wind and solar installation—double the time it took a decade ago" (Plumer 2023).

Reskilling and upskilling the workforce must be concurrent with onboarding new talent. The transition to renewable energy and the race to net zero will create opportunities but should also offer the chance to leverage transferable skills across the oil and gas workforce (Krauss 2023).

The number of new positions created by the transition is expected to dwarf the number of jobs lost. The World Economic Forum, for example, predicts that the transition to clean energy will generate 10.3 million net new jobs globally by 2030 (Wallach 2022), more than offsetting the 2.7 million jobs expected to be lost in fossil fuel sectors. The Forum projects that job gains will likely be largest in electrical efficiency, power generation, and the automotive sector. Many of the new positions will require engineering skills. Unfortunately, McKinsey and others report that most new engineering graduates are not focusing on careers in energy but instead seek jobs in IT and artificial intelligence (Abenov et al. 2023; ASEE 2021).

The United Kingdom is at the forefront of analyzing the suitability of its engineering workforce for a net zero carbon future (Hardisty 2022), and NZC electrification projects are expected to create over 400,000 new jobs there by 2050. In the United States the energy transition is projected to create 500,000 to 1 million new jobs in the 2020s.[3]

[3] Princeton Andlinger Center for Energy and the Environment, "Net-Zero America: Potential Pathways, Infrastructure, and Impacts," 2021 (https://netzeroamerica.princeton.edu/?explorer=pathway&state=national&table=ref&limit=200)

Regulatory Policy

As the difference in European and US wind farms shows, renewable energy technologies will not scale uniformly across all economies. They may be more rapidly and widely deployed if matched with economies that can accommodate and support them with the financial wherewithal, a strong regulatory environment and enforcement provisions, and a skilled workforce.

Most companies in the energy area are aware of potential changes in the regulatory environment; they anticipate them and try to stay out in front of them. Being at the vanguard can be a competitive advantage, especially if it means being viewed as an environmentally responsible company by employees, shareholders, and the public.

A "Disorderly Transition"

A 2022 Bain & Co. survey of 1,000 executives across the national and international energy and natural resources sector reported "a growing consensus" that the transition will be "disorderly" (Parry et al. 2022). Concerns about a disorderly transition are due to problems associated with raw materials and talent acquisition and challenges in matching business models to a changing business environment (a form of scalability).

The Bain & Co. survey also showed that the executives had very different ideas about the timing to achieve net zero carbon: 42 percent felt that it could be achieved by 2050, and 25 percent felt that it would not be achieved until after 2070; the median date projected by the executives was 2057.

Conclusions

There are no simple strategies to assuage energy industry decision makers' concerns related to critical raw materials availability, adequate experienced technical staffing, and scalability.

As recommended by the IEA (2021b), diversification of raw material sources and greater emphasis on recycling while focusing on environmental compliance may increase the supply of copper, nickel, cobalt, and rare earth elements.

Enhancing interest in STEM careers—and especially engineering—may help address the anticipated shortage of technical professionals in the energy industry, given, as noted above, that many more jobs will be created than destroyed in the energy transition. Both reskilling and training of the next generation of engineers will be important, but the reality is that experienced technical professionals develop their expertise over decades. Success in the rapid, widescale deployment of efficient energy technologies can likely be improved by matching the technologies to economies that have a capable workforce as well as well-conceived policies and subsidies.

That said, the widespread availability of new technology will probably remain constrained by about a decade between invention and commercialization. Compounding this inherent constraint, the Bain & Co. report notes that "executives are finding it challenging to square the traditional demands of their business—delivering products safely, securely, reliably, and affordably—with new demands to operate more sustainably and with a smaller carbon and ecological footprint. To succeed they're facing new challenges such as finding the right talent and navigating the policy regimes" (Parry et al. 2022).

Unless industry executives' concerns are addressed, their predictions for achieving net zero carbon may likely be more accurate than those of nonindustry experts.

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NAE News and Notes

NAE Newsmakers

Ilesanmi Adesida,[1] provost, Nazarbayev University, received the **2022 IEEE EDS Education Award**, which recognizes distinguished contributions to education in the field of interest of the IEEE Electron Devices Society.

William A. Anders, founder and chair, Heritage Flight Museum, and Apollo 8 astronaut, has been awarded the **2023 Michael Collins Trophy for Lifetime Achievement**. The award was established in 1985 and named in honor of Apollo 11 astronaut Michael Collins in 2020.

Frances H. Arnold (NAS/NAM), Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, California Institute of Technology, will receive this year's Perkin Medal from the Society of Chemical Industry for lifetime technical achievement. The award is widely acknowledged as the highest honor in American industrial chemistry. Dr. Arnold will be honored during a ceremony in Philadelphia on September 12.

The American Mathematical Society has announced that beginning in January 2024 it will award the **Ivo and Renata Babuska Thesis Prize** annually to the author of an outstanding PhD thesis in mathematics that is interdisciplinary in nature, possibly with applications to other fields. Interested in fostering collaboration among mathematicians, engineers, and physicists, **Ivo M. Babuska** (1926–2023), Robert B. Trull Chair in Engineering, University of Texas at Austin, and his wife, Renata (who holds a degree in mathematical statistical engineering), established the prize to encourage and recognize interdisciplinary work with practical applications.

Mary T. Barra, chair and CEO, General Motors Company, will be **inducted into the Automotive Hall of Fame** on July 20 during a ceremony in Detroit. The recognition is for "noteworthy individuals whose efforts have helped shape the automotive and mobility market." Mrs. Barra is the first female CEO of an automotive OEM to be inducted, widely considered the highest honor for individuals in the auto industry.

Vinton G. Cerf (NAS), vice president and chief internet evangelist, Google Inc., has been recognized by the Marconi Society with its **Lifetime Achievement Award**. He is the first person in the Society's history to receive both the Marconi Prize (1998) and the Lifetime Achievement Award. His work will be celebrated at the organization's annual gala October 27.

President Biden has appointed **Mark D. Dankberg**, chair and CEO, ViaSat Inc., a **member of the National Security Telecommunications Advisory Committee**. The committee supports national security and emergency preparedness solutions by providing innovative policy recommendations backed by industry perspective.

Ingrid Daubechies, James B. Duke Professor of Mathematics, Duke University, was awarded the **Wolf Prize in Mathematics** on February 7. Professor Daubechies, a trailblazer in the field of signal processing, was recognized for her work on wavelet theory and applied harmonic analysis.

Ali Erdemir, professor and Halliburton Chair in Engineering, J. Mike Walker '66 Department of Mechanical Engineering, Texas A&M University, has been **inducted a fellow of the National Academy of Inventors**.

Luis Esteva, professor, Institute of Engineering, National University of Mexico, has won the **National Engineering Award** from the Association of Architects and Engineers of Mexico. The award is the highest honor that can be given to an engineer in Mexico.

Richard L. Garwin (NAS/NAM), IBM Fellow Emeritus, IBM Thomas J. Watson Research Center, has been selected for the **2023 Vannevar Bush Award**, recognizing his continuing contributions to society, both as a scientific researcher and presidential advisor, that help bolster national security and improve international collaboration. The National Science Board recognized him May 9 during the National Science Foundation Awards Gala at the National Air and Space Museum.

Kazunori Kataoka, director general of the Innovation Center of NanoMedicine and professor, Kawasaki Institute of Industrial Promotion, received the **Biomaterials Global Impact Award**. The award is presented by the international journal *Biomaterials* to researchers recognized as globally influential in biomaterials, biodevices, biologics,

[1] Here and throughout the following pages, names in bold are NAE members.

or nanomedicine. Dr. Kataoka is the first non-US recipient. The award ceremony took place April 21 at the Society for Biomaterials Biology Annual Meeting in San Diego.

The 20th BioAsia forum, a healthcare and life sciences event organized by the Telangana Government of India, presented the 2023 **Genome Valley Excellence Award** to **Robert S. Langer** for his pioneering research that led to development of the first commercial mRNA vaccines used for a variety of infectious diseases. On April 19 Dr. Langer received the **Cornell Engineering Distinguished Alumni Award**. And in September 2022 he was awarded the **Balzan Prize for Biomaterials for Nanomedicine and Tissue Engineering**, "For pioneering research on biopolymers and biomaterials, and their synthesis, and developing the field of nanomedicine, including advances in mRNA vaccines and tissue engineering."

Asad M. Madni, retired president, COO, and CTO, BEI Technologies Inc., and independent consultant, has received the **2022 Elmer A. Sperry Award** in recognition of his leadership in the development and commercialization of the first solid-state gyroscope and its subsequent integration into a complete automotive inertial measurement unit integrated circuit for stability control. The award, jointly sponsored by six professional societies, will be presented at the IEEE-HKN Student Leadership Conference dinner November 4.

Diane M. McKnight, professor of civil, environmental, and architectural engineering, University of Colorado Boulder, won the **2021 Robert E. Horton Medal** of the American Geophysical Union. She was recognized as a major contributor and leader in the aquatic sciences. Dr. McKnight has made seminal contributions in physical, chemical, and ecological aspects of natural waters and is a world-class scholar and scientific leader in understanding the complexities of biogeochemical/ecological/hydrological interactions of lakes and streams as well as surface water-groundwater interactions.

Robert M. Metcalfe, emeritus professor of electrical and computer engineering, University of Texas at Austin, has won the **2022 ACM A.M. Turing Award** for "the invention, standardization, and commercialization of Ethernet." It was presented at the annual ACM Awards Banquet June 10 in San Francisco.

Julio M. Ottino (NAS), dean, R.R. McCormick Institute Professor and Walter P. Murphy Professor of Chemical & Biological Engineering, Northwestern University–Evanston, has been selected as the **2023 G.I. Taylor Medal** recipient by the Society of Engineering Science (SES). Professor Ottino was recognized "for pioneering theoretical and experimental contributions to the fluid mechanics of mixing." He will be recognized during the SES 2023 annual meeting in October in Minneapolis. A symposium is organized for the recipient of this honor.

The Stockholm International Water Institute (SIWI), in cooperation with the Royal Swedish Academy of Sciences, announced **Andrea Rinaldo** (NAS), professor of hydrology and water resources, École Polytechnique Fédérale de Lausanne, as the **2023 laureate of the Stockholm Water Prize**, often regarded as the Nobel Prize of water. Dr. Rinaldo was chosen for his achievements and groundbreaking work in the fields of hydrology, hydrogeomorphology, and epidemiology. The prize will be presented by King Carl XVI Gustaf of Sweden, the official patron of the prize, at World Water Week in August.

Alberto L. Sangiovanni-Vincentelli, Edgar L. & Harold H. Buttner Chair, University of California, Berkeley, received the **Frontiers of Knowledge Award** for transformative scientific contributions in chip designs. Dr. Sangiovanni-Vincentelli was cited for paving the way to a "worldwide explosion of integrated circuit design" in research, industry, and academia.

Ratan N. Tata, chair emeritus, Tata Sons Private Ltd., has been appointed to the **Order of Australia**, for his distinguished service to the Australia-India relationship, particularly in trade, investment, and philanthropy.

John A. White Jr., retired Distinguished Professor of Industrial Engineering and chancellor emeritus, University of Arkansas, received the **Joint Publishers Book of the Year Award** from the Institute of Industrial and Systems Engineers (IISE) for his new book, *Why It Matters: Reflections on Practical Leadership*. This is his fourth Book of the Year award from IISE.

The Earthquake Engineering Research Institute (EERI) has announced its 2023 award winners. **T. Leslie Youd**, professor emeritus, Brigham Young University, received the **George W. Housner Medal** in recognition of his pioneering contributions in the field of geotechnical earthquake engineering. In addition to his research contributions, Professor Youd has been a leader in postearthquake field reconnaissance and consulting. **James O. Malley**, group director and senior principal, Degenkolb Engineers, received the **Alfred E. Alquist Special Recognition Medal** for his long and distinguished career as a structural engineer connecting research and practice on the seismic design and retrofitting of steel building structures.

NAE International Secretary and Councillors Elected


Nadine Aubry


Anjan Bose


Fiona M. Doyle


Cherry A. Murray


Elsa Reichmanis


Geraldine Knatz


James M. Tien


Brenda J. Dietrich


Katharine G. Frase


Yannis C. Yortsos

In early May the NAE elected a new international secretary, reelected an incumbent councillor, and elected three new councillors. All terms begin July 1, 2023.

Nadine Aubry, professor in the Department of Mechanical Engineering at Tufts University, was elected to a four-year term as NAE international secretary.

Reelected to a second three-year term as councillor is **Anjan Bose**, Regents Professor in the School of Electrical Engineering and Computer science at Washington State University. Newly elected to three-year terms as councillors are **Fiona M. Doyle**, Donald H. McLaughlin Professor Emerita and distinguished professor emerita of materials science and engineering at the University of California, Berkeley; **Cherry A. Murray**, professor of physics and director of the Biosphere2 Institute at the University of Arizona; and **Elsa Reichmanis**, professor and Carl Robert Anderson Chair in Chemical Engineering in the Department of Chemical and Biomolecular Engineering at Lehigh University. **Geraldine Knatz**, retired executive director of the Port of Los Angeles and professor of practice in the Schools of Engineering and Public Policy at the University of Southern California, was elected by the NAE Council for a one-year term as councillor to fill the seat vacated by Nadine Aubry.

On June 30, 2023, **James M. Tien** will have completed his four-year term as international secretary, and **Katharine G. Frase**, International Business Machines Corporation (retired), and **Yannis C. Yortsos**, dean of the USC Viterbi School of Engineering and Zohrab Kaprielian Dean's Chair in Engineering, will have completed six continuous years of service as councillors, the maximum allowed under the NAE bylaws. **Brenda J. Dietrich**, Arthur and Helen Geoffrion Professor of Practice in the School of Operations Research at Cornell University and retired vice president of International Business Machines Corporation, served one three-year term as councillor. They were recognized in May for their distinguished service and other contributions to the NAE.

NAE Honors 2023 Fritz J. and Dolores H. Russ Prize Winner

Hugh Sherman, David R. Walt, and John L. Anderson

With the Fritz J. and Dolores H. Russ Prize the NAE honors outstanding individuals for significant innovation, leadership, and advances in bioengineering. **David R. Walt** was awarded the 2023 Russ Prize "for the development of microwell arrays that greatly advanced the fields of genomics and proteomics." He was honored at a black-tie dinner on February 22 at the National Academy of Sciences building in Washington, DC. The award was presented before an audience of more than 90 guests, with NAE president **John L. Anderson** at the podium and Hugh Sherman, president of Ohio University, assisting in the presentation.

Walt is credited with pioneering the use of microwell arrays for single-molecule detection and genetic measurements, an advance that has revolutionized the process of genetic and proteomic analysis. As noted by the Wyss Institute at Harvard University, it is "the gold standard for genomic analysis for a variety of applications, including screening embryos for genetic defects before in vitro fertilization, studying disease in preserved or frozen tissues, improving crop disease resistance, and identifying individuals' metabolic profiles to ensure proper drug dosage." Equally important, over the past decade the technology has greatly reduced the cost of DNA sequencing and genotyping, enabling greater access to diagnosis, treatment, and continued research.

Walt is the Hansjörg Wyss Professor of Bioinspired Engineering at Harvard Medical School; professor of pathology at Brigham and Women's Hospital and Harvard Medical School; core faculty member of the Wyss Institute at Harvard University; scientific founder of Illumina and Quanterix; and cofounder of multiple other life sciences startups, including Ultivue, Arbor Biotechnologies, Sherlock Biosciences, Vizgen, and Torus Biosciences.

Walt is a member of the NAE and National Academy of Medicine and a fellow of the American Academy of Arts and Sciences, American Institute for Medical and Biological Engineering, American Association for the Advancement of Science, and National Academy of Inventors; and he was inducted into the US National Inventors Hall of Fame.

His national and international honors for his fundamental and applied work in the field of optical microwell arrays and single molecules include the Kabiller Prize in Nanoscience and Nanomedicine (2021), American Chemical Society (ACS) Kathryn C. Hach Award for Entrepreneurial Success (2017), Ralph Adams Award in Bioanalytical Chemistry (2016), ACS Gustavus John Esselen Award (2014), Analytical Chemistry Spectrochemical Analysis Award (2013), Pittsburgh Analytical Chemistry Award (2013), and ACS National Award for Creative Invention (2010).

He received his bachelor's degree in chemistry from the University of Michigan and his PhD in chemical biology from the State University of New York at Stony Brook (now Stony Brook University).

Russ Prize Acceptance Remarks by David R. Walt

Thank you, John, for the very kind introduction.

I have many people to thank for this honor:

First and foremost, my sincere thanks to Fritz J. and Dolores H. Russ for creating this prize and to the Russ family members in attendance tonight.

Thank you, Dr. Sherman and the Ohio University leadership. I look forward to my visit to your campus.

My sincere gratitude goes to the prize selection committee for their hard work. I served as a member and also as chair of the Gordon Prize committee until recently, so I understand and appreciate the amount of work it takes to come to a decision.

I thank all the nominators and supporters of my case. I want to acknowledge **Fran Ligler**, who is here tonight and has been a strong supporter of mine for many years.

And thanks to Deborah Young for her extensive planning behind the scenes leading up to this evening.

Finally, special thanks to my family: Michele, my wife and partner for 43 years, whose support, guidance, and strength enabled me to achieve the accomplishments that led to this recognition. I share this prize with you. And thanks to my daughters Stephanie and Rachel, who put up with their dad's travels and busy schedule as children and who have always been among my strongest supporters.

As you heard, bioengineering was not part of my educational background—I was trained as a chemist and chemical biologist. But over my career, technology and engineering have become the cornerstones of my efforts.

As a kid, I thought engineering was about large construction projects. One of my cousins was a civil engineer and a neighbor was an engineer involved in large construction projects, which biased my perception. Over time, I learned that engineering was much more—mechanical, chemical, electrical, civil, aerospace, and more recently bioengineering.

When my lab developed the microwell arrays, at first a serendipitous discovery without a clear use, I ignored the discovery because we were trying to do something quite different. I should have paid attention because the microwells we fabricated were 5 *billion* times smaller than what were called microwells at the time.

Once I figured out what the microwell arrays were good for—about a year later—it set me on a path to translate the discovery to the private sector by founding the company Illumina. This is when I really learned about engineering—how engineers could take a scientific discovery and scale it so that it wasn't a one-off laboratory experiment or demonstration but something that worked every time. And it could be fabricated by the millions.

The scaling required engineers from many fields—electrical and optical engineers to build the optics and electronics that could visualize the microwell arrays; mechanical engineers who built the pumps and fluidics systems that delivered the reagents to the microwell arrays; chemical engineers who formulated the chemicals and biochemicals and dealt with mixing and heat transfer; and bioengineers who developed and evolved new enzymes to make the biochemistry more efficient. It was a true team effort to design and build a *system* that worked and delivered consistent results every day with few failures.

Bioengineering, in particular, parallels biology—it operates at the micro and even nano scale. How small is a micrometer? A single human hair is 100 micrometers wide and about 100,000 nm wide! So at the microscale, think cells and subcellular organelles. But biology also scales to extremely large—whales, the redwoods in California, and even entire ecosystems—all composed of these microscale cells and nanoscale organelles. Similarly, bioengineering operates from the scale of the microwells and nanowells discovered in my laboratory to large medical systems, such as surgical robots and MRI instruments.

The key is that these systems are designed to address unmet needs. This is what engineers do.

When we first launched Illumina, we made instruments and consumables that could carry out sophisticated genetic analysis at the touch of a button. We provided the research community with the ability to gather genetic data at an unprecedented scale. Little did we know that eventually discoveries made using the technology would be used to diagnose diseases, such as cancer, or to enable couples whose families had a history of genetic disease to undergo in vitro fertilization that could select an embryo free from the inherited mutation. What an incredible feeling it is when you learn about a patient who benefited from something to which you contributed—even if it was a small contribution among many that led to its use.

To me, this is the message we need to convey to the next generation.

As you heard, yesterday I attended the Future City Competition, where I addressed middle school students. The event is appropriately held during Engineers Week. I've learned over my four decades as an educator that young people have one goal—they want to make a difference, they want to change the world for the better. The best way to inspire these potential future engineers and scientists is to help them understand that STEM is the path to effecting change—whether it is to benefit patients in need, help clean up our environment, reverse the damage to our climate, create better and more sustainable foods, produce clean energy, or design and build more efficient vehicles for transportation—the list goes on.... This is the message that they need to hear.

We need to give young people *from all backgrounds* the exposure to what one can accomplish in science and engineering and provide them with a vision of the impact they can make. And we need to enable each and every one of them—whatever their background or economic status—to achieve their utmost potential. The next Einstein, Edison, George Washington Carver, **Frances Arnold** (NAS/NAM), or Jennifer Doudna (NAS/NAM) is more likely to come from a background traditionally underrepresented in science and engineering.

I'm hoping that one day, some of the students I spoke with yesterday, or students like them, will be up here receiving a Fritz J. and Dolores H. Russ Prize or other recognition for an engineering or science innovation.

My sincere thanks to all of you for coming to this celebration. It is truly an honor to be a recipient of this incredible prize.

EngineerGirl Receives the 2023 NSB Science and Society Award

The NAE's EngineerGirl was selected to receive the 2023 National Science Board (NSB) Science and Society Award for its "extraordinary efforts to increase participation and diversity in the science and engineering fields."

Dan Reed, NSB chair; Guru Madhavan, NAE program director; and Simil Raghavan, NAE senior program officer, and Mary Mathias, NAE program officer, EngineerGirl.

EngineerGirl began more than 20 years ago to inspire women and girls to become engineers. Initially targeted to middle school–aged girls, the program expanded to meet the interests of high school–aged girls as well as the general public. Today, its resources include Ask an Engineer, an annual writing contest, Try This design challenges, and an ambassadors program. Since its inception, EngineerGirl has introduced many thousands of girls across the country to opportunities in all areas of engineering.

The NSB noted that the "bright, colorful site has shared new, relevant, and engaging content that features a variety of role models and ways to engage with the overall mission. EngineerGirl focuses on empowering young women to engage in engineering and consider engineering as a career path because girls and women remain underrepresented in the engineering profession."

Simil Raghavan, director of the NAE's program on Inclusive, Diverse, and Equitable Engineering for All, and NAE program officer Mary Mathias accepted the honor at the NSF awards gala May 9 at the National Air and Space Museum in Washington.

German-American Frontiers of Engineering Held in Jülich, Germany

The 2023 German-American Frontiers of Engineering Symposium (GAFOE) was held in Jülich, Germany, March 22–25. The NAE partners with the Alexander von Humboldt Foundation to organize this event, which was the first bilateral Frontiers of Engineering program and started in 1998. The symposium organizing committee was cochaired by NAE member **Thomas Kurfess**, Distinguished Professor and HUSCO/Ramirez Distinguished Chair at the George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, and Olivier Guillon, director of the Institute of Energy and Climate Research at the Forschungszentrum Jülich GmbH.

Modeled on the US Frontiers of Engineering Symposium, the 2½-day meeting brought together about 60 early-career engineers from German and US companies, universities, and government for presentations and discussion on four topics: supply chain resiliency, the hydrogen economy, neuromorphic computing, and sustainable production and circular economy. The theme of the meeting was On the Way toward Sustainability and Resiliency.

Supply chain disruptions caused by events like the blockage of the Suez Canal or covid-19 show the need for resilient supply chains that can respond effectively to disruptions and emerging risks. While lean and just-in-time manufacturing may reduce operational cost of supply chains, it increases their fragility. Moreover, industry lacks the ability to effectively monitor and control supply chains today. The first session explored novel ideas for addressing global supply chain issues, through sociotechnical system design, advanced modeling and simulation, behavioral economics, and actuarial and management sciences combined with law and policy.

Speakers in the second session called for careful attention to buildout of the hydrogen (H_2) economy in efforts to facilitate sustainable decarbonization, because not all H_2 production pathways are consistent with long-term decarbonization goals. For example, in terms of material intensity, energy consumption, and water consumption, environmental benefits and potential negative impacts are highly dependent on the scale of the H_2 economy. This scale is in turn dependent on whether to deploy hydrogen selectively for extremely high-value applications, where there are few options for decarbonization, versus lower-value, high-volume applications, where more alternatives might be available. Presentations covered energy system modeling; biological H_2 conversion; Hydrogen Lab Görlitz, a research lab to study H_2 production, storage, and use; and hydrogen for grid support.

As modern computing technology contributes more and more to global energy costs, it is increasingly important to reduce computation's power demands. The human brain remains the strongest exemplar of energy-efficient computation, and in recent years neuromorphic computing has become a reality. The third session surveyed the impacts of neuromorphic computing research on novel algorithms, architectures, and electronics hardware. The presentations covered an overview of the field and outlook on how this technology is enabling energy-efficient computing, translation of neuroscience into computing, AI strategies that can be converted into neuromorphic AI algorithms, and the challenges of integrating neuromorphic systems into current computing technologies.

A circular economy is a model of production that reuses goods and products in order to tackle global challenges such as waste, pollution, biodiversity loss, or climate change. The approach reduces primary material use, redesigns materials to be less resource intensive, and recaptures postconsumer products and waste as a resource in the manufacture of new materials and products. The final session, Sustainable Production and Circular Economy, examined the topic through the lenses of four industries: global cycles of metals and minerals, plastic waste management and recycling, scalable and sustainable recycling of electric vehicle batteries, and alternative construction materials.

Abstracts of the papers and presentation slides where permission has been granted can be accessed in the list of sessions for the 2023 GAFOE at www.naefrontiers.org.

Photo by Sherri Hunter.

Alexander von Humboldt president Hans-Christian Pape, NAE president **John L. Anderson**, and German Federal Parliament member Thomas Rachel welcomed the group to the symposium at a dinner the evening before the start of the meeting. The next morning, opening remarks were provided by Dr. Anderson, Inka Lock from the Alexander von Humboldt Foundation, and Drs. Guillon and Kurfess. In addition to the day's technical sessions, a poster session preceded by flash poster talks was held the first afternoon, as an icebreaker and opportunity for participants to share information about their research and technical work. The posters were displayed throughout the meeting, which facilitated further discussion and exchange during the coffee breaks. A one-hour networking session was held on the second morning, and that afternoon attendees enjoyed a bus tour of the interdisciplinary campus of Forschungszentrum Jülich as well as a visit to the Jülich Supercomputing Center and a guided tour of the Institute of Energy and Climate Research, with a focus on hydrogen technologies such as high-temperature electrolysis and fuel cells as well as circular economy (repair and recycling of components and inorganic materials). This was followed by dinner at Restaurant Elisenbrunnen in Aachen.

Funding for the meeting was provided by The Grainger Foundation, the National Science Foundation, and the Alexander von Humboldt Foundation. The next GAFOE meeting will be held in 2025 and hosted by Oak Ridge National Laboratory. Thomas Kurfess will continue as US cochair.

The NAE has been holding Frontiers of Engineering symposia since 1995. The Grainger Foundation Frontiers of Engineering Symposium for US attendees is held annually. In addition, there are four bilateral FOE programs with Germany, Japan, China, and the EU. For more information about the symposium series or to nominate a highly accomplished early-career engineer to participate in future Frontiers meetings, contact Janet Hunziker in the NAE Program Office at JHunziker@nae.edu.

University of Illinois Urbana-Champaign Hosts NAE Regional Meeting: The Mobility Electrification Revolution

More than 200 NAE members and public attendees met at the University of Illinois Urbana-Champaign (UIUC) in early April to explore the massive 21st century economic shift to electric mobility. About a third of primary energy powers transportation, and it is anticipated that almost all of this will shift to electricity. The meeting addressed critical challenges in the transformation of the US national transportation system to low-carbon electrical energy.

Dean Rashid Bashir, a Frontiers of Engineering (FOE) alumnus, and university president **Timothy L. Killeen** opened the public symposium on April 4. They highlighted Illinois as the epicenter of the nation's massive freight and multimodal transportation network, and the Great Lakes region as the heart of US transportation manufacturing.

NAE president **John L. Anderson** described the purpose of NAE regional meetings and presented the "Call to Action for Leadership in a World of Accelerating Change" video. Tributes were made to late NAE members **Nick Holonyak Jr.**, **Gordon Moore**, **Pete Sauer**, and **Wm. A. Wulf** (NAE president 1996–2007). President Anderson also discussed the critical contributions of the engineering profession and the NAE in societal revolutions. University of Illinois chancellor Robert Jones and Vice Chancellor for Research and Innovation Susan Martinis described priorities for research and education in transportation electrification, and emphasized the critical role of comprehensive interdisciplinary work in this once-in-a-generation transformation.

In the keynote address **Philip Krein**, Grainger Emeritus Chair in Electric Machinery and Electromechanics, linked Holonyak, Sauer, and Wulf to modern advances in electric mobility. He emphasized broad engineering challenges of universal mobility for people and goods, ranging from air and road transport to active prosthetics. He pointed out that society often overestimates costs of major transitions and underestimates benefits. Citing federal survey data showing that 95 percent of daily passenger car trips do not exceed 31 miles, he explained that such trips can be supported with basic electrical outlet infrastructure at homes and workplaces, supplemented by plans for fast charger networks to support long distances and truck freight.

UIUC faculty member Imad Al-Qadi, director of the Illinois Center for Transportation (ICT) and a meeting sponsor, showed that transportation electrification is an essential path toward renewable energy and emissions reduction. The challenges are growing, since 72 percent of US goods move by road. Heavy batteries cause trucks to stress pavement and damage roads. Solar panels along highway rights of way, overhead electrical lines, or roadbed electrification can reduce battery weight needs in trucks and for long-distance travel.

UIUC faculty member and FOE alumnus Kiruba Haran, director of the NSF Power Optimization of Electro-Thermal Systems (POETS) Engineering Research Center, also a meeting sponsor, laid out challenges in electrification of air transport. The industry's target of zero carbon emissions by 2050 will require a 50-fold electric power increase from the most electrified modern jetliners to future systems. The flip side is that electrification opens up the design space and brings new innovation opportunities. He discussed emerging projects in superconducting motors for aircraft propulsion.

Ohio State professor and FOE alumnus Giorgio Rizzoni described the Electric Mobility and Innovation Alliance (EMIA), which is building a coalition for transportation electrification along the I-75 corridor. He reported rapid growth in needs for continuing education and workforce development. A wide range of transformative technology development will impact every layer of the industry, from car manufacturers to small firms that support engines, transmissions, vehicle subsystems, and lower-level parts. EMIA seeks to help lead the full breadth of industry through this transition.

Eleftheria Kontou, a UIUC faculty member and FOE alumna, discussed critical infrastructure challenges for electrification (which, for example, can disrupt conventional safety strategies). She pointed out the enormous economic impact, given that an average US household devotes about 20 percent of income to transportation costs. Equitable benefits are a major consideration, given the disproportionate impact of both transportation costs and pollution on disadvantaged communities. She reported on a project to optimize charging infrastructure in Illinois based on energy needs, proximity to electrical substations, benefits to low-income households, improvement in local air quality, and other factors.

UIUC faculty member and FOE alumnus Paul Braun described both the fundamental promise for battery improvement and challenges in battery design for recycling. Only a fraction of the material in a battery is active, and there is a substantial "balance of plant" in packaging and operating a reversible cell. The combined cost impact of lithium, nickel, cobalt, and copper in a modern battery cell adds to about 50 percent of the cell cost, and this is the portion with the highest promise for recovery.

UIUC professor David Nicol discussed challenges associated with cybersecurity in electric transportation. Grid interfaces, sophisticated software, and electronic controls add new "attack surfaces" that attract bad actors and also represent vulnerabilities to software bugs and electrical noise. Electric vehicle safety might be compromised by cybersecurity problems.

Tesla cofounder Martin Eberhard said that energy fundamentals convinced him almost 20 years ago that transportation electrification is inevitable. This motivated the founding of Tesla Motors, he said, and he explained why effective electric vehicle designs will ultimately overtake fueled vehicles in almost every sense. He also presented a "wells to wheels" analysis demonstrating that a battery vehicle can travel about three times farther on a given amount of primary energy than a hydrogen fuel-cell car. His talk generated considerable excitement, especially among students, by showing how a fundamental scientific and engineering viewpoint can lead the way toward considerable economic impact regardless of barriers.

The meeting continued on April 5 with a distinguished panel of industry leaders from less conventional electrification applications, such as recreational boating, construction and mining equipment, and aerospace systems. The panelists were Perissa Millender Bailey of Mercury Marine, a Brunswick Company, Brian Dershem of Caterpillar, Tim O'Connell of PCKA, and FOE alumnus Juan de Bedout of Raytheon. **John F. Reid**, an Illinois faculty member formerly at Deere, Inc., described the considerable effects of electrification on farms and farm equipment. He reported that electrical motion control and transportation drives are already enhancing productivity and capability in all aspects of agricultural production, and the impact will double (or more) over the next few years.

A state policy panel that featured Holly Bieneman and Elizabeth Irvin from the Illinois Department of Transportation and Lisa Clemmons Stott of the Illinois Department of Commerce and Economic Opportunity discussed how the state plans to enhance electrification from the perspectives of potential manufacturers, users, and drivers. The state has announced plans to incentivize at least 1 million electric vehicles registered by 2030.

The meeting was cohosted by the NAE, POETS, ICT, the Grainger College of Engineering, Grainger Lecture Series, Tykociner Lecture Series, Kent Seminar Series in Transportation, and Materials Research Laboratory Distinguished Lecture Series.

MIT Lincoln Laboratory Hosts NAE Regional Meeting and Symposium on Microelectronics

On April 25 MIT Lincoln Laboratory hosted members of the National Academy of Engineering (NAE) for a regional meeting and symposium on the laboratory's wide-ranging and innovative work in microelectronics. This area has been a focus of the lab's research and development (R&D) since the 1960s, said Lincoln Laboratory director **Eric Evans** in his opening remarks, and has produced advanced imagers, miniaturized technology, and sensors fundamental to national security. Lincoln Laboratory is a federally funded R&D center supported by the Department of Defense.

NAE president **John L. Anderson** reflected on the mission of the NAE in convening the best talent in engineering for the public good and its role in leading the next generation of engineers amid rapid transformations in technology. "Change will keep coming, and we better adjust. The NAE tries to channel innovation into good purposes and make sure we are on the right course," he said, emphasizing the need for social awareness in engineering.

Microelectronics is one such field going through transformation, as Moore's law (the doubling of integrated circuit components every two years) reaches its limit. The field has recently been a hot topic of discussion, with supply chain disruptions affecting access to microchips during the covid pandemic and the passage in 2022 of the CHIPS Act, which aims to boost US semiconductor research and manufacturing. Bob Atkins, who leads the laboratory's Advanced Technology Division, discussed these events and a strategy for reestablishing US leadership in the field, which he says will require looking for technology advantages in "edge" microelectronics (in devices like cell phones and cameras), pursuing disruptive technology in mainstream computing, and find-

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ing opportunities to improve microelectronics integration.

Next, Erik Duerr, who leads the laboratory's Advanced Imager Technology Group, provided an overview of advances in imaging technology and their applications, with two recent examples. The lab's charge-coupled devices are the "eyes" of NASA's Transiting Exoplanet Survey Satellite, capable of detecting the slight dim in a star's luminosity when a planet passes in front of it, and Geiger-mode avalanche photodiodes integrated into lidar systems are capturing high-resolution data of damaged areas after hurricanes.

Jonilyn Yoder, an assistant leader in the Quantum Information and Integrated Nanosystems Group, presented research into superconducting electronics, which she describes as having a rich application space, such as in low-energy computing, despite being historically overlooked because of the need for cryocooling to operate. "Lincoln Laboratory is fabricating the most advanced superconducting electronics process in the world and is driving forward the next wave of technology maturation, working closely with academia and industry," she said.

Mollie Schwartz, an assistant leader in the same group, shared collaborative work in investigating the best candidates for qubits (the "transistors" of quantum computing) and the controls and architectures that will allow qubits to work together at testbed scales. "We are applying an engineering mindset to drive progress in quantum technology," Schwartz said.

One qubit candidate is trapped ions, which can be held in place above an electronic chip and controlled via laser light. Cheryl Sorace-Agaskar discussed the laboratory's work developing an integrated photonics platform to integrate the necessary optical control elements directly into an ion-trap chip. She then discussed the varied photonics platforms fabricated at the lab, spanning a wide range of wavelengths and applications, including microwave photonics, quantum, lasers, and sensing.

Melissa Smith, a leader in Lincoln Laboratory's Advanced Materials and Microsystems Group, presents concepts for an innovative satellite the size of a silicon wafer. Photo: Glen Cooper.

Melissa Smith, an assistant leader in the Advanced Materials and Microsystems Group and an alumna of the US Frontiers of Engineering Symposium, then switched gears to discuss an innovative spacecraft system that is compact, versatile, configurable, and mass producible and can be launched on demand. Her team is pursuing a prototype of a "WaferSat," a satellite approximately the size and thickness of a silicon wafer, which could present a new opportunity for rapid and low-cost access to space.

Closing out the symposium, Sasha Stolyarov presented innovations in multifunctional fibers, which have semiconducting chips integrated into them to enable new uses. These fibers can enable clothing that can monitor the wearer's health, for example, or be deployed in the ocean to capture data at various depths. Stolyarov is leading this work at Advanced Functional Fabrics of America, a partner of the laboratory's Defense Fabric Discovery Center.

After the symposium NAE members, Lincoln Laboratory staff, and guests from industry and academia had the opportunity to socialize at a reception and discuss technology development. Microelectronics represents just one of the lab's many R&D focuses, which span areas such as air traffic control, cybersecurity, biotechnology, communications, and artificial intelligence.

USC Viterbi School of Engineering and NAE Launch New Social Media News Series

USC Viterbi and the NAE have launched The Circuit, a weekly social-forward news network dedicated to promoting engineering to the public through stories of notable engineering figures and feats in just minutes each week. The program launched during National Engineers Week, on February 23, 2023, which was also Introduce a Girl to Engineering Day.

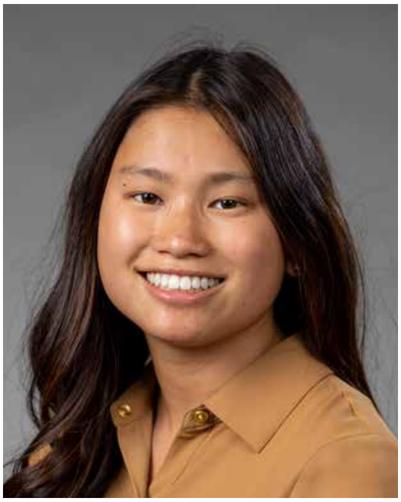
Building on messaging strategies in publications such as the NAE's *Changing the Conversation*, *Messaging for Engineering*, and *Raising Public Awareness of Engineering*, as well as the recently released *Messages Matter* from DiscoverE, The Circuit brightly conveys the creativity, wonder, and value of engineering and the role of engineers in creating our future.

Yannis C. Yortsos, dean of the USC Viterbi School of Engineering, said: "It is important to keep changing the conversation about engineering, which is the enabling discipline of our times, with a tremendous positive impact in creating a better world for all. This social media-focused program will reach people wherever they are and however they get their news."

Weekly episodes can be viewed at @CircuitNewsTV on Twitter, Instagram, Facebook, or YouTube. For links directly to these accounts, visit Linktr.ee/thecircuitnews. or 202-334-1741.

NAE Welcomes New Staff Members

INDIA AFRIYIE is the newest addition to the NAE Office of Outreach and Communications team. She will take the lead in communicating about the NAE, engineering, and engineers in ways that inform and engage diverse audiences about the beauty, power, wonder, excitement, and relevance of engineering in daily life. As a multimedia journalist for two years in Peoria, Illinois, India strengthened her writing, editing, interviewing, and creative skills, and she's eager to apply those skills to her NAE work. She received her bachelor's degree from Stevenson University and her master's from the University of Maryland. Born in Kumasi, Ghana, India came to the United States at age 3. When she's not at work, you can find her browsing at a thrift shop, perched at the top of an indoor rock wall, or exploring the nation's capital. And she's always open to discussing Taylor Swift's latest release or Harry Potter. India can be reached at IAfriyie@nae.edu or 202-334-1844.



CHESSIE BRIGGS joined the NAE Program Office March 13 as a senior program assistant. Her initial assignments are on projects related to the health risks of indoor exposures to fine particulate matter, extraordinary engineering impacts on society, and other CESER activities, and she also supports the NAE Awards program. She previously worked as a legislative intern for two members of the House of Representatives. Chessie completed her undergraduate education at the University of Redlands with degrees in public policy analysis and political science. In her spare time, she enjoys watching documentaries, visiting as many national parks as she can, and going on hikes. Chessie can be reached at CBriggs@nae.edu or 202-334-1741.

Calendar of Meetings and Events

July 17–20	2023 Japan-America Frontiers of Engineering Symposium Tokyo
August 2–3	NAE Council meeting Pasadena, California
September 10–13	The Grainger Foundation 2023 US Frontiers of Engineering Symposium University of Colorado Boulder
September 29–30	NAE Council meeting
October 1–2	**National Academy of Engineering Annual Meeting**

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

John C. Angus, 88, professor emeritus, Case Western Reserve University, died February 20, 2023. Professor Angus was elected in 1995 for research in the growth of diamond and diamond-like films by low-pressure chemical vapor deposition.

Ivo M. Babuska, 97, Robert B. Trull Chair in Engineering, Institute for Computational Engineering & Science, University of Texas at Austin, died April 12, 2023. Dr. Babuska was elected in 2005 for contributions to the theory and implementation of finite element methods for computer-based engineering analysis and design.

David K. Barton, 95, independent consultant, died February 11, 2023. Mr. Barton was elected in 1997 for contributions to radar system design and analysis.

Meyer J. Benzakein, 84, assistant vice president, Aerospace and Aviation Research, Ohio State University, died February 17, 2023. Dr. Benzakein was elected in 2001 for achievements in international technical cooperation and propulsion engine technology.

John E. Breen, 90, Nasser I. Al-Rashid Chair Emeritus, University of Texas at Austin, died February 14, 2023. Dr. Breen was elected in 1976 for leadership in the field of reinforced and prestressed concrete research specifically directed toward improving engineering design practice.

William J. Carroll, 99, chair emeritus, Montgomery Watson Harza, died February 23, 2023. Mr. Carroll was elected in 1987 for outstanding contributions to the advancement of water supply and wastewater system planning and design.

Gary L. Cowger, 75, chair and CEO, GLC Ventures LLC, died February 17, 2023. Mr. Cowger was elected in 2006 for contributions to the development and implementation of systems and methods that have dramatically improved flexibility, quality, and productivity in automobile manufacturing.

Fred N. Finn, 99, retired consulting civil engineer, Monticello, Illinois, died March 18, 2023. Mr. Finn was elected in 1993 for contributions in formulating fundamentally based analytical methods and procedures for pavement structures and in developing pavement management systems.

Ivan T. Frisch, 85, Presidental Fellow, New York University, died January 28, 2023. Dr. Frisch was elected in 2000 for innovation and implementation of data, voice, and integrated communication networks.

Richard J. Goldstein, 94, Regents' Professor and James J. Ryan Professor, University of Minnesota, died March 6, 2023. Professor Goldstein was elected in 1985 for his outstanding contributions in heat transfer measurement techniques and in film cooling, leading to improved efficiency of gas turbines.

Jessica E. Kogel, 63, associate director of mining, National Institute for Occupational Safety and Health, died January 25, 2023. Dr. Kogel was elected in 2019 for sustainable development and innovation of industrial clay products and processes.

Gordon E. Moore, 94, chair emeritus, Intel Corporation, died March 24, 2023. Dr. Moore was elected in 1976 for contributions to semiconductor devices from transistors to microprocessors.

Virginia Norwood, 96, retired manager, Hughes Aircraft Company, died March 26, 2023. Ms. Norwood was elected in 2023 for the original design and implementation of radar multispectral satellite systems forming the basis for Earth-observing Landsat missions.

C. Paul Robinson, 81, president emeritus, Sandia National Laboratories, died March 2, 2023. Dr. Robinson was elected in 1998 for pre– and post–Cold War leadership in the nation's nuclear weapons program through technical and managerial excellence.

Enders A. Robinson, 92, Maurice Ewing Professor Emeritus, Columbia University, died December 6, 2022. Dr. Robinson was elected in 1988 for pioneering contributions that have led to the evolution of seismic processing from hand digitization of the 1950s to today's custom deconvolution chip.

Stanley T. Rolfe, 88, Albert P. Learned Distinguished Professor Emeritus, University of Kansas, died January 23, 2023. Dr. Rolfe was elected in 1982 for major technical and educational contributions in applications of fracture mechanics to engineering design of structures such as bridges, pressure vessels, and ships.

Paul E. Rubbert, 83, retired Boeing Technical Fellow, Boeing Commercial Airplanes, died December 23, 2020. Dr. Rubbert was elected in 1993 for contributions to the development of computational fluid dynamics as an effective tool for aerodynamic design.

Shivaji Sircar, 75, Distinguished Research Fellow, Lehigh University, died February 13, 2020. Dr. Sircar was elected in 2004 for contributions to the fundamental science and technology of adsorption separations and their applications in process industries.

Charles R. Steele, 89, professor emeritus of applied mechanics and mechanical engineering, Stanford University, died December 9, 2022. Dr. Steele was elected in 1995 for contributions to the theory of thin shells, to understanding of human hearing, and to bioengineering.

Morris Tanenbaum, 94, retired vice chair and chief financial officer, AT&T Corporation, died February 26, 2023. Dr. Tanenbaum was elected in 1972 for achievements in solid state research and technology and in technology transfer from research to manufacturing.

Shoichiro Toyoda, 97, Honorary Chair, Toyota Motor Corporation, died February 14, 2023. Dr. Toyoda was elected a foreign member in 1994 for global leadership and the development and manufacture of fuel-efficient, high-performance, high-quality automobiles.

Harry L. Van Trees, 92, University Professor Emeritus, George Mason University, died December 29, 2022. Professor Van Trees was elected in 2015 for contributions to detection, estimation, and modulation theory and leadership of defense communication systems.

James G. Wenzel, 96, chair and president, Marine Development Associates Inc., died October 26, 2022. Mr. Wenzel was elected in 1975 for leadership in the applications of technology to ocean engineering, and the development of the Navy's deep submergence rescue system.

Wm. A. Wulf, 83, AT&T Professor of Computer Science and University Professor Emeritus, University of Virginia, and former NAE president, died March 10, 2023. Dr. Wulf was elected in 1993 for professional leadership and for contributions to programming systems and computer architecture.

Abe M. Zarem, 106, founder, Frontier Associates, died March 8, 2023. Dr. Zarem was elected in 1987 for distinguished achievements in developing and applying space power and propulsion devices, and for creation of sophisticated electro-optical night vision equipment.

Jacob Ziv (NAS), 91, Technion Distinguished Professor Emeritus, Technion-Israel Institute of Technology, died March 25, 2023. Dr. Ziv was elected a foreign member in 1988 for contributions to semiconductor devices from transistors to microprocessors.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